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NTNU
Norwegian University of Science and Technology

Doctoral thesis

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ISBN 978-82-326-6751-2 (printed ver.)
ISBN 978-82-326-5534-2 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (electronic ver.)

Doctoral theses at NTNU, 2021:143

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PRINTED IN NORWAY
NO - 1598

NORDIC SWAN ECOLABEL
Printed matter
2041 0731

Printed by Skipnes Kommunikasjon AS

To my wife Kate and daughter Maya

Abstract

The present work focuses on the development of a novel application that aims to better understand energy-related indoor occupant behaviour (OB). The thesis briefly introduces the key features of OB, presents the current state of the art and highlights the present challenges related to this field. The goal of the thesis is to present how potential challenges can be addressed with the use of a novel monitoring technique for in-situ occupant tracking. It is a depth registration technique that has practical implementations in various applications focusing on surface scanning. The main goal of the use of this technique in OB studies is to increase the quality of the measurement resolution to better understand the reasons for occupant activities regarding indoor energy use. It is expected that with an increase in the measurement resolution, it will be possible to observe and collect new information about occupants and their energy utilization. Therefore, it will be possible to detect avoidable waste of energy.

The proposed monitoring technique has not previously been commercially implemented in this research domain. Thus, there were no guidelines allowing for quick implementation. The methodology presented in the thesis describes step-by-step all the basic information required to understand the ideas and proposals for device utilization. Extended explanations are included in the appendices, and each subchapter refers to relevant appendices. Beyond the direct monitoring of occupants, the thesis explains the use of the collected data and shows how the data can be implemented in an agent-based model (ABM). The proposed model focuses on direct simulation of an occupant's activities by recreating these activities through the portrayal of the occupant as an agent. The main functionalities that are provided by the model enable simulation of occupant movement, sensation of the thermal environment, interaction with indoor appliances and decision-making processes. The results obtained from the simulation show that a novel approach for the simulation of occupants is achievable. The OB represented by the ABM can be implemented as a calculation engine, which considers the occupant's actions as activity triggers. The model is designed to connect various scientific specialities that focus on OB aspects, and combines each of the aspects into one common platform. The communication between scientific specialities that can be initialised by the proposed platform will bring a greater understanding of energy-related OB. Consequently, it may lead to a greater reduction in the use of energy resources without compromising occupants' indoor comfort.

Acknowledgements

I would like to express my gratitude to my supervisor, Professor Vojislav Novakovic, for his support, advices and encouragement. Thanks to his patience and understanding, through the past four years, I was able to fulfil all the targeted research goals. Beyond that, due to Professor Novakovic's persistent motivation, I was able to establish helpful network and numerous collaborations that have enriched my professional and private life.

Additionally, I want to express my sincere appreciation to my co-supervisor, Professor Da Yan from Tsinghua University. In 2017 Professor Yan was hosting me during my one-year research exchange, and thanks to his support and welcome I was able to feel that I belonged to his research group Sustainable Energy Systems. Thanks to this research exchange, and the environment provided during this period, I was able to become accustomed to a different culture without feeling isolated. During this stay, I was able to formulate many influential ideas that were implemented in my subsequent work.

Next, I would like to express my gratitude to other members of the Norwegian University of Science and Technology: Professor Arild Gustavsen and all the members of the ZEB/ZEN project, for their support and for allowing me to use their research facilities; Associate Professor Laurent Georges, for his advices and for sharing his thoughts regarding numerical problems; Professor Guangyu Cao, R&D Coordinator Liv-Inger Stenstad and Managing Director Jan Gunnar Skogås, both at Operating Room of the Future St. Olavs hospital, for the invitation to participate in the NorMIT project; Professor Per Olav Tjelflaat and Professor Hans Martin Mathisen for fruitful sharing of their perspectives regarding HVAC systems in buildings; Senior Engineer Eugen Uthaug for his tremendous IT support; and the entire EPT Administration for their help in solving various administration issues.

During the period of my PhD (2016-2020) I participated in two international projects inside the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC), Annex 66 Definition and Simulation of Occupant Behaviour in Buildings and Annex 79 Occupant-Centric Building Design and Operation. Both these projects were close to my research interest and allowed me to get first-hand experience and thoughts from leading international scientists, focusing on occupant behaviour phenomena. This allowed me to identify existing knowledge gaps and define my research topic. Both projects gathered approximately 100 participants, which makes it hard to list everyone. Therefore, I would like to express my gratitude to all the projects' participants. It has been a pleasure to be a part of such an inspirational community.

In the words of the African proverb, to raise a child, you need a whole village. I would like to re-phrase that and claim that, to do a PhD, you need an entire community. Beyond strictly focusing on work and the research topic, it is necessary to have time for discussions, creative procrastination, mental support and entertainment. Therefore, I would like to express my gratitude to Dmytro, Daniel, Tymoffi, Peng, Maria, Amar, John, Masab, Artur, Markus, Ignat, Haoran, Nicola, Zsofi, Mehrdad, Elyas, Xingji, Michał, Mateo, Yash and Anooshmita.

Finally, I would like to express my sincere gratitude to my family, Katarzyna and Maja; my parents Jerzy and Janina; and my parents-in-law Mirosław and Małgorzata. Without your understanding and support, I would not have been able to finish this thesis. Therefore, my gratitude towards you is beyond measure!

List of papers

Paper No.1 J. Dziedzic, D. Yan, V. Novakovic; Occupant migration monitoring in residential buildings with the use of a depth registration camera; Procedia Engineering 205; 2017; 1193-1200. Conference Paper

Paper No.2 J. Dziedzic, D. Yan, V. Novakovic; Measurement of Dynamic Clothing Factor (D-CLO); Proceedings of the 4th International Conference on Building Energy & Environment 2018; 208-212. Conference Paper

Paper No.3 J. Dziedzic, D. Yan, V. Novakovic; Real-Time Measurement of Dynamic Metabolic Factor (D-MET); Cold Climate HVAC 2018, Springer Proceedings in Energy; 2018; 677-688. Conference Paper

Paper No.4 J. Dziedzic, V. Novakovic; Occupant behavior modeling based on migration registration technique; ENERGODOM 2018, IOP Conf. Series: Materials Science and Engineering 415 (2018) 012044. Conference Paper

Paper No.5 J. Dziedzic, D. Yan, V. Novakovic; Indoor occupant behaviour monitoring with the use of a depth registration camera; Building and Environment; 148; 2019; 44-54. Journal Paper

Paper No.6 J. Dziedzic, D. Yan, V. Novakovic; Framework for a transient energy-related occupant behaviour agent-based model; REHVA 2019/5, 39-46. Conference Paper

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Paper No.8 J. Dziedzic, D. Yan, V. Novakovic; Evaluation of the occupants' exposition to the indoor environment; IAQVEC; IOP Conf. Series: Materials Science and Engineering 609 (2019) 042066 Conference Paper

Paper No.9 J. Dziedzic, D. Yan, H. Sun, V. Novakovic; Building occupant transient agent-based model - Movement module; Applied Energy Journal; Journal Paper

Paper No.10 J. Dziedzic, D. Yan, V. Novakovic; Exploring possibilities to quantify the qualitative description of occupant behaviour, BuildSim Nordic 2020, Conference Paper, Under Review

Paper No.11 A. Das, J. Dziedzic, M. Annaqeeb, V. Novakovic, M. B. Kjærgaard; Human Activity Recognition Using Data Fusion and Deep Learning Methods, Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Journal Paper, Under Review

List of abbreviations

ABM	- agent-based model
ASHRAE	- American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEMS	- building energy management system
BIM	- building information modelling
BMI	- body mass index
BOT-ABM	- building occupant transient agent-based model
BPS	- building performance simulation
BSA	- body surface area
CDFs	- cumulative distribution functions
CFD	- computational fluid dynamics
CLO	- clothing insulation levels
DBSCAN	- density-based scanning clustering technique
D-CLO	- dynamic clothing factor
DeST	- Designer's Simulation Toolkit
D-MET	- dynamic metabolic factor
EPA	- United States Environmental Protection Agency
E-SM	- extended skeleton model
GUI	- graphical user interface
HSV	- hue, saturation and value colour map
HVAC	- heating, ventilation, and air conditioning
IDA ICE	- IDA Indoor Climate and Energy
LIDAR	- light detection and ranging detection systems
MPC	- model predictive control
MR	- metabolic rate
OB	- occupant behaviour
OBFMU	- OB functional mock-up unit
PIR	- pyroelectric infrared sensor
PMV	- predicted mean vote
PPD	- predicted percentage dissatisfied
REHVA	- Federation of European Heating, Ventilation and Air Conditioning Associations
RGB-D	- red, green and blue channel + depth colour channel
SD	- standard resolution
SDK	- software development kit
SM	- skeleton model

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1. Introduction

1.1. Motivation

At present, the target of civilization and the focus of research is on lowering energy use in all sectors. According to the annual reports of the International Energy Agency, the building sector is responsible for approximately 40% of total annual energy use [1]. This portion has been stable over the years and has not decreased despite the significant improvement in energy-saving technologies. The one of the main priorities of the United Nations Millennium Development Goals [2] is to reduce the general energy use. Regardless of the scenarios for climate change or population growth that will occur, the issue of appropriate energy demand management has to be resolved. During recent decades, research has mainly focused on addressing building energy management using a top-down approach [3], [4]. The main feature of the approach was to observe total energy use at different temporal and spatial resolutions. Doing so would make it possible to track particular patterns related to daily/weekly/seasonal rhythms and to display them at the resolution of individual buildings, neighbourhoods, districts or entire cities, making it possible to classify or cluster patterns that share similar properties [5]. The main goal of this application was to visualize the metabolism of the whole observed region and to try to capture the energy use dynamics and use this information to control the system. Such an application was intended to complete its task using an approach focusing on the reduction of peaks in the power demand, but such an effect was not obtained. The conclusions provided by researchers have shown that the limited amount of classifications is insufficient to achieve such ambitious goals [6]. As proposed by Hensen and Lamberts [7], to address this issue, the whole energy management problem should be solved through the use of a bottom-up approach, where each influential parameter of the system should be recognized and taken into account [8]. The debate between the bottom-up and top-down approaches is parallel to the discussion about the black box and white box model concepts in mathematical modelling. Both are theoretical model concepts, and each has its own positive and negative aspects.

On the one hand, the black box model represents a simplified description of phenomena that do not require a fundamental understanding of the modelled system. It is a simple input–output model that provides an output that can be considered reliable if the input information fits the model training parameters. On the other hand, it blurs the information about the details of the system that might be crucial markers of system operation. The white box model focuses on each element of the system separately, expressing the essential characteristics. This solution introduces nearly infinite complexity because it requires individualization on a global scale of observation. Each part of the system is identified and described. Therefore, it is necessary to find a balance between the two approaches and to introduce an acceptable compromise.

One of the biggest challenges in building performance simulation is the implementation of occupant behaviour (OB) in the observation spectrum. Occupants are the main energy users in a building. It is supposed that OB causes performance gap between monitored, and simulated building energy use [7]. From the perspective of the whole building management system, occupants tend to have specific patterns of behaviours, but this generalization does not produce representative results that would increase the overall forecast accuracy. According to the present findings presented in the IEA EBC Annex 66 final report, current research should aim to expand the monitoring and simulation resolutions of features related to occupant behaviour [9]. Previously conducted studies usually aimed to observe one specific occupant-related phenomenon, such as the operation of windows or blinds, thermostat adjustment, the occupancy state, indoor air property dynamics, and plug load metering. Such research enabled essential insights into building operation, and a combination of these inputs was used to define occupant profiles [8], [10]–[12]. However, as presented by Dong et al. [13], the sum of all these inputs transformed into numerical models does not guarantee the successful representation of energy-related OB.

Current directions suggested by the scientific community involved in OB research aim to directly detect the occupants' involvement in specific activities [9]. Such detection would make it possible to increase our insights into the activities performed indoors. A combination of this type of detection with already existing inputs would enable a tool for profiling occupants and their energy use and would make it possible to identify individual occupant energy profiles and label their activities. Such a tool would make it possible to combine already existing knowledge about energy use in buildings and to introduce a fit-for-purpose building design and control. The major obstacle is the lack of widely available, market-ready solutions that would provide the necessary information, which can be considered an opportunity to discover new measurement methodologies.

1.2. Objective and research questions

To fill the existing gap in occupant detection, we proposed to investigate the possibilities for the acquisition of data on the behaviour of individual occupants. To do so, it was necessary to review the existing motion capture technology that would enable the indirect identification of individual users of indoor space.

The scope of this thesis was to investigate new possibilities for detecting building occupants with a temporal and spatial resolution able to capture their activities. The operational resolutions should make it possible to pinpoint the occupants involved in each single energy-related event. Therefore, the research target is to investigate the applicability of a depth registration technique for capturing indoor OB. The selected monitoring technique specifications allow for an in-situ capture of occupants' activities. The technique does not influence their routines and requires only their passive engagement. Devices that are capable of registering depth are usually stationary. Therefore, the application of this technique in building monitoring should not be different from other, already known measuring techniques, like passive infra-red sensors or plug load meters. The hypothesis has been proposed that an increase in the spatial and temporal measurement resolution of indoor activities can give valuable insights into the relation between OB and building energy use. The investigation of the correctness of the hypothesis is supported with an attempt to answer three research questions.

Research question No. 1: Is it possible to increase the temporal and spatial resolution of OB sensing?

Research question No. 2. How can the new type of information contribute to current knowledge about OB?

Research question No. 3. How can the increased insight into OB be implemented in existing building performance simulation (BPS) tools?

Answers to these questions will be elaborated in the following text. The presented thesis is a summary of conducted studies that have been published over the past four years. This thesis is supported by eleven published scientific papers that are attached to the thesis. Each publication provides a specific contribution to answering the research questions.

1.3. Development steps and scope of the thesis

Occupant-related studies should aim towards the implementation of agent-based modelling techniques in the simulation of OB. The development of a comprehensive model that can be implemented as an energy co-simulation tool requires a significant amount of resources and time. Managing this task requires the setting up of a proper framework of model development that is supported by a reliable source of data that can be transformed into proper functionalities and sub-parts of the model. A description of the entire procedure, which starts with the core data collection and is followed by framework establishment and model development, will be a crucial feature of this thesis. The development of the answers to each research question will be addressed in the methodology chapter. In addition, each research question will be supported by a separate sub-section of the results chapter. The overall state of the model and future direction of development will be described in the discussion chapter, and the implications of model implementation will be explained in the summary chapter. To make the development process more readable, the chapters in this thesis will follow a description as displayed in Figure 1.

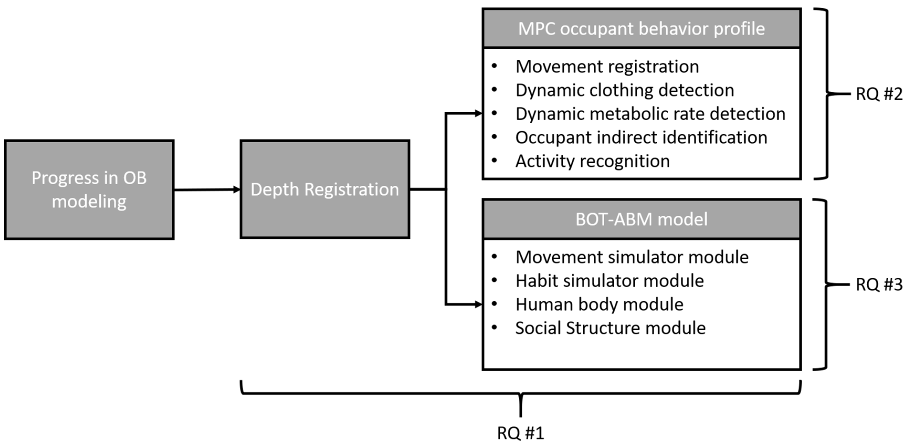

Figure 1. Thesis flow chart graph

To better enable the reader to understand how the papers address the research questions, a list of the publications with pinpointed main features and a relationship between the published papers and the specific research question (Table 1) are presented below. Papers are sorted by chronological publication order.

Paper No.1 J. Dziedzic, D. Yan, V. Novakovic; Occupant migration monitoring in residential buildings with the use of a depth registration camera; Procedia Engineering 205; 2017; 1193-1200. Conference Paper

- The first introduction of the Microsoft Kinect used for precise occupant monitoring.
- Development of an algorithm for depth data accusation.
- Recognition of device functionaries for occupant behaviour studies.
- One of the first occupant behaviour test cases with the use of the Zero Emission Building Living Lab.

Paper No.2 J. Dziedzic, D. Yan, V. Novakovic; Measurement of Dynamic Clothing Factor (D-CLO); Proceedings of the 4th International Conference on Building Energy & Environment 2018; 208-212. Conference Paper

- The data fusion of streamed Microsoft Kinect outputs.
- The ability for on-line measurements of occupant clothing.
- Integration of the clothing thermal insulation values with real-time readings.
- Outline for further research related to clothing detection and in-situ occupant behaviour monitoring.

Paper No.3 J. Dziedzic, D. Yan, V. Novakovic; Real-Time Measurement of Dynamic Metabolic Factor (D-MET); Cold Climate HVAC 2018, Springer Proceedings in Energy; 2018; 677-688. Conference Paper

- Application development for in-situ on-line investigation of occupants' activity.
- Direct link of the recorded output with occupants' thermal comfort and metabolic rate.
- Integration of the human activity metabolic rates values with real-time readings.

Paper No.4 J. Dziedzic, V. Novakovic; Occupant behavior modeling based on migration registration technique; ENERGODOM 2018, IOP Conf. Series: Materials Science and Engineering 415 (2018) 012044. Conference Paper

- The first iteration of an agent-based model for simulation of occupants' indoor transitions.
- Implementation of the basic functionaries that mimic human transitions.
- Development of the outline for a fully procedural transition of the agents.
- Highlighting the complexity of the movement simulations for BPS purposes.

Paper No.5 J. Dziedzic, D. Yan, V. Novakovic; Indoor occupant behaviour monitoring with the use of a depth registration camera; Building and Environment; 148; 2019; 44-54. Journal Paper

- Formulation of in-situ based occupant monitoring profile.
- Combination of all the utilisations of depth monitoring applications into one application.
- The ability for a holistic description of energy-related occupant behaviour in residential spaces with high granularity.
- Outline for further development of the application for identification of activities and personalised control of HVAC.

Paper No.6 J. Dziedzic, D. Yan, V. Novakovic; Framework for a transient energy-related occupant behaviour agent-based model; REHVA 2019/5, 39-46. Conference Paper

- A summary of the existing independent agent-based model implemented in BPS.
- The proposition of the new platform for simulation of occupant behaviour as an independent agent.
- Overview of functionalities that have to be implemented to provide functional mock-up.

Paper No.7 J. Dziedzic, M. Annaqeeb, D. Yan, V. Novakovic; Zone layout simulator for energy-related occupant behaviour modelling; Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019), 2020 Conference Paper

- Development of the application of autonomous design of the indoor layouts.
- The ability for rapid prototyping of the layout to investigate its impact on occupant energy-related behaviour.
- Tool for the established agent-based model framework.
- The preliminary study was focusing on one type of room (kitchen).

Paper No.8 J. Dziedzic, D. Yan, V. Novakovic; Evaluation of the occupants' exposition to the indoor environment; IAQVEC; IOP Conf. Series: Materials Science and Engineering 609 (2019) 042066 Conference Paper

- Merge of depth data output with computational fluid dynamics.
- Ability to explore the whole human body exposition to the indoor environment.
- Development of the tool that can use data from activity monitoring and simulations.
- Fundamental application for simulation of occupant thermal reaction based on the sensed environment.

Paper No.9 J. Dziedzic, D. Yan, H. Sun, V. Novakovic; Building occupant transient agent-based model - Movement module; Applied Energy Journal; Journal Paper

- First fully functional module of building occupant transient agent-based model (BOT-ABM).
- Ability to simulate an independent transition of occupants within linear scalability.
- Investigation of pathway likelihood selection among occupants.
- Ability to simulate in any geometrical layout without the need for predefine of movement maps.
- Validation of the designed solver.

Paper No.10 J. Dziedzic, D. Yan, V. Novakovic; Exploring possibilities to quantify the qualitative description of occupant behaviour, BuildSim Nordic 2020, Conference Paper, Under Review

- Development of the action-driven solver.
- Simulation tool that generates qualitative outputs from quantitative input.
- Simulation of occupants' indoor interactions and relationships.

Paper No.11 A. Das, J. Dziedzic, M. Annaqeeb, V. Novakovic, M. B. Kjærgaard; Human Activity Recognition Using Data Fusion and Deep Learning Methods, Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Journal Paper, Under Review

- Development of the indoor occupants' activity labelling tool
- Design of the calibration and labelling application for combining multiple data sources
- Acquisition and formulation of occupants indoors action database
- Validation of the developed tool

The relation between the published papers and the specific research questions is presented in Table 1.

	P No.1	P No.2	P No.3	P No.4	P No.5	P No.6	P No.7	P No.8	P No.9	P No.10	P No.11
RQ #1	X	X	X		X			X			X
RQ #2					X	X			X	X	X
RQ #3				X		X	X	X	X	X	

Table 1. Relation between the published papers and the specific research question

2. Literature review

2.1. Occupants in buildings

2.1.1. First steps toward acknowledgement

According to the United States Environmental Protection Agency (EPA) report [14], humans spend approximately 90% of their lifetime indoors. This fact considers the sum of time spent inside residential, public and commercial buildings. Additionally, as studies have shown [15], occupants are the main reason for the energy use in buildings. The annual building energy budget mainly consists of the energy used to provide an acceptable indoor environment quality and to support occupants' activities, habits and needs.

The reasons behind specific behaviours are nearly infinite. Each person has a preference that can be motivated by more or less logical arguments [16]. Therefore, it is difficult to define the ultimate rule or scripts of behaviour. However, the importance of occupants and their demands on buildings has already been observed. Since the beginning of the previous century [17], the well-being and sensation of comfort of building users have been a target. As claimed, indoor well-being is directly connected to human health, and any omissions in this respect might have serious long-term consequences [18], [19], [20]. The research and discoveries of Fanger and his team have made it possible to formulate appropriate theories that allow us to evaluate occupants' comfort on a global user level [21]. The proposed evaluation methodology has become so influential that it has become a global standard for the evaluation of indoor occupant comfort, as acknowledged by international heating, ventilation, and air conditioning (HVAC) organizations such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) [22], [23].

By offering solutions for comfort evaluation, a new branch of building-related science, in which human comfort was the centre of interest, was developed. The extended focus on this subject has allowed the parameterization and formulation of theories regarding human body thermoregulation that made it possible to support the building design process. With the scientific development of a uniform comfort evaluation method, it became possible to examine a proposed building design during the design phase [24], [25]. Additionally, parameterization has made it possible to benchmark specific designs and to highlight the most prominent solutions. In other words, once occupant thermal comfort was defined, it was possible to quantify it. The main challenge connected to this methodology is its access to the operational parameters.

The methods proposed by Fanger [21] operate based on a number of equations:

$$H - E_d - E_{sw} - E_{re} - L = K = R + C$$

$H - Internal\ heat\ production\ in\ the\ human\ body$
$E_d - Heat\ loss\ by\ water\ vapour\ diffusion\ through\ skin$
$E_{sw} - Heat\ loss\ by\ evaporation\ of\ sweat\ from\ skin\ surface$
$E_{re} - Latent\ respiration\ heat\ loss$
$L - Dry\ respiration\ heat\ loss$
$K - Heat\ transfer\ by\ radiation$
$R - Heat\ transfer\ by\ radiation\ from\ clothing\ surface$
$C - Heat\ transfer\ by\ convection\ from\ clothing\ surface + others$

$$H = M - W$$

$M - Metabolic\ free\ energy\ production\ per\ unit\ body\ area$
$W - External\ mechanical\ work\ per\ unit\ area$

Some variables used in these equations (e.g. surface temperature and partial pressure of water vapour in the air) can be obtained by simple measurements or calculations However, the mean radiant temperature needed for calculation of the parameter R is a difficult parameter to establish. Specifically, this parameter requires an assumption to be made regarding the furniture placement state that does not reflect reality. To simplify the calculation process, it is assumed that the measurement point of the mean radiant temperature is exposed in an unfurnished room. However, such conditions are not typical. Nevertheless, it is understandable that, due to past computational limitations, such an assumption was necessary.

Despite the criticism that this methodology has received over the years [26], [27], it has remained a measure that can be considered valid. Notably, the main calculated variables are the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD). Both variables operate on a subjective perception of thermal comfort. Therefore, it might be considered as a supportive indicator for thermal comfort assessment, and it cannot be considered an ultimate measure.

The offspring of the solutions presented by Fanger includes the following. The reintroduction of the adaptive comfort model proposed by de Dear [28] has provided complementarity to the previously developed method [29] and indicates the importance of the occupant's insulation level. Melikov's solution [30] for personalised ventilation initialises the discussion about thermal preferences on an individual level. Additionally, it showed the engineering challenges connected with the fit-for-purpose design solutions. Other essential parameters have been taken into account, such as the CO_2 concentration [31] or overall contamination and odour [32], and the issues connected to indoor comfort have started to extend toward a more comprehensive definition.

2.1.2. Occupant behaviour

Beyond occupants' thermal comfort, it was necessary to define a term that would bind the whole spectrum of the demands concerning indoor conditions and human interactions with building appliances. According to the definition provided by M. Schweiker [33], one of the scientists from IEA EBC Annex 66, indoor OB is a "human being's unconscious and conscious actions to control the physical parameters of the surrounding built environment based on the comparison of the perceived environment to the sum of past experiences".

This definition not only takes into account all information about the indoor environment but also attempts to cover the expectations and activities of occupants, as well as the dynamics related to their interactions with the indoor environment. The scientific community that focuses on investigations related to energy-related OB is trying to define all the drivers of occupant activities. The proposed approach can provide a broader picture of human activities and does not explain all activities only by their thermal comfort. The main research interest of OB studies is the interactions with the appliances (broadly understood) installed in buildings. The scope of investigations relies on the observation of related parameters: thermostats, windows, blinds, artificial lights, the CO_2 concentration, pyroelectric infrared (PIR) sensor responses or readings from plug load meters. Many studies have attempted to capture OB using these "classic" methods, which operate on a simple signal interpretation. Table 2 summarizes the advances in this field:

	Reed switches	Light switches	Plug load	PIR sensors	Temperature	Humidity	Air velocity	CO_2 sensors	Sound	Survey	Pressure	Illumination	Thermal array sensors	Wireless sensor	Digital video camera	VOC	Depth	Tweeter	Ultrasonic distance sensor
[34]																	x		
[35]										x		x							
[36]				x	x														
[37]															x				
[38]		x		x															
[39]																	x		
[40]				x															
[41]		x			x							x							
[42]					x									x					
[43]	x	x		x	x	x		x											
[44]	x			x															x
[45]		x										x			x				
[46]				x	x	x		x	x			x							
[47]		x			x	x		x						x	x				
[48]															x				
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[66]				x	x	x		x	x							x			
[67]	x			x										x					
[68]					x	x	x					x							
[69]															x				

Table 2. Brief overview of monitoring methods used in occupant-related studies

By observing the trends in the related research field, it is possible to conclude that more studies are being conducted trying to capture OB in a more holistic manner. By combining several available inputs, the conducted measurements are trying to draw a clearer picture of OB. This is an appropriate direction but, as pointed out by Yan et al. [8], future development should make it possible to formulate the individual profiles of occupants. If there are no tools capable of identification based on data provided by devices in a monitoring rig, it will be difficult to extend existing knowledge. The data collected in such a process may contribute to the overall observation database, but they will not make it possible to extend our general understanding of OB. When observing occupants without any identification method, it is difficult to define their real nature. Current activity monitoring solutions focus on a few specific phenomena rather than on observing the process as a whole. With such solutions, it is challenging to determine the origin of a specific state.

Therefore, we propose to gather inputs that make it possible to identify the origins of a particular behaviour [70]. In such identification there is no need for direct person recognition, but only to make it possible to tie the registered activities to the specific occupant and to use the information for further processing. Such application will support the formulation of an occupant profile and potentially the forecasting of the occupant's activities. It is anticipated that once all system users are recognized and their profiles are formulated, it will be possible to formulate a more precise model for simulation and control purposes.

2.2. Occupants during the design process

2.2.1. Occupant modelling

Due to the extensive monitoring of activities of occupants in buildings, it has been possible to formulate models that describe various activities. In most cases, the model is based on observation of one specific phenomenon. Therefore, it is possible to find multiple models that focus on a similar phenomenon but with the local state as the context. As Gaetani et al. [71] proposed, there must be an appropriate mapping of the model used to make it applicable. There are comprehensive reviews of the existing OB models [8], [13] and the numerical methods that are being used. Based on these reviews, it is possible to formulate a picture of the investigated applications, the modelling area, and the modelling techniques used for numerical simulation (Figure 2).

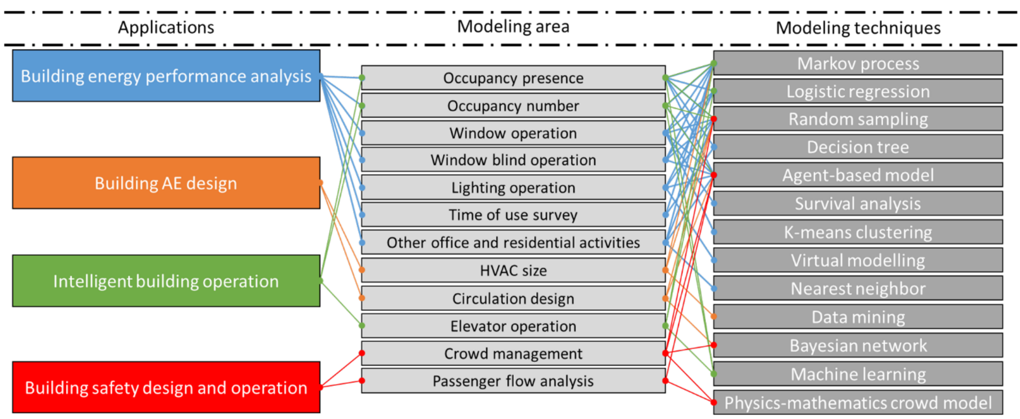

Figure 2. Comparison of various modelling techniques, modelling areas, and potential applications

Most of the modelling techniques presented in Figure 2 are based on classical sensor outputs, where the approaches that attempt to capture OB as a whole are unique. Most of the developed models were introduced to a number of BPS tools , such as EnergyPlus [72], [73], IDA Indoor Climate and Energy (IDA ICE) [74], [75] and the Designer's Simulation Toolkit (DeST) [35], [76], that use co-simulation methods, where each particular phenomenon is covered by the separate model or software. This method could be considered as a possible solution, but it has some shortcomings. Based on the overview shown in Figure 2 of each of the sub-parts of the BPS tools offering solutions for OB, there are obstacles regarding the time resolution of the model. For energy simulations, upscaling the high time resolution is not a major issue. For an annual simulation, fluctuation of the weather data on the level of minutes or seconds will not dramatically influence the overall results. A similar situation will apply to the building's physical properties. The physical properties of construction materials are assumed to be static, even though they may be dynamic. However, they will probably not drastically influence the annual simulation horizon. The main parameters that are sensitive for time resolution are automatic control and simulation of occupants. Testing the various control strategies found in publications [77], [78] requires an increase of the simulation time resolution, at least to the level of the resolution of the tested controllers. Doing so will make it possible to appropriately tune the controller performance and its behaviour.

To describe the challenges connected to the simulation of occupants, it is necessary to define the activities of building users as they are portrayed by social behaviourists and to compare them with the numerical tools available. Each person operates based on a set of rules, and their activities, according to the theory of planned behaviour, follow a certain plan [16], [79], [80]. It is expected that each activity performed has a reason grounded in a reaction to a previous event, occupancy routine, belonging to a particular social group, or physical or psychological needs/preferences [81], [82], [83], [84]. This categorization does not evaluate the correctness of the activities performed. The ability to adequately perform most activities depends on a specific measure used to evaluate the same activity. A specific decision made by an occupant may not be considered energy-efficient or may be considered discomforting, but it has to be assumed that it is the conscious decision of the occupant. This does not mean that if appropriate training is introduced to this individual, his or her behaviour will not shift toward the training goal. In most cases, the activities of occupants are considered deterministic [85]. This statement can be considered undisputable, and it has a significant influence on the whole concept of OB simulations.

If the sum of all activities performed is representative of a group of occupants, then simulating their behaviour using probabilistic and stochastic methods is justified. If the observation methods for model formulation do not allow for personal profile generation, such an approach is the only option. This does not block the possibility of performing a similar simulation using a composition of the individual behaviour profiles. Such simulation increases the computational complexity exponentially with the number of simulated occupants included in the simulation. To simulate individual OB, it is necessary to implement different mathematical methods. The individual activities of occupants are not the effect of spontaneous decisions and random activity. As explained by the theory of planned behaviour [16], it is assumed that each individual follows his or her own particular plan or procedure.

On the other hand, such simulation cannot be strictly rule-based due to the nearly infinite possibilities of rule application. Therefore, the proposed methodology has to operate as if it is capable of individuality. It can learn over time when exposed to knowledge, and it can make mistakes that can be corrected or evaluated. Based on the current scientific proposal [7], [86], [13], a new model should capture the record and decision-making process to evaluate whether an activity was planned or reactive. At the same time, the structure of the model cannot be rigid, and it should hold a certain degree of freedom. It is proposed that the next iteration of OB models should use agent-based modelling techniques.

2.2.2. Agent-based modelling of occupant behaviour

The mathematical methodology that is closest to provide a “similar to human nature” response is agent-based modelling. In terms of application, an agent can represent a being that has its own properties and functionalities, which can be tested in a simulation environment [48], [64], [87]. Regarding application, the use of this method makes it possible to mimic the natural properties of the observed phenomena by feeding it inputs that are directly related to the phenomena. For example, to simulate the behaviour of a hunting bat seeking its prey with the use of echolocation, it is necessary to define the spread of the echo waves in a simulation environment and the basic properties of the bat and the prey, such as their location and transition speed, in a time step. The last part is a rule of the behaviour of both simulation participants [88]. With this simple set of rules, it is possible to test existing sophisticated simulations that can be enriched even more by additional properties or boundaries. This simulation methodology promotes a modular model design that can be implemented gradually. The main disadvantage of applying this type of methodology is access to data and the reproducibility of the simulation. Such drawback was reported in a multiple studies focusing on an agent-based model (ABM) investigating natural phenomenon [89]–[91]. To define the rules of simulation, it is necessary to gain significant insights into the simulated phenomena covered by the comprehensive observations with a detailed recording.

The validation of the model, which has to do with testing its stability, can be performed only in a highly limited environment. If the agent finishes a targeted goal within a limited time and without crossing specific boundaries, the simulation test obtains a positive result. If the agent violates any rules, the simulation test obtains a negative result [92]. Establishing the performance baseline is highly critical. For agent-based modelling, it assumed that the baseline is an operation with random parameters for each module. Modules are sub-parts of the entire ABM that focus on one functionality. A module can have one or more parameters that can be described by a variable, a state or a status. Therefore, there is a substantially low chance of passing the baseline test. To prove the usability of the implemented solution, each single module of the OBM can be introduced using the connection matrix, where the first case is a baseline and the last case is a combination of each module that operates based on its functionalities and tuned parameters. Once the goal is reached, the OBM can obtain a positive simulation outcome, which allows different combinations of modules to be sorted. The main issue is how to evaluate the potential new extension. The OBM will perform correctly, and it will obtain a positive simulation test result, but there is no procedure for claiming that a specific set of activities performed by the agent is more or less human-like. It is possible to increase the baseline threshold, but this operation will not solve this issue if the commitment to the specific activities depends on a multiparametric function that depends on a previous activity history, a simulated desire/plan and exposure to a particular environment. The purpose of applying agent-based modelling is to observe the process instead of directly solving the problem.

3. Methods

3.1. Occupant tracking - Methods

3.1.1. Fundamentals of occupant tracking - Methods

There are many techniques that can be used to track occupant activities with an acceptable resolution. In short, it is possible to divide all these techniques into two main categories: wearable and non-wearable.

Each measuring method has its own advantages and disadvantages. Each wearable measuring tool (such as a data stream from smartphone accelerometers and magnetometers) can provide direct personalized data, but it cannot provide constant coverage of each activity. With this type of data collection, it has to be acknowledged that there is no guarantee that the wearable device will be worn by a person each time he or she moves around indoors. Therefore, such devices leave room for a lack of information, and the data might not be reliable. Similar concerns can be raised about any other wearable feature or device. It might not include visitors and/or it might produce false data about indoor movement patterns.

On the other hand, fixed position registration devices can provide reliable data resources, but the information extraction procedure is more demanding. This monitoring technique will register any potential activity within its range of operation when it is operating properly. This aspect is an important factor because it provides data collection reliability. The whole measurement procedure should be implemented according to the in-situ principle, as defined in subchapter 1.2. Therefore, no monitored participant should actively participate in the process of data collection. This means that no kind of switch or data log board should be used for the registration process. Beyond all the reasons listed above, the selected monitoring solution should not raise privacy concerns, and it should allow only indirect identification.

To comply with all of the restrictions noted above, there are only a few market-ready, viable solutions that can provide occupant tracking information: light detection and ranging (LIDAR) detection systems, stereovision cameras, multi-frequency Wi-Fi analyser, and depth registration cameras. LIDAR systems have already been implemented based on the systems available on the market [93], [94], but the proposed system does not make it possible to go beyond recognition of the position of the occupant. Additionally, the device has a constant moveable part (for high frequency sampling for ultrasonic probing), which might influence the operational lifetime of the device. Promising studies by researchers from the University of Southern Denmark have shown the capabilities of stereovision cameras. Such cameras make it possible to track occupants and, as proposed in the specifications of the leading manufacturer, they enable a partial identification (via height) of occupants and their selected pathways. This application has great potential to become a standardized solution for large spaces. The main advantage of this application is its ability to cover large spaces and to track multiple occupants simultaneously. The main disadvantage is its relatively weak performance in narrow environments, which will limit the view of the device, and will reduce its measurement potential. Such devices do not have a specific limit in detecting the number of occupants. Additionally, this type of measuring device is considered expensive; thus, its applicability should cover the main arteries of a building so as to detect the main stream of occupants [95], [96]. The use of a multi-frequency Wi-Fi analyser is the most promising technique because such devices are able to register the activities of individual occupants. They operate based on a reflection analysis of the Wi-Fi waves propagated on a few different frequencies, which makes it possible to track the reflection of the wave propagation of the surroundings while penetrating walls and other obstacles. While drawing a differentiated picture of obstacles, these devices make it possible to detect differences if the objects are dynamic, as human beings are. Therefore, this method of occupant observation makes it possible to track the activity of the whole body while covering a wide area with only one sensor [97], [98]. They should be a perfect choice for indoor OB studies; unfortunately, this technology was not available on the market when the development of this thesis began.

Depth registration cameras are measurement devices that can fulfil all the criteria regarding data quality, the sampling rate, market viability and price. This type of device was selected due to its ability to operate on numerous platforms and to access a decent software development kit (SDK). Due to past market availability, a Microsoft Kinect device was selected [99]. One of the main parts of the whole work was the development of functional software capable of data collection and processing.

3.1.2. Depth registration - Methods

A depth registration camera operates based on the same principle as a three-dimensional scanner. Both devices are equipped with a laser that projects a defined mesh or cloud of points. The reflection of the projected beam of light is registered by an in-built sensor that makes it possible to calculate the distance through the delay time of the reflection. The main difference in terms of operation is the sensor light spectrum registered. Most commercial 3D scanners register a visible frequency, while depth registration cameras operate based on a selected range of infrared spectra [100]. The operational sensor range depends on the application. Sensors that function within visible light are more accurate, but their sole purpose is to capture the surface and the steady or semi-fixed position (with one degree of freedom) of objects. Therefore, they are mainly applied to capture observed surfaces and for three-dimensional re-creation. A depth registration camera has the main purpose of observation, collision avoidance, motion capture, and surveillance. All these applications promote a constant, passive operation of the device. Therefore, a projected laser beam of the grid must always be turned on. It is possible to imagine that this aspect will produce a certain degree of inconvenience if the monitored area is constantly highlighted by the visible beam of the laser. For this reason, each continuous observation application operates based on a specific infrared range.

Reflection data are collected by a sensor that operates based on a selected light wave range. The size of the sensor and its sensitivity depend on the manufacturer. The higher the specification is, the higher the price of the separate unit. Commonly used depth registration cameras have an operation range of 1 to 10 meters, with a sensor that can capture pictures with slightly lower than standard resolution (SD), 720x480 pixels. This technology is not directly dependent on the lighting conditions during measurement. The projected laser grid can be considered an artificial lighting source for the sensor. This feature circumvents the dependency on lighting conditions found in video tracking solutions. Therefore, depth registration cameras can be used independently of the lighting conditions of the observed area. The main obstacle is the property of the observed surfaces. If the radiation absorbance of the measured object is high, it might produce registration artefacts, which could be a source of potential errors.

Data collection based on a depth registration camera is performed by a separate computing device. The sampling speed and buffer memory strictly depend on the specifications of the device used. The depth registration camera is responsible for streaming all the required data into the device for further processing. For this reason, access to appropriate SDKs that provide certain functionalities is essential for further development. When this work began in 2016, the most popular depth registration camera was the Microsoft Kinect V2.0, which had full support for the most popular coding languages. The selected device could track up to six people within its monitoring range with a sampling frequency of 30 Hz, and it could cover an area up to 5 meters in a 46-degree radius. Based on the specifications of the device, it seems that it is suited to close indoor environments. For this reason, it was decided to focus on the development of new functionalities and applications that would enable the monitoring of indoor OB.

During each step of method development, the proposed solutions were tested to determine whether any of the sources violated ethical issues. According to the Norwegian Board of Research Ethics, none of the collected data may allow a direct recognition of the observed occupants. Each monitored person was informed about the quantity and quality of the collected data, the data collection methods and the purpose of the use of the data. Once the scientific scope was introduced to the participant, each person was asked to give written or oral consent. If any part of the research methods led to hesitation or resistance, the research methods were reduced to an agreed-upon level or the participant was not included. If any observations were made on a group level, all the participants had to agree; otherwise, the experiment was not conducted at all to avoid any problems as a result of group pressure. Additionally, all participants had the option of withdrawing for a specific period from the recording process.

3.1.3. Movement registration - Methods

The main purpose of the Kinect device was for use in entertainment systems. Once the publisher officially enabled the SDK, it opened space for third-party developers wanting to introduce the use of the device in fields other than entertainment. The introduced SDK has made it possible to obtain all the data streams and basic functionalities. Kinect can stream raw depth input, normal video output (at a high-definition standard), and infrared video. The main advantage is access to the human body skeleton model (SM), which is a derivative of depth registration. The SM is a human body represented as 25 joint points connected in a way that formulates a humanoid shape (Figure 4). Each joint point is described in three dimensions, where the reference point is the centre of mass of the device, and its corresponding axis is hitched to the frontal surface of the beam projector. Each SM joint is associated with the same body limb if it works properly. For example, the head point will always be positioned on a human body head. Each sampled frame is marked by the time stamp of when the data were collected. The SDK provides the hardware functionalities and software library, but beyond that, there were no other additional applications. Each proposed functionality had to be manually crafted according to needs. A general overview of the use of this device mainly focuses on applications in motion capture and animation [101]–[103], and there are only a few applications that focus on research related to OB.

For the purpose of movement registration, it was necessary to develop an application capable of gathering the necessary data. The main target data for movement registration required a stream of human body transitions inside the monitored space. As a review of SDK output has shown, the collection of the SM data enables such measurements. The main obstacle was the selection of the SM. As mentioned above, the device is capable of detecting up to six persons in the same frame. This means that in each given frame, there is a buffer space for registering up to six skeletons. The SM is attached to a person if the device sensor detects a humanoid-shaped circuit. Attachment to the body is performed by a pretrained neural network model. The main issue is the association with a specific SM identification number. Each skeleton has its own identification number, from one to six. The device selects a random available SM, and streams information about the joint positions of the specific SM.

The data about observed occupant SMs can be gained through a continuous probing of all streamed SMs, even those with empty records. Each SM has 25 joint points in three dimensions with 30 Hz sampling, and one skeleton produces a recording of a 75x30 matrix per second. Collecting six SMs at the same time increases the amount of the data stream to a 450x30 matrix per second, which can be considered a significant data stream for non-integrated recording. To address this issue, it was necessary to tune the data collection parameters to balance the data collection stream. General-purpose computers cannot handle such a large data stream due to the memory buffer of each sub-component (processor, rapid access memory, and hard drive). Therefore, it was necessary to establish the amount of data capable of being stored in the buffer memory of the processor unit. If this step was not performed, the recording procedure might crash without the possibility of an automatic reset of recording. Once the amount of data that fitted the specifications of the computer used for the recording was established, it was possible to conduct a series of measurements. More specifications about the whole monitoring procedure can be found in Papers No. 1 and No. 5.

3.1.4. D-CLO - Methods

As mentioned in the description of the Kinect specifications, the device was equipped with a depth registration camera and a standard high-definition camera. The combination of these two recording techniques grants access to red, green and blue channel + depth (RGB-D) simultaneous recording of both data sources. With this ability, it was proposed to connect the two devices and to use the depth input to probe the data from the video data streams. The direct recording and storage of the video data can be considered too invasive and would constitute a violation of research ethics. To overcome this issue, a new application was developed. If the data from the RGB camera are temporarily loaded in rapid access memory, their output is available for only a short period of time and is subsequently overwritten. Therefore, there is no possibility of recovering a previous video sample, which prevents any potential misuses of data or direct occupant recognition. This solution guarantees that occupant privacy will not be violated.

Despite the short time window of data availability, it is possible to obtain an additional set of data that can contribute to overall OB research. If both cameras operate at the same time, it is possible to project an SM onto the video RGB stream and use it to extract colour information from pixels that are close to each SM joint. This data package provides information about the colour of each SM joint, and it can be translated into a mosaic picture of the observed occupant. Such data themselves have no specific value, but if they are combined with appropriate labelling regarding colour composition, it enables a dynamic estimation of occupant clothing (CLO) insulation levels. It is assumed that the skin pantone is exposed on joints that are hitched to the head and face. These two points are considered a skin pantone reference colourmap. The points of the colourmap are extended to two spheres in which the origin is loaded exactly in the probed colour information and the range of each colour channel value. It was assumed that the range value represents a value of 3% of the total colour channel range. This parameter was used for threshold-based skin pantone classification. Every other joint is compared with the skin pantone colourmap. If the value fits within the tolerance of the colourmap, it obtains a positive value, confirming exposure of the skin of this specific joint. If the joint comparison does not fit the tolerance of the colourmap, it obtains a negative value. This result means that this part of the body is covered by some textile, which is considered to be part of CLO. Once all the SM points were examined, a binary response was formulated, producing at the same time a binary SM. Once the information on each joint is evaluated, it is possible to formulate a binary picture of the exposure of skin of the human body. The whole evaluation process and example results are shown in Figure 3.

To evaluate a binary picture of skin pantone exposure, it is necessary to formulate a response library. This library is a composition of the various skin coverage setups that was cross-referenced with ASHRAE Standard 55 [22] and it made it possible to formulate a response matrix for any detected CLO setup. Each time recordings of skin coverage are made, the formulated binary response is evaluated by its fit to one of the library setups. To that end, each library setup obtains as many values that are correctly representative values for each SM joint as possible. The highest scoring setup from the library is considered a match, and the observed occupants are labels that have a current CLO value that corresponds to the matched setup from the CLO library. If there is a tie between two or more setups, the CLO insulation value is averaged. More descriptions of the monitoring procedure, the library developed, and the software can be found in Paper No. 2.

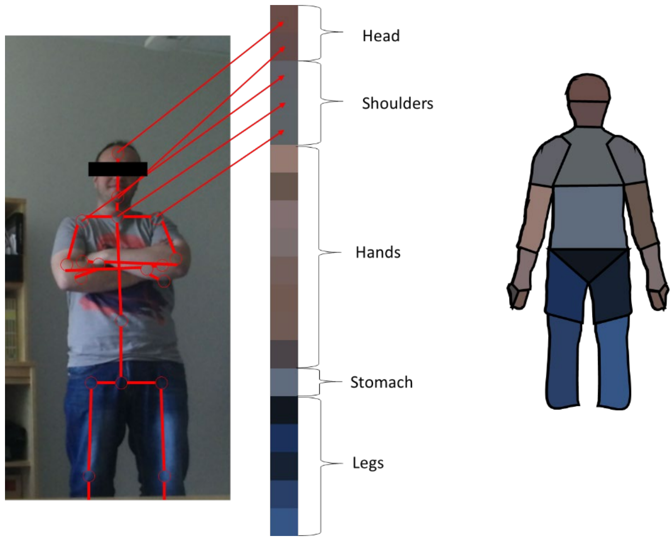

Figure 3. Colour data sampling with use of the SM projected into the video camera stream

Beyond the standard SM, it was proposed to extend the localization of the joints. Each visible joint was used to calculate the midpoint between joints connected to each other in the default SM. Thus, the extended skeleton model (E-SM) was generated. The procedure of E-SM formulation is shown in Figure 4. With the use of E-SM, it was conjectured that the detection rate and more diverse CLO setups could be detected. The visual representation of the whole E-SM is displayed in Figure 4. Due to the significant extent of the CLO setup library, it was suggested to switch to modern classification and processing techniques such as machine learning and deep learning. The sample results from this processing method are shown in subchapter 5.1.3.

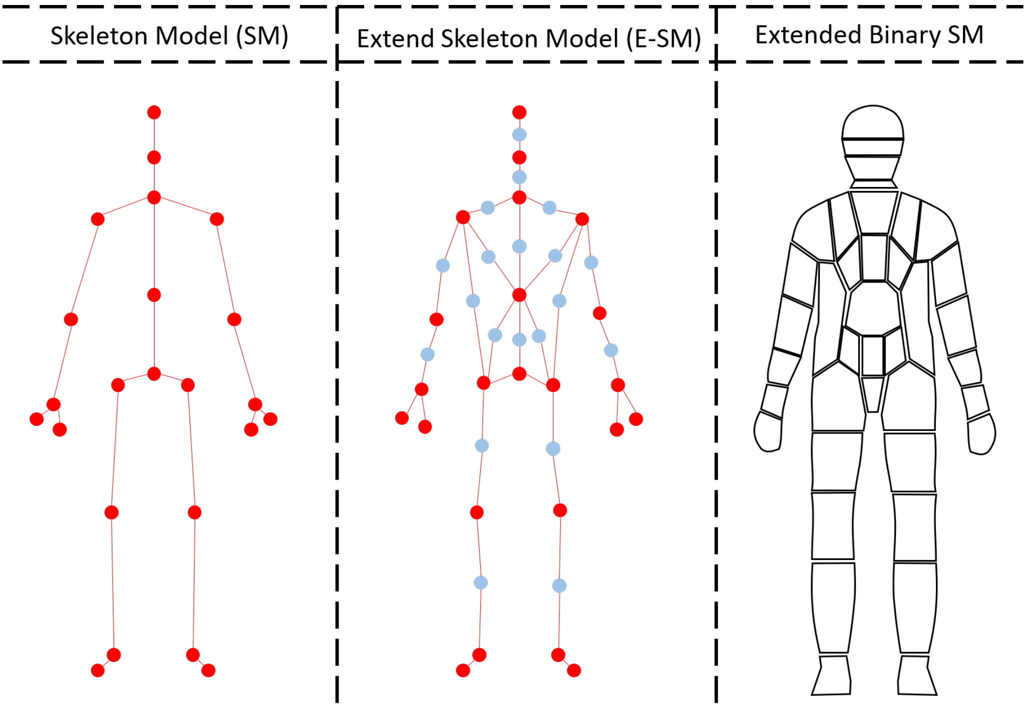

Figure 4. Extension of SM to E-SM

3.1.5. D-MET - Methods

Human activity is one of the parameters that is critical for building design and control. Knowledge about occupants' energy release from heat and sweat plays an important role for indoor air quality. Therefore, constant access to this information, which can provide dynamically changing readings, is highly desirable. A standardized solution that is defined by existing standards describes an occupant's activity through a specific zone type. If an occupant is inside a specific zone, his or her activity value is equal to the value defined by the standard. Such assumptions can be a source of potential under- or oversizing of the ventilation unit. To address this issue, a dynamic-metabolic rate measurement tool was proposed. The ability to capture an occupant's movement can be useful not only for mapping his or her indoor transitions but also for monitoring his or her activity. During the data collection process, all the SM joint information is collected, because whole-body limb movement can support dynamic-metabolic factor estimation.

There are limited ways to track an occupant's metabolic rate (MR) without wearable devices. Combining the SM with ASHRAE Standard 55 allowed us to estimate the MR based on an occupant's location and body transition [22]. Information about the occupancy of a specific room can be extracted if the raw recordings of movement are combined with the layout of the observed building. The best conditions are if each room has monitoring coverage and it is possible to register all the activities and transitions performed inside the space being monitored. If this condition cannot be fulfilled, camera placement should focus on a re-creation of the transition "aorta" of the indoor space. If this condition is met, it will be possible to calculate the occupancy time inside each specific room type, bounding the occupant with a specific MR value. The standard also provides a table that can be used to directly estimate the MR based on human movement speed. The submitted table has only a few reference points, but it makes it possible to estimate the value of the continuous data stream. Therefore, each time an SM is being registered, instead of assigning an MR value based on the room type classification, the MR can be directly calculated via the proposed table. This procedure will show a more realistic contribution of energy by human body activity.

Estimating the MR is necessary to check how body limbs contribute to the average limb speed and whether the data are unified or can produce certain variations. To that end, one camera was set in an open space room, where a participant was asked to move with different velocities. Each trial was registered for 60 seconds. The participant was asked to transit back and forth on a selected pathway. The pathway start position was 1 meter from the recording device, and the pathway was a straight line 4 meters long. The trial measurements show that it is possible to select the specific mean value of a whole-body transition. It was expected that the average movement of limbs would be slightly higher than average due to the more complex movement mechanics (Figure 5).

With the average movement transition, it is possible to recalculate the MR value so that it can directly contribute to calculating indoor thermal comfort. To translate these values into the amount of the energy emitted through heat, it is necessary to know the occupant's body mass index (BMI) and body surface area (BSA). Through mathematical operations, it is possible to calculate the human body skin surface area and multiply it by the MR value. If these parameters are not available, the MR of each occupant can also be used for direct control strategies.

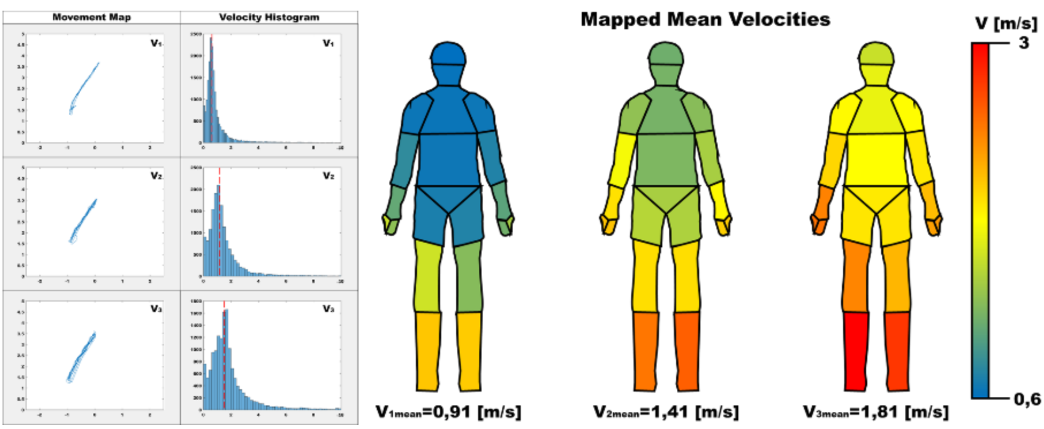

Figure 5. Example calculation of mean human body velocities for metabolic rate estimation

3.1.6. Activity labelling - Methods

The direct observation of occupants can provide significant inputs about their actions. Depth data can be used to recognize an activity in which occupants are involved. This applies to activities that require the active or passive involvement of different indoor appliances. It is assumed that an activity consists of several discrete actions. Associating occupants with a recognizable activity can be used to formulate an event-based activity model, which can be used to indicate their desires. According to the theory of planned behaviour [16], each person has his or her own explanation for activities performed that is logical for them. Therefore, it is possible to claim that observing the actions of occupants reflects their activities, desires and needs. The experimental setup with enlisted types of activities is shown in Figure 6.

To develop a tool capable of labelling activities in real time, it is necessary to define the target amount of potential activities that can be captured. Additionally, each activity has to be defined by the number of discrete actions and the number of reactions to these actions. Therefore, to enable the ability to recognize an activity, each discrete action has to be defined. To that end, it is necessary to establish a list of capturable actions and to build a list of reactions to these actions. The developed list can be used as a checklist for database development. The action database has to have three main parameters: motion records, the label, and temporal information. To contribute the data to the formulated database, each action has to be pre-recorded and labelled accordingly. A database prepared in this format will make it possible to train recognition models. Each data point from the occupant will represent a series of frames that are organized chronologically, and a bundle of collected frames will cover the observation of one person and his or her SM while performing one specific action. The whole data set representing the position of each joint will have a label associated with the recorded activity.

For the recognition of actions and activities, the use of machine learning techniques, which require a significant number of cases to train them properly, is proposed. Each action has to be pre-recorded numerous times. Beyond that, it is crucial to test how the extension of this method influences successful classification by the model. The greater the number of actions that are defined is, the larger the spectrum of actions that must be covered by the model. Therefore, more research is needed to enable this recognition technique. A detailed explanation regarding data collection, processing and development of action recognition tool can be found in Paper No. 11.

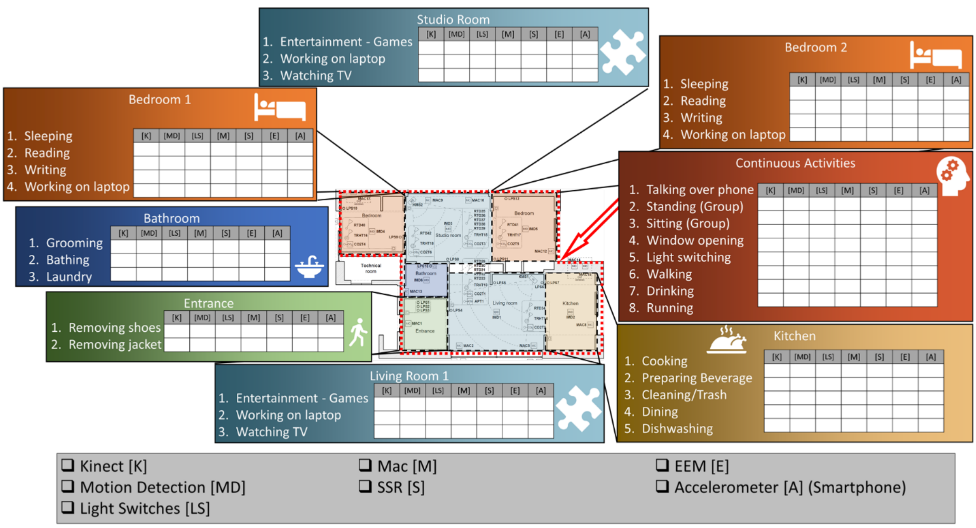

Figure 6. Continuous activity and discrete action mapping inside a residential building

3.1.7. Sensor fusion - Methods

Measurement connectivity is a crucial parameter if a study requires more than one measuring device. It simplifies the data post-processing. One depth registration camera can cover only a limited indoor area, and to cover most non-private rooms, it is necessary to use several cameras. That requires the development of a platform for data source synchronization. Each depth registration camera produces its data output according to the projected beam. Therefore, measurements are made in correspondence to the beam source. This means that the position and angle of the device play a significant role in the synchronization of the data sources. This issue occurs only when one space is monitored by more than one camera. Such a solution might be considered an exaggeration, but if the place being monitored is crowded and there are many obstacles, it might be a necessity.

To combine one or more sources, each device must be spatially localized inside the monitoring zone, corresponding to one “MASTER” device. Additionally, each data sample stream from the “NON-MASTER” camera must be analysed according to the movement surface. The centre of mass is the reference point of each device, and each dimension axis has its zero point in this centre of mass. If the device is tilted and angled, the movement registered from an SM will show a transition through a rotated surface. Establishing the function of this surface makes it possible to calculate the camera angle with regard to the floor surface. If the localization and camera angle are established, it is possible to calculate a transformation vector for each “NON-MASTER” camera. Each device that monitors a similar area has to have a synchronized clock. The depth registration camera collects time information from the fixed time in the operation system software. Due to the high data acquisition rate, a small difference between time labels can produce a significant issue related to SM synchronization.

Synchronisation with more than one data source was supported by implementing semi-autonomous software. The application was developed to support data synchronization issues and direct data action labelling. The main responsibilities of a user are the micro tuning of the input and the selection of the frames containing the SM involved in a specific activity. The main output is sorted and synchronized data with proper labelling.

3.2. Processing of data from the depth registration camera - Methods

3.2.1. Functional software development - Methods

3.2.1.1. Challenges

Each application described in the subchapter 3.1 has required access to a specific set of information accessible from the depth camera. The SDK provided by the depth registration camera manufacturer delivers basic functionalities, like access to a structured data set, but it did not support solutions for the extended measurements. Therefore, the development of all functionalities, performance balancing and post-processing methodologies was a part of this research work. The flow chart of performed work is shown in Figure 7.

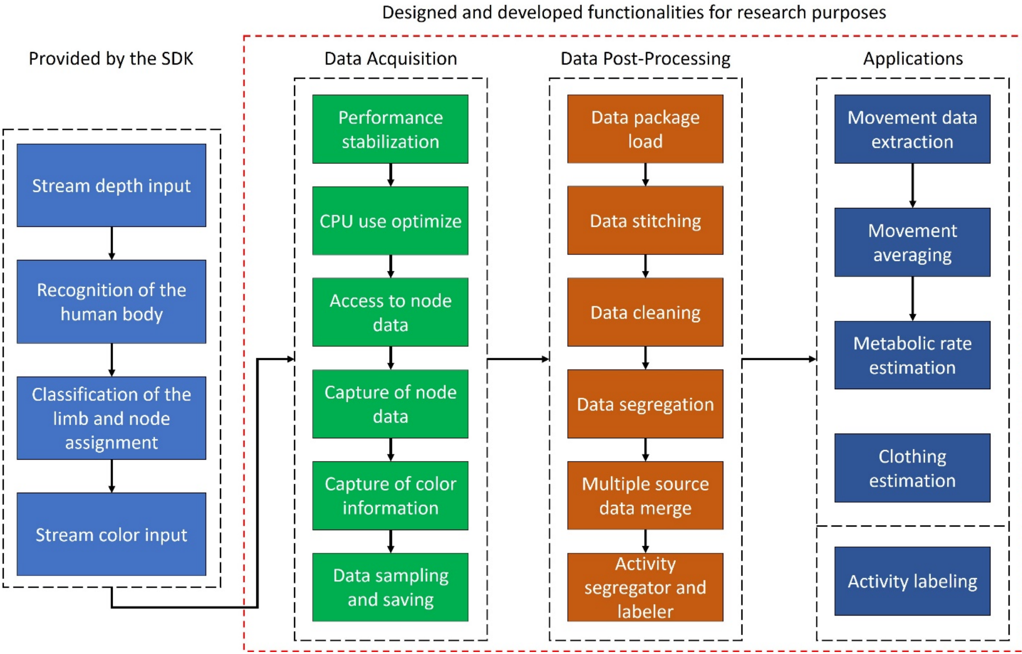

Figure 7. Flow chart of developed functionalities to collect and investigate data from depth registration camera

The processing flow chart shown above summarises all the work put into software development necessary to achieve all the occupant tracking functionalities. At the beginning of the development, the main goal was to enable functionalities that can initialise basic research. Those functionalities were aiming to track occupants within indoor spaces. It required only capturing of the streamed data about SM node position and saving it into a hard drive. This solution was considered sufficient for the first step of the research. The main flaws of unoptimized code utilisation were deliverance of unstable performance, that unable unsupervised monitoring. Additionally, the size of the saved file was vast. It was estimated that one hour of recording was delivering one gigabyte of a data file. Such operational conditions were considered as not sufficient. To improve the recording algorithm performance, a series of tests were conducted. This procedure delivered a list of limitations that has to be addressed while modifying the simplistic recording algorithm. Observed limitations where: unstable performance, CPU overload, performance "hiccups", operation mode and overuse of drive space. Additional challenges were the design of a reliable post-processing software that can reduce the number of labour hours for using recorded data for application purposes.

3.2.1.2. Device operation mode

The limitations of the first version of the recording algorithm required a powerful computer to run it with acceptable performance. For the research perspective, access to the high-performance computational power was not considered as an issue. However, if the advanced, depth monitoring technique would be considered as a commercial option for monitoring occupants, its calculational demand had to be optimised. The only limitation that could not be overcome was the constant recording of the depth input. Due to the time latency between the initialisation of recording and data acquisition, the depth camera had to collect information continuously. During the trials, there were many attempts to reduce the time needed to initialise gathering data, but even the fastest solution was taking more than three seconds. Such time delay was unacceptable if the monitoring system had to operate on a stand-by/active mode. During three seconds occupant might conduct a series of actions that will not be reflected in a collected data. In consequence, collected information would be considered as an incomplete, which would complicate the interpretation procedure.

3.2.1.3. Memory use optimisation

To reduce the amount of the sorted information, it was necessary to detect captured frames without any occupant. Implementation of the detector in a recording loop allowed to reduce the volume of delivering data substantially. From the fixed size of one gigabyte per hour, it was strictly depended on the amount of activities collected during the measurements. Usually, the data size for typical day time was varying between ten and fifty megabytes per hour. During evenings, it could have size up to one hundred megabytes per hour. By introducing empty records detector, the data size from one day was reduced by average from twenty-four gigabytes to two hundred megabytes. It was a substantial reduction of data volume that accelerate the overall recording performance and data post-processing.

3.2.1.4. Performance stabilisation

The most important issue that had to be corrected was the software reliability. The cause of potential errors could be caused by numerous factors, like lack of updated device drivers, miscommunication with computer or issue with a USB port connection. In most of the error cases, simple virtual disconnection of the device was able to fix the above-enlisted issues. To automate this procedure, a diagnostic loop was implemented. The initial conditions of the recording software were to check the status of the depth camera. If there was no response from a device after ten seconds of contact initialisation, the whole code was rebooted, and marked file with recording procedure status was saved on a hard drive. This procedure allowed to track the status and if a device has any constantly re-appearing error. If such condition was noticed during a daily interview of collected data, it required manual re-installation of the drivers. During whole investigation, such a situation has happened only twice.

3.2.1.5. CPU usage balancing

The last significant issue was a selection of a number of operational frames. Data collection procedure required limitation of frames that are captured by CPU and transferred to RAM. Due to the variety of available CPU units on the market, it was unreasonable to expect that each computer used for measurements will have a high-performance CPU unit. The more powerful unit would be installed, the higher number of frames can be captured. If the number of frames was too high, the camera was delivering a flag message about losing a frame. This condition was used to auto-tune the developed recording code. If the losing frame issue was re-appearing (five times within the last ten recordings), the function was reducing the number of captured frames by ten. During the conducted experiments, the highest set point of frames reached tree hundred frames and the smallest ninety frames. It was desired to have the highest number of collected frames as it is possible. Each time the number of collected frames reached its set value, the algorithm had to restart depth input, which generated a small data collection gap that lasts approximately half of second. On a default setting, each time four thousand frames where collected, the data was saved into the hard drive. Files were saved in a selected folder name. The name of the file had information about: recording case name, number of used cameras (if there were more than one cameras used in a study), date and time. If several collected frames were not reached due to the unexpected error, whole collected information on a RAM was saved, with an “error” annotation at the end of filename.

3.2.1.6. Accessibility

Overall performance stabilisation allowed to reduce calculation power substantially. The initial conditions for the recording required access to the powerful working station. After implementing all mentioned above improvements, recording sessions could be conducted by small desktop units that have a built-in motherboard with USB 3.0 port chip. Most of the recent computers have such feature included. Thus, it makes a proposed monitoring technique more accessible to market solutions.

Additionally, during the end phase of research, the depth registration camera was tested with the use of a powerful Audrino/Raspberry micro-computer, and it was able to operate with reducing frames sampling of 10 Hz. The compact nature of micro-computers allows to assemble it with a depth registration camera within a limited volume. Thus, it allows building a standalone measurement device for measurement of occupant behaviour.

3.2.1.7. Skeleton model stitching

Through the progression of the research, each new addition of the functionalities was developed to data collection and post-processing methodology. The most challenging issue regarding post-processing was stitching up SM. Every observed person inside depth registration field had assigned to the SM, which is identified by its number (from one to six). Each time device would reach the selected number of recorded frames to transfer it to RAM (as described in subchapter 3.2.1.5), it would break the assignment of SM and re-assignee it. The number of particular SM was semi-sequenced, semi-random. Each time a new SM was observed, the new SM number was assigned. If the SM number was six, the counting started from one. During observation of a single person, there were no issues to process such data. Still, if the observation includes more occupants, the post-processing of recording output is getting more complicated. A series of tests were conducted to stitch SM assignment for multiple occupants properly. The procedure that grand success requires two-step validation.

The first step requires the calculation of the body proportions. It measures body proportion between distances of the spine base and head, and the distance between two shoulders of the same SM. The measurements are counted if the detected occupant is in a standing or walking straight position. If the body measures are different between the two skeletons, it is sufficient evidence to distinguish SM from different persons. If such conditions are not met, the second stage of verification is required. The second stage of verification requires the usage of three variables from collected data: two-dimensional projection of SM movement on a floor surface and time data. Combination of these parameter allows using DBSCAN clustering technique to classify if the different SM are originating from the same person. This technique uses a movable window of collected frames and overlays SM projections from three second period. If there is a sudden change of SM number, clustering technique will capture the gap by setting the classification range appropriate for the investigated period (as a default one meter). Points that are belonging to the same cluster are crosschecked with the first identification condition (body metrics). If there is a positive match, it means that all of the SM is describing the actions of one person. If the match is negative, it means that used SM is describing the activities of different persons. After this procedure, the SM assignment matrix is formulated for each person, and such a matrix is used for further processing. The algorithm that utilises this functionality was design to operate independently, without a selection of the number of people included in a study. The only necessary input is a sorted by time and stitched together data from depth registration camera.

3.2.2. Validation of measurements - Methods

3.2.2.1. SM data collection

All of the proposed applications relayed on the accuracy of the depth camera and depiction of the SM model. Both, manufacturer [99] and other independent sources [104], [105] are pointing out that most of the joints have an accuracy of one centimetre. Except for lower parts of legs and hands, which readings have an accuracy of approximately ten centimetres, readings from Microsoft Kinect camera are accurate at an acceptable level. Most of the research that utilises a selected camera validates its measurements with camera frontally facing occupant. In research related to indoor occupant behaviour, such conditions can be met in a rare occasion. The typical solution for such research is the placement of the cameras in upper cases or corners, trying to maximise the investigation range. Due to this reason, it was decided to conduct a series of measurements that will investigate the influence of recording device position on the accuracy of recordings. The study included investigation of an influence of device elevation and angle towards observed pathway direction.

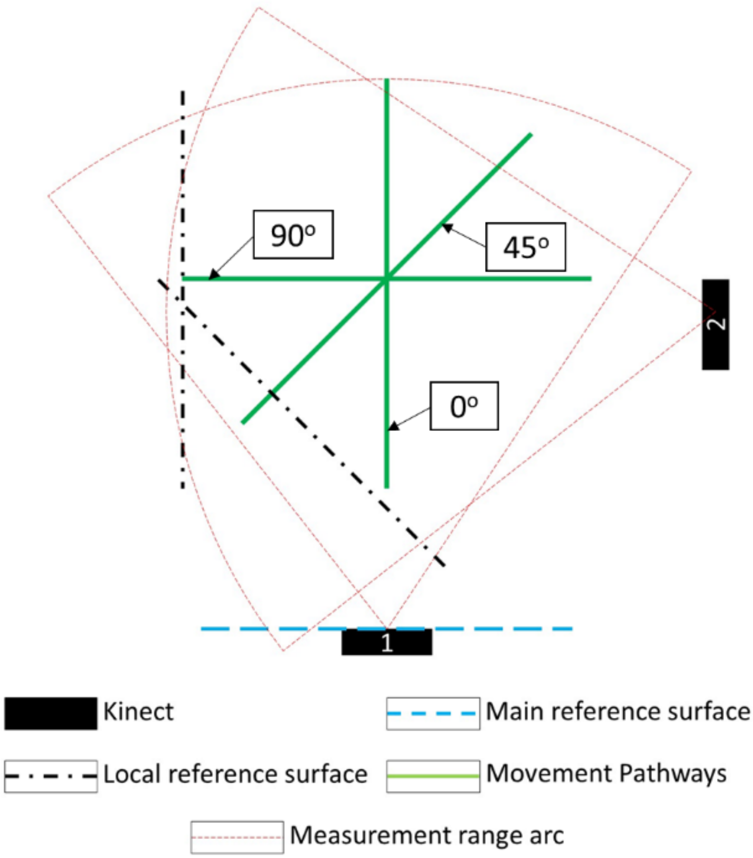

Figure 8. Depth registration device validation equipment setup, view from above.

The validation experiment required collection of the reference data and stable pathway collection. Thus, a series of pathways of similar lengths were drawn on a surface. The overall validation experiment setup was shown in Figure 8. The reference position of the camera was elevated on one meter from floor level, and the device was facing a pathway of movement (zero degrees turn). The data collected for reference were aggregated per SM node and plotted as a scatter plot of points height and fluctuating dimension parallel to the floor surface. The distance from device was discarded as all of the points should be projected into one reference surface. Collection of scatter plots and their heat maps can be found in Figure 9.

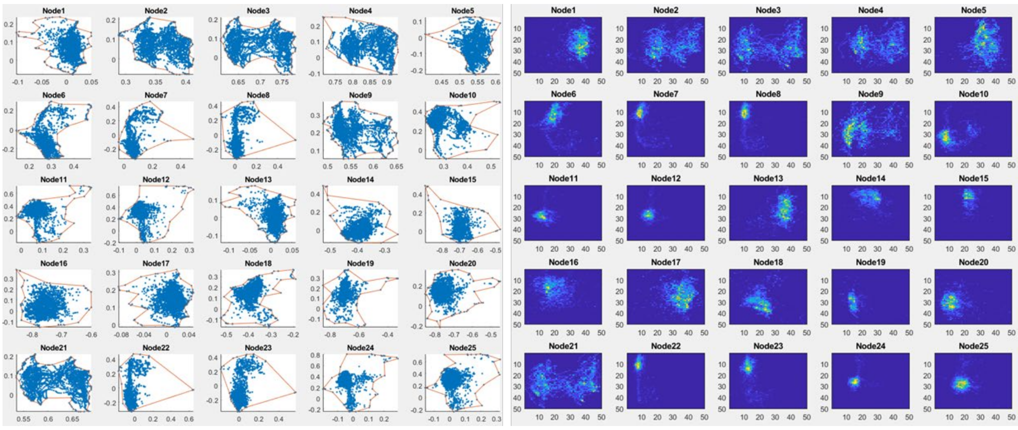

Figure 9. Reference samples projected on a reference surface, scatter plot with initial boundaries to the left, heat maps of collected data to the right

Each scatter plot was processed to formulate an outline surface. Generated surfaces were considered as the reference to measure the data collection spread of the specific SM node collected from different positions of the camera. The measurement was showing the percentage of collected SM node fitting into specific SM node reference surface. Additionally, to check what is the acceptance boundary of probed SM nodes spread , each generated original surface was modified by growing its boundary by one centimetre, this operation was done ten times. The data collected from the validation study was only recalculated to turn the movement pathway into the same angle as reference (zero degrees), to fit the same projection surface as the reference sampling. To ensure the non-bias performance of the device, the validation study used two independent measurement devices. The results of the validation are shown in Figure 10.

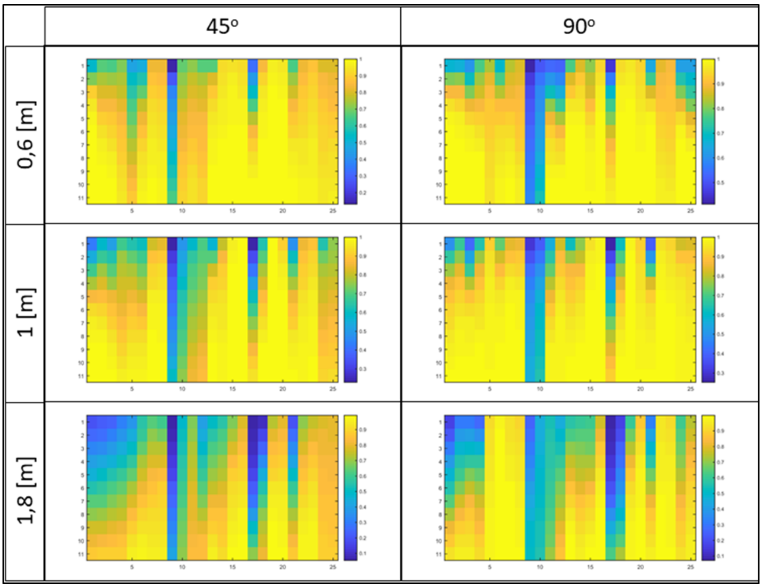

Figure 10. Results of validation test. Horizontal axis - SM node number; Vertical axis -number of boundaries growth (1 – 0 cm, 11-10 cm); Colour corresponds to a percentage of fitted in nodes. Yellow -100%, deep blue- 0%

As the results are showing, there is an influence of the camera position on direct data representation. The only issue that might interfere with the results outcomes was an imperfect re-creation of the pathway. It is impossible to re-create perfectly the whole set of a pendular swing of limbs. However, depth registration aims at a description of the indoor occupant position. In most of the cases, it is acceptable if the detection margin has a resolution of five centimetres. Most of the interactions with an indoor appliance can be detected if an assumed margin is used. The proof of this statement can be found in the result section of Paper No. 11. Therefore, most of the device placement scenarios have fulfilled these conditions. Addition of five centimetres to the reference boundary delivers high percentage (above 90%) of fitting into extended reference surface in most of the validation cases that are not collected above one meter. It is noticeable that there is a significant loss of accuracy if the device is placed on a higher elevation (above one meter) and its acceptable detection rage is reduced to the eight centimetres resolution. The only problematic issue that can be observed is miss-fitting of the reading of one arm. Base on a node number, it is possible to detect that the torso constantly covered one particular arm. The device was estimating positions of nodes from this particular arm which did not fit into the reference surface. It shows that the information from nodes that are not visible for the device does not reflect reality.

3.2.2.2. SM data for metabolic rate estimation

The accuracy of the metabolic rate estimation strictly depends on the accuracy of SM. As it is shown in the subchapter 3.2.2.1, occupants' actions can be depicted with an average accuracy of five centimetres. To ensure that this technique does not cross this accuracy limit, spatial data that is used for the metabolic rate estimation has to be decimated to the resolution of five centimetres. The factor with greatest importance for estimating the metabolic rate is average movement velocity of the human body. The result of averaging is compared with an ASHRAE Standard 55 [22] table which includes body metabolic rate related to the human body transition velocity. Even if the decimation might cause the local brakes of velocity (lack of transition between spatial data), it is justified to interpolate the recording between two neighbouring readings (reading before and after calculated mean velocity), with an assumption that the higher values are bases for interpolation. This assumption follows a principle of the human physiology and limbs movements. Thus, the error related to SM monitoring is not transferred towards metabolic rate estimation. The output from the depth registration camera also provides information if the particular SM node has an origin from measurements or from the software estimation. If the particular node has a reading that originates from the software estimation, it is not used for estimation of the average body velocity. It is important to exclude these readings from metabolic rate estimation due to the unpredictable nature of the software-based node position estimation.

3.2.2.3. SM and CLO-value estimation

As similar as metabolic rate, estimation of the CLO-value strictly depends on the accuracy of SM. With an exception that in this type of measurements it is not possible to decimate the readings. To estimate CLO-value, it is necessary to project the SM on a colour video stream and sample the closest pixel to projected SM nodes. An application that would average colour sample area could produce unreliable results, especially if the particular node is on edges of occupant body outline. If the averaging would be implemented, the colour information might mix with background colours that are not belonging to the colour of occupants' clothes. Therefore, it makes it difficult to validate the methodology in another way, then test its performance. It requires a split of the data used for the model development and test data that can validate the accuracy of a detection/estimation model. In a validation comparison, two colour models were used (RGB and HLS), and two lighting scenarios (good lighting and poor lighting). The results of the validation can be found in Table 3

	All		Poor Light		Good Light	
	HLS	RGB	HLS	RGB	HLS	RGB
CATBOOST	97,58%	97,01%	97,54%	97,23%	98,78%	98,36%
GradientBoost	96,25%	95,83%	96,43%	96,21%	97,99%	97,60%
KNN	98,01%	97,28%	97,62%	97,11%	98,73%	97,88%
XGBoost	96,25%	95,11%	95,80%	95,70%	97,62%	96,96%
DBSCAN	81,65%	75,21%	73,81%	66,79%	85,43%	76,42%

Table 3. CLO-estimation accuracy with use of various model development techniques

3.2.3. Experiments setup - Methods

3.2.3.1. Device and software setup

Each time a new experiment was scheduled, it required defining specific research tasks. Among potential tasks were: movement and room occupancy states investigation, occupants' clothing routines, occupants' metabolic activities, occupants' actions detection and routines monitoring. During experiments, any combination of tasks could be included. After defining the investigation tasks list, the recording devices are set up to meet the requirements of the selected tasks. If the main research goal aims to understand spatial and temporal occupancy states, the investigation area should cover all the existing corridors and entrances. This allows observing the indoor "transition artery", with the ability to define several occupants and their time of presence in each of zones or rooms. If the selected tasks list aims towards a description of detailed actions, it requires placement of the monitoring devices in specific rooms or zones.

The investigated monitoring devices had no permanent experimental setup in which they were applied. The devices were mobile, and whenever there was established an occupant acceptance for the study, the devices were just deployed in their location. It is assumed that devices will not change their initial positions, and its placement will not influence the regular indoor activities of the occupants. The optimal placement of the device should cover most of the investigated floor area, and it should be located on the height of approximately one meter above the floor level. It can be deployed on a shelf or on a simple bar with brackets, and it should have a clear view of the investigated area. To ensure that the device kept the same position, the distance between one of the device corners and a room reference point (e.g. a wall corner) should be measured while setting up the experiment, and right after the experiment. In the situation when there is a difference between measured values, it is a clear that the device position was altered during the experiment.

3.2.3.2. Occupants preparation

Before experiments were conducted, participating occupants were introduced to information about the quality and quantity of collected data. Usually, the target of the study was aiming towards the maximisation of research tasks. In a situation when occupants were unsure about any form of data collection, the sample data output was shown to them. If the demonstration of the sample output did not meet their approval, this particular research task was erased from the experiment.

The selection of the participants did not share any kind of group belonging, rather willing to participate in the study. The main point of the experiments was to check the performance of the proposed methodology and extract data from studies that can be useful for agent-based model development.

3.3. Modelling of BOT-ABM - Methods

3.3.1. Fundamentals of BOT-ABM - Methods

The development of an OB simulator requires a significant amount of foundation data. Regardless of which modelling technique is selected, the operational resolution of the model cannot exceed the resolution of the collected data. Based on the available data streams from the depth registration, the fundamental temporal data resolution is 30 Hz, and the spatial resolution is 0.01 m in each axis. This resolution will be considered the operational resolution of the formulated model. As mentioned in the introduction chapter, the focus on new model development should concentrate on the formulation of an ABM for energy-related OB simulations. Therefore, the proposed model will follow the principles of formulating such models. The goal of the model is to develop a tool that will recreate and reperform actions that could be registered in indoor scenarios. With all these abilities, it will become a building occupant, transient agent-based model (BOT-ABM).

3.3.2. Movement simulation - Methods

Access to a large data set of occupant transitions has made it possible to formulate a solver for movement simulation. Movement itself can be considered as a trivial phenomenon, but from the perspective of human-like simulations, it is a fundamental action and activity carrier. Without transitions, indoor occupants are incapable of performing most activities, and they cannot adjust their comfort level. Therefore, to recreate patterns of OB, it is essential to enable agents to freely move on an indoor layout surface. The development of this feature of the ABM can be considered fundamental, and its appropriate functionality relies on this sub-model.

After collecting data from several cases, it was possible to perform analysis regarding occupant transitions. All the data collected from monitoring campaigns were connected, and each registered SM had extracted information about the spin base point. This information allowed us to obtain the most reliable information about movement characteristics. Based on the data analysis, it was possible to observe that indoor movement has its own characteristics. It was shown that there is no correlation between occupants' movement speed and the next step angle selection. This finding might be considered a counterintuitive claim, but transitions inside buildings are not fast and are more dependent on a transition desire and local layout scenario than on direct movement speed. Therefore, it was necessary to include both parameters as an important part of the movement solver. Each of the metrics of transition (movement speed, angularity) was extracted from the whole data set and organized in a histogram, as shown in Figure 11. Each of the variables was translated into cumulative distribution functions (CDFs) for use in future steps of movement simulation.

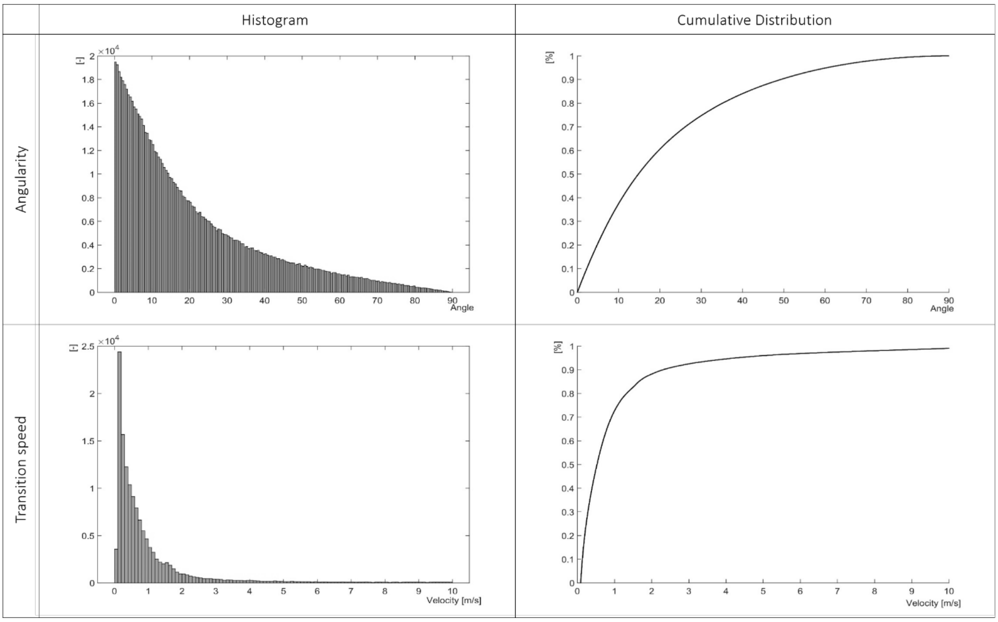

Figure 11. Histograms and cumulative distribution functions of movement variables (discrete transition speed and angularity)

The use of the movement solver grants the ability to simulate one discrete step at the same resolution as the source data. Further development of the solver had to focus on establishing the basic rules of step simulation. The principle of transition between different points is displayed in Figure 12, where the simulation from point A (start) to B (finish) is displayed. The whole solver assumes that the occupant wants to transit to his or her destination point with the shortest distance, but the solver is not fully aware what will be the next step size and angularity. The transition will iterate each step, and through the cumulative distribution function (CDF) of angularity and velocity, it will calculate the potential location of movement. Angularity is considered a function of the angular difference between two vectors of the following step. For this reason, the formulated angular distribution does not operate with a turn side, and it produces a state of angular difference between steps. It is necessary to simulate both sides of the transition with the same distance, and each pre-simulated step is tested based on the shortest distance from the destination point. If the distance to the end point is achievable through the simulated step, the solver snaps the last step without considering the angular distribution. Without this feature, the simulation of one separate transition will last until the exact spot is achieved, which could take an unreasonable number of iterations.

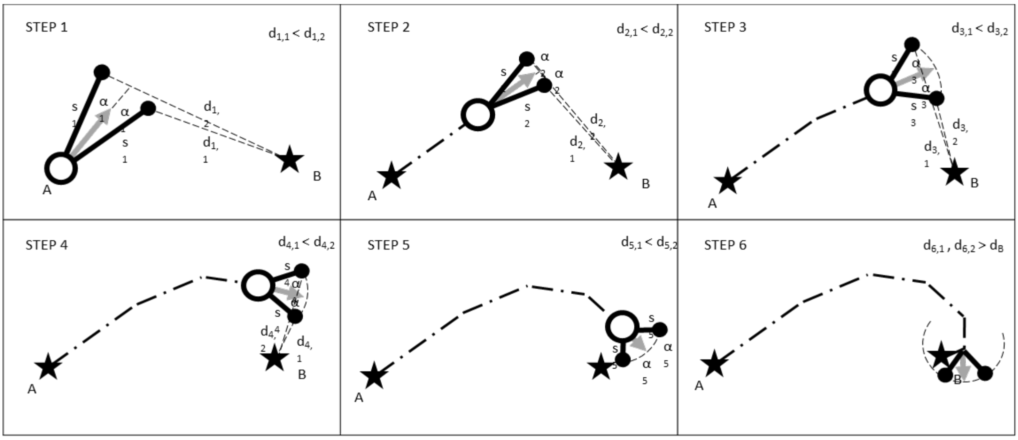

Figure 12. Simplified process of movement simulations from point A to B

Once the one specific transition was enabled, it was necessary to implement a solution to transit inside a layout having obstacles and corridors. Detection of these objects has to be performed separately, and to prevent an increase in the cost of calculation, it cannot be computationally expensive. To address this issue, an information system for agent navigation was proposed. This system requires the detection of the central points between each visible corner. Once the counterpoints are established, the grid of connections between centre points is set. With routing optimization, it is possible to detect the families of the centre points that provide similar connections. Each such family begins to be reduced to one representative centre point. Once all point family reductions are complete, it is possible to formulate a simplified connection map that can be used to simulate transitions inside any layout. The procedure of connection map formulation is displayed in Figure 13. Each time a transition in a layout is simulated, a connection between the main point and end points is established. If the main points are visible, the transition is simulated immediately; if they are not visible, the transition is developed with the use of the simplified connection map. More details about the whole solver are included in Paper No. 9

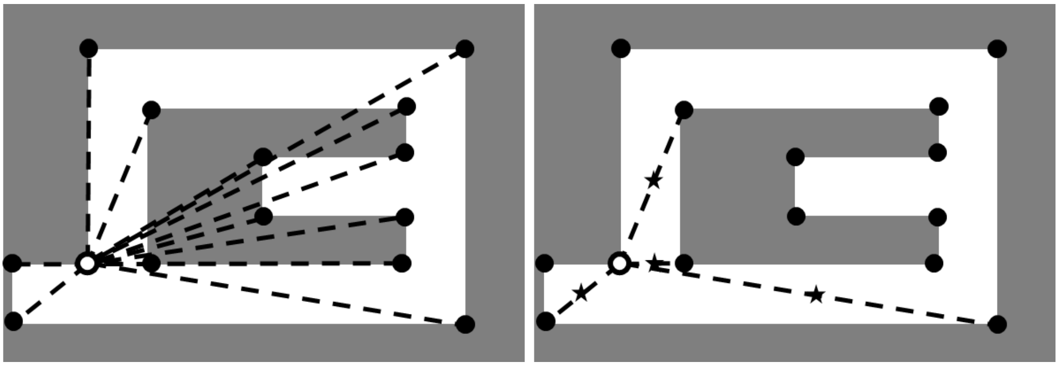

Figure 13. Corresponding points detection for movement simulation

3.3.3. Body limb movement simulation - Methods

Beyond the simple transition of the human body, it was necessary to develop a simulation model of other body limbs with respect to the velocity of the whole-body transition. Modelling this phenomenon cannot be avoided because it is an essential component of movement and contributes to the general energy release of the human body. Additionally, if the whole-body movement data can be implemented in a computational fluid dynamics (CFD) simulation of the room or zone, an appropriate representation of human body motion is critical. The natural transition of limbs significantly contributes to the generation of air vortexes surrounding the human body. Therefore, if this feature is not included, the transitioning body will generate a false representation of the air distribution.

To address this issue, it was necessary to analyse the swing frequency of each specific body part during movement. The dynamics of limbs are considered a phenomenon that is directly connected to movement speed [106]. The faster the transition is, the greater the limb swing frequency that can be observed. Therefore, if it is possible to capture limb swings during a specific movement regime, it is possible to generate a model that describes such phenomena and the transitions between different movement regimes. To simplify the description, the targeted parameter will be a description of the periodic function and its frequency. Each joint from the SM will be analysed separately, and each dimension of each joint will have its own separate frequency function. It is assumed that the stable position of limbs is the reference pose, and each analysed derivative of movement will refer to it.

To perform an investigation related to this phenomenon, conducting a series of experiments with different movement regimes on a treadmill is conducted. Use of the treadmill will produce stable observation conditions, which will provide significant leverage for data postprocessing and model formulations. The measurement step was equal to 0.5 km/h with a range of 4 to 11 km/h. The sample result of one joint frequency acceleration in one dimension is presented in a Figure 14. Each movement regime was tested for one minute, and each measurement trial was repeated three times.

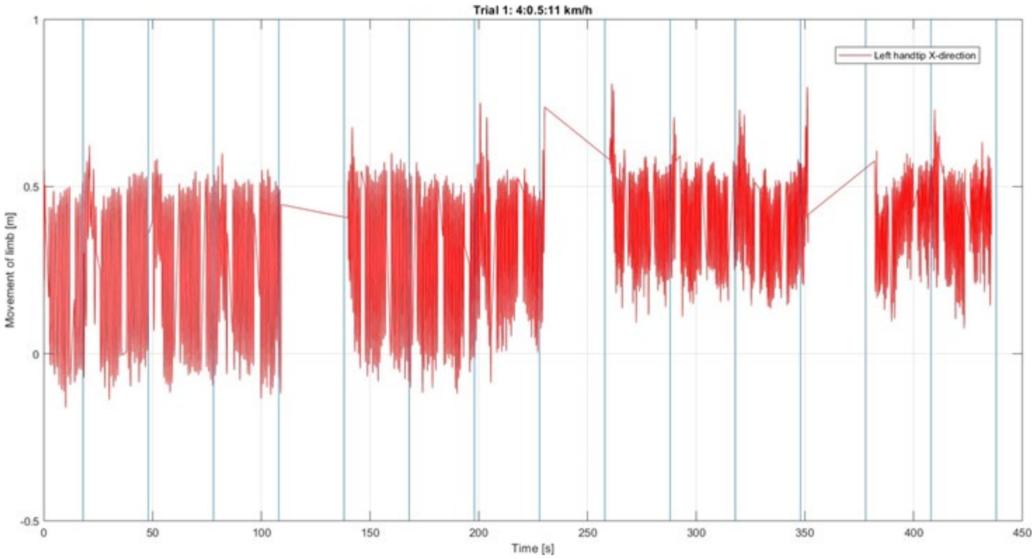

Figure 14. Raw data from the pendular movement investigation of the left-hand tip

The main objective of this study was to generate a functioning surface that operates based on a single movement axis position, velocity and time variable. The generated functions of position and time for each movement regime can be connected, formulating a surface that represents a wave table. Formulating the wave table allows us to calculate the position of a specific joint, even if the transition speed changes. The current status of this research is still under development, and the results of it are yet to be published.

3.3.4. Indoor body exposure - Methods

The possibility of including occupants inside the virtual environment allows a variety of applications. If human body motion is recreated correctly, it will be possible to use it for energy calculations and indoor comfort assessment. The purpose of the movement and limb simulations is to recreate body limb movement data similar to what can be obtained from depth camera registration of the SM. Regardless of the source of the data, it should be possible to implement such data as a tool for investigating indoor exposure. Each joint represents one defined body part, which is why if each joint is analysed independently, it can be transformed into a three-dimensional polyline. If the sources of the data are calibrated to the geometry where the data were collected, it will be possible to import joint polylines into the CFD environment.

Access to accurate data points can be used in multiple ways. The most straightforward application consists of using the generated polylines to export the data from the post-simulated environment. With such ability, it is possible to gain insights into the exposure of joints to the environment. The selection of variables that can be extracted depends on the selection of the equations initially used in the CFD simulation. It is possible to access data about aspects such as local temperature, air velocity and direction, and local radiant temperature. Access to data on the position of SMs can solve the issue of CFD's applicability for human comfort simulations, allowing the coupling of this technique without extensive data post-processing.

Beyond directly extracting indoor air environment data, it is possible to use SM information to implement an iterative feedback loop, where an SM is used to provide additional heat and pollutant gains into transient CFD simulations. Additionally, since the SM is an actual motion capture of the human body, it is possible to use this medium to dynamically adjust the mesh of the simulations. The humanoid movements implemented do not additionally have to be animated. Therefore, by appropriately setting up dynamic meshes, it is possible to simulate the general interaction between the human body and the indoor environment. More information about this data merging and extraction can be found in Paper No. 8.

3.3.5. Layout export and simulator - Methods

Beyond a standard simulation of occupant movement, it is necessary to adopt a tool that can implement and simulate various floor layouts. Movement itself is a crucial phenomenon to simulate, but general indoor transitions happen due to the potential need or desire to transit to a place in time, which can be caused by the need to use the space due to the location of the desired appliance, tool, controller or person. Access to the spatial distribution of the set of points of interest is usually available once the layout is already set. Therefore, occupants adjust to selected or imposed layouts. The selection of the layout does not guarantee that the placement of devices is optimal. There can be a trade-off between space utilization and ergonomic and thermal comfort. Without knowledge of the indoor layout, it is difficult to estimate its impact on local air circulation and how it will be possible to make a series of microspatial adjustments that can be beneficial for the users of the indoor space.

It cannot necessarily be expected that during the design phase, it will be possible to forecast what the exact layout design will be. At the same time, a crucial decision must be made about the placement of all HVAC installations. Additionally, during this phase, the implementation of any layout designs is not anticipated. On the other hand, once the layout design phase begins, crucial design decisions have already been implemented, and there is little room for adjustments. To address this issue, it was decided to design the layout simulator, which can be a supplementary tool for designers to check the potential influence of the specific HVAC design on comfort. As conjectured, there is no “best” solution in design, but with a layout simulator, it will be possible to check families of designs and to describe their implications for potential ergonomic and thermal sensation. This technique will use a procedural design. Therefore, it has to operate based on the specific type of rules implemented throughout data collection, which will become a boundary condition of these functionalities.

To develop a tool capable of simulating the floor layout, it was necessary to build a platform for data collection. Additionally, the tool should make it possible to merge data despite varying initial room and zone shapes. The principal operation of the application was the ability to outline the placement of specific appliances on the floor of a selected room. The application operates based on an adjustable Cartesian grid. If the specific grid shape was found to be too coarse, it was possible to scale it down to fill in the grid in a more fine-grained manner. The application was developed with the support of APP DESIGNER, provided as a toolbox of the MATLAB environment. The selected environment made it possible to port the application as an online application that can be used as a surveying tool. Example pictures of the application are shown in Figure 15. Once a significant amount of data was collected, it was possible to simulate an example layout. More precise information about the simulator design can be found in Paper No. 7.

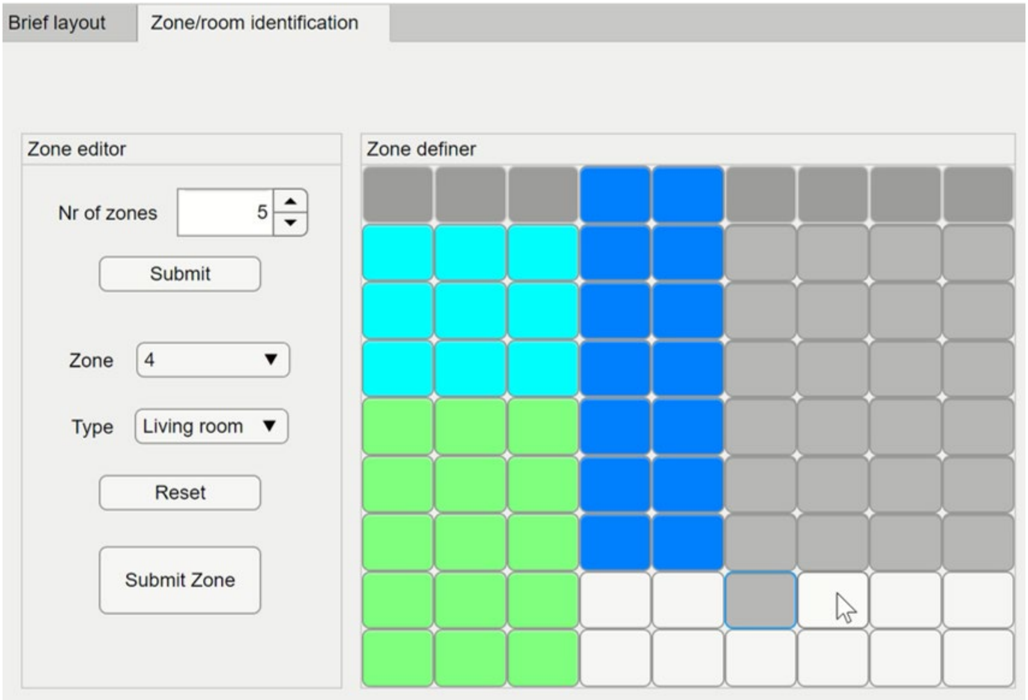

Figure 15. Screenshot of the layout surveying and simulating tool

3.3.6. Action associations - Methods

To simulate fully functioning occupants, it is necessary to trigger their activities. Previous subchapters described the basic ability to simulate movement (3.2.2, 3.2.3), the sensation of the properties of the environment (3.2.4) and the distribution of appliances (3.2.5). Each of these modules provided an important piece for the simulation of OB. However, none of these sub-parts can trigger any activity or reaction. To initialize movement or any sort of interaction, it was necessary to develop a solver capable of handling this task. Notably, the proposed solver must operate for each occupant independently, not as a separate model but as a computational engine that operates based on a database provided. To that end, an application that operates on four levels of description was proposed. Each level defines one specific sub-part of occupant motivation and interaction with the environment. The inspiration of the model was taken from a combination of the theory of planned behaviour [16], Maslow's hierarchy of needs [80] and Pavlov arching [107]. This solver is not yet tuned, but it enables the formulation of complex living scenarios that can force occupants to interact with virtual surroundings.

The main concept of the solver is that each artificial occupant (agent) has his or her main motivations and desires (Figure 16). Those motors of activity are prescheduled or predefined. Each day, each agent has his or her own set of targets, where reaching these targets grants the agent specific gains related to the subject (level one). Each agent is motivated to fulfil his or her desire. If the specific set of activities allows the agent to reach his or her target, this chain of activities is reinforced, and vice versa if the target is not reached. Beyond reaching the target, each agent has a hierarchical structure, where the position of each agent is defined (level two). Each agent shares his or her own list of responsibilities and relationships with other agents. The third level of the solver operates based on a library of activities and described gains connected to the completion of these activities. Inside the proposed library, there are predefined activities that can be completed by following a series of predefined activities. Each activity has its own specification and resource requirements. The order of visited places required also indicates the number of mandatory and supplementary agents that can be involved in this activity. Additionally, each activity has its own gains and penalties that are imposed on the agents involved. The last level of the solver associated with activities focuses on a description of the individual needs of the agent. The level contains information about the agent's well-being, hunger, daily rhythm, stamina, etc.

The activity solver operates based on the principle of a survival model, which estimates how long a specific agent's focus on a subject can last. With each time step an occupant is involved in an activity, his or her focus is depleted, and the likelihood of quitting involvement in the activity increases. The level of occupant focus is co-dependent on the occupant's individual status. For example, if the agent has a simulated sensation of hunger, then his or her focuses will be abnormally high due to the urgent desire to complete basic need tasks. The whole description of the model solver is included in Paper No. 10. The general purpose of this solver is to produce a tool that is capable of an unsupervised simulation of occupants and that also makes it possible to check the registration history of their actions. The proposed solver has simple mechanics, even though it makes it possible to simulate complex scenarios and to check potential side effects. This ability makes it possible to simulate various indoor scenarios and allows us to analyse the potential interplay between parameters such as occupant personality, preferential thermal range, and indoor conditions.

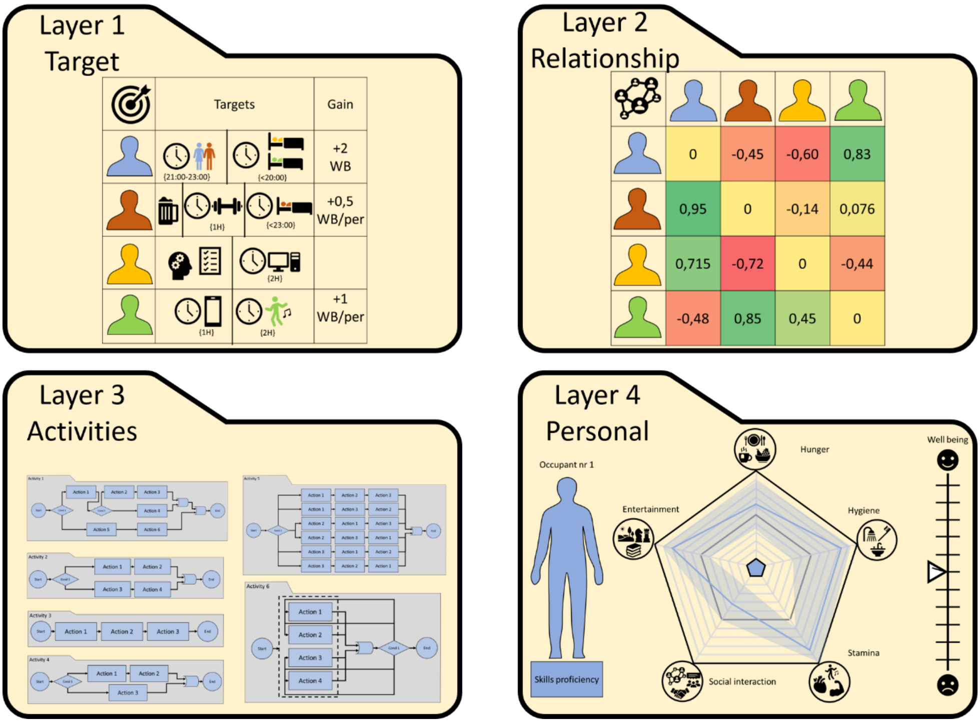

Figure 16. Structure of action association module

4. Results and comments

4.1. Occupant tracking - Results

In following subchapters few samples of measurements and simulation results are presented. The goal was to display the applicability of the monitoring device and its capabilities. The total number of monitoring campaigns has reached 40 cases, but displaying whole sets is avoided because of the ongoing development of specific model functionalities.

4.1.1. Movement registration - Results

The test trial shown in Figure 17 summarizes the results obtained from the case study where two depth registration cameras were used. These results show an overview regarding floor use inside the monitored zone (Figure 17). The monitoring results show 48 hours of recordings of occupants living inside the Zero Emission Building (ZEB) Living Lab, which is a residential house test laboratory [108]. All the coloured lines display the singular transitions inside the monitored zones. The presented building layout is a scaled and calibrated building layout used during the monitoring trial. The placement of furniture is only tentative. Based on the results obtained, it is possible to draw indoor transition arteries, which can also suggest the placement of a specific piece of furniture.

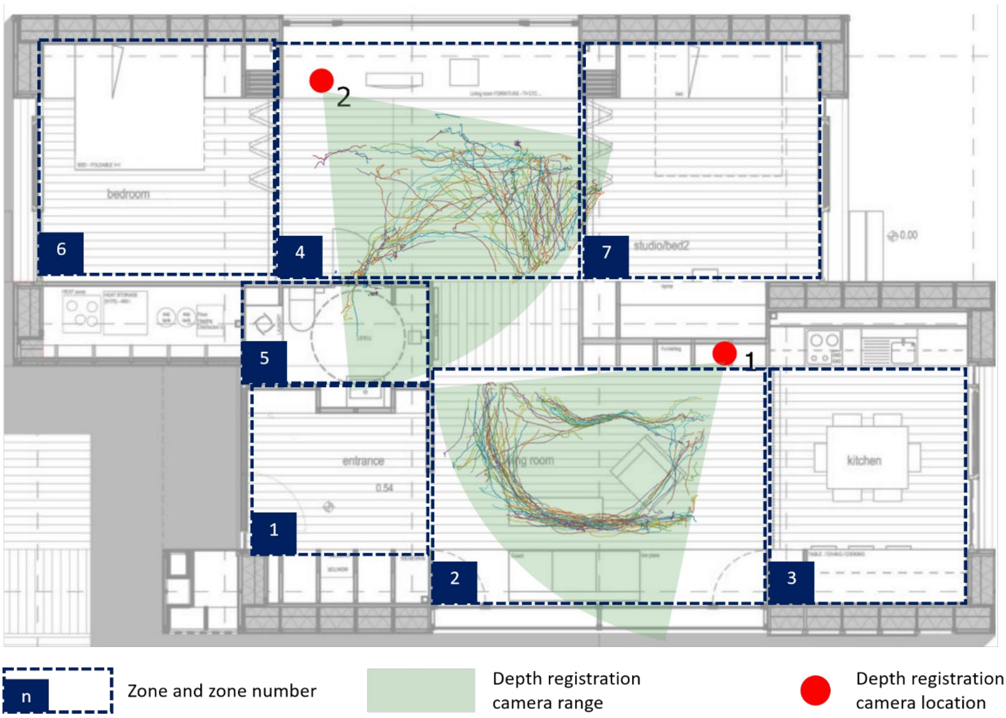

Figure 17. Overview of pathways recorded during monitoring trial

If the time of occupancy is connected to the spatial placement inside the building, it is possible to detect the zonal transitions and potential periods of days. Despite the lack of monitoring tools inside all rooms, it is possible to monitor zone entrances, which allows us to observe the times when the zone was occupied. Through the additional processing steps, it is possible to detect any kind of disturbance, such as unscheduled visits by maintenance staff. The graph presenting the transitions between zones is shown in Figure 18. The numbering of the zones corresponds to the numbers displayed in the zones on Figure 17.

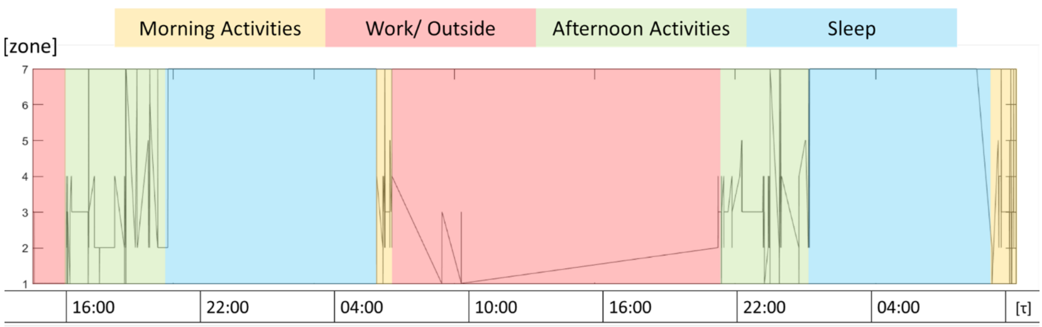

Figure 18. Zone occupancy plot during monitoring trial

4.1.2. D-CLO - Results

The detection of CLO requires several steps. As shown in Figure 19, the raw recording produces colour information in eight bits of information per channel. The carpet plot colours shown depend on the value of the channel colour from a specific joint. Based on the colour information from facial joints, the remaining joints were differentiated. If the value of the colour range was relatively close to the facial joint colour, the joint is considered to be exposed. Formulated in this way, a binary SM was compared with prescheduled layouts. Based on this classification, it was possible to check the detection accuracy. The accuracy of this method depends on the lighting conditions. The darker the visual scenario is, the lower the success rate that can be registered. The results displayed show a sample detection success rate of specific skin coverage associations. This colour threshold-based technique produced a success rate of approximately 70%.

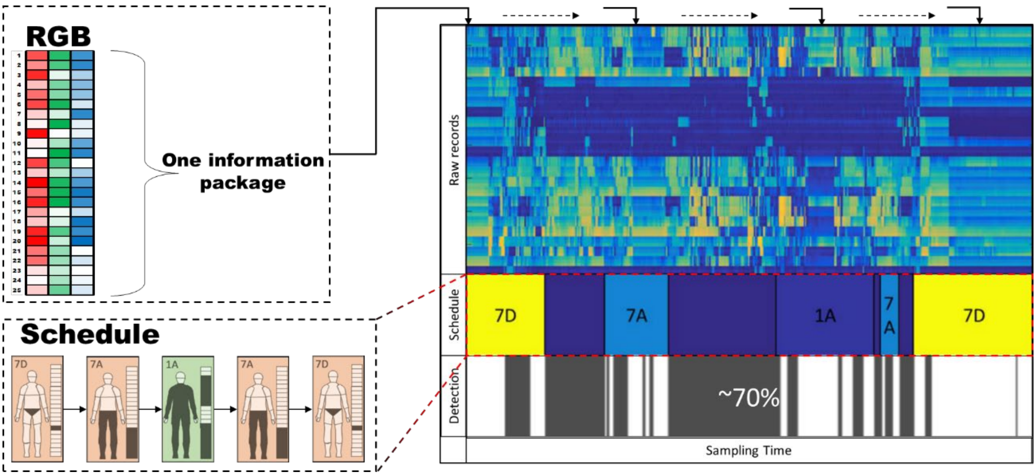

Figure 19. Clothing detection algorithm with an example result

To check how machine learning classification techniques can influence the detection success rate, the same subject was investigated using machine learning and deep learning methods. After training the model, the success rate of classification jumped to 85% when using the red, green, and blue (RGB) colour map and 92% when using the hue, saturation and value of lightness (HSV) colour map.

4.1.3. D-MET - Results

Data obtained from the SM can be translated into the heat gain realised to the indoor environment. Depending on the available data regarding the building layout, it is possible to generate a full MR graph that can contribute to the building energy management system (BEMS). It can provide a detailed report of occupant activities and contribute it to BEMS for control improvement. The monitoring setup was equal to that in subchapter 4.1.1. The location of the cameras made it possible to capture the activities performed in each zone. The results presented show the indoor heat gains as the result of human body activity. Each of the presented graphs shows the same case, but with a different time resolution. Data upscaling was performed by weight-averaging the results to adjust to the selected temporal resolution range. (Figure 20)

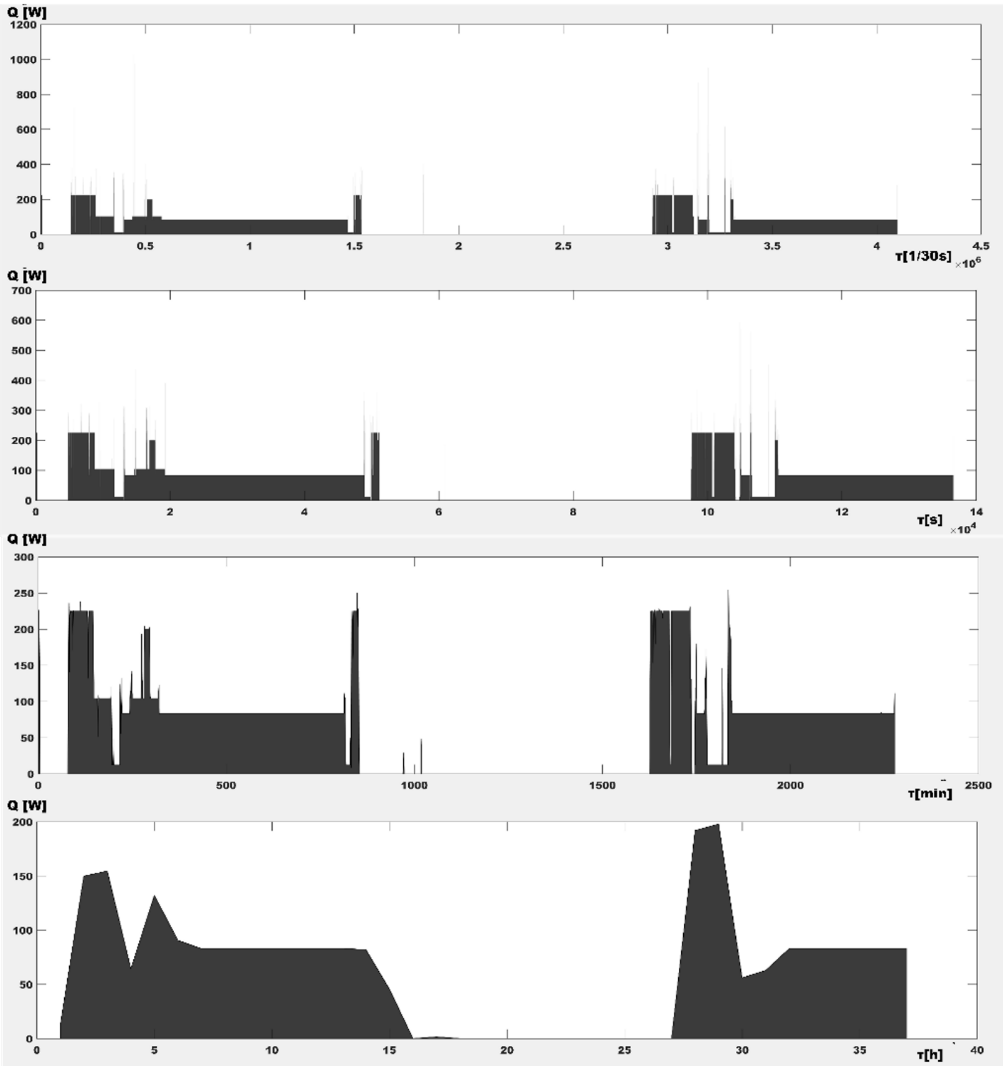

Figure 20. Metabolic rate estimation by a movement recording and spatial occupancy

Each time the monitored occupant was registered, the registered transition was captured, and it was recalculated as the heat gain value Q [W]. If the occupant was outside the monitoring zone, his or her time of occupancy was calculated. Based on the database provided by ASHRAE Standard 55 [22], the energy contribution was estimated by the calculated time and zone type. The heat gain values from direct observation tend to generate a “comb”-like shape, whereas data estimated from the ASHRAE standard produce more even recordings. Data from direct observation show more diverse recordings, which might indicate that the formulation of the unified activity table is not as accurate as expected. Additionally, the activities recalculated from the ASHRAE Standard 55 [22], treat each zone as homogeneous in terms of activity, which might not always be the case.

4.2. Modelling of the BOT-ABM - Results

All the results shown in this section are considered an example of the performance of each application, and the possibilities of testing the model in different combinations are nearly unlimited. Therefore, it was decided to show the example performance of each application.

4.2.1. Movement simulation - Results

The simulation of transitions inside a virtual building layout can be performed for any type of building, floor, room or zone. The necessary input for such simulation is access to the virtual layout, which is defined in subchapter 4.2.3. On Figure 21, sub-figures A and C show the existing layouts of the office building (A) and residential flat (C). Each has a fixed shape, although the geometries might seem distorted. Each simulation was performed at the original geometric scale. During the simulation runs, two random points were generated: one point represented the start of a transition, and the second represented its end. The agent's task was to find the connection between these two points without supervision and to recreate the pathway that must be taken to reach the destination point. The main assumption of the simulations is that the agent is fully aware of the layout shape and that it knows where the end point is. Each layout was tested 60 times. More runs of the agent would produce a sum of output that could be considered unreadable. Sub-plots B and C show a heat map of the transitions. Each layout plot was downscaled to fit a heat map resolution of 1000 x 1000, and each layout dimension had its own compression value. Each time the agent took a step in a specific pixel of the heat map, the value of this cell increased by one. The higher the value of the heat map cell is, the brighter its plot. Therefore, the heat map highlights the most used space of the layout. The simulation results show the capabilities of the model to simulate a "real life" way of transiting by generating pathways similar to those of human steps.

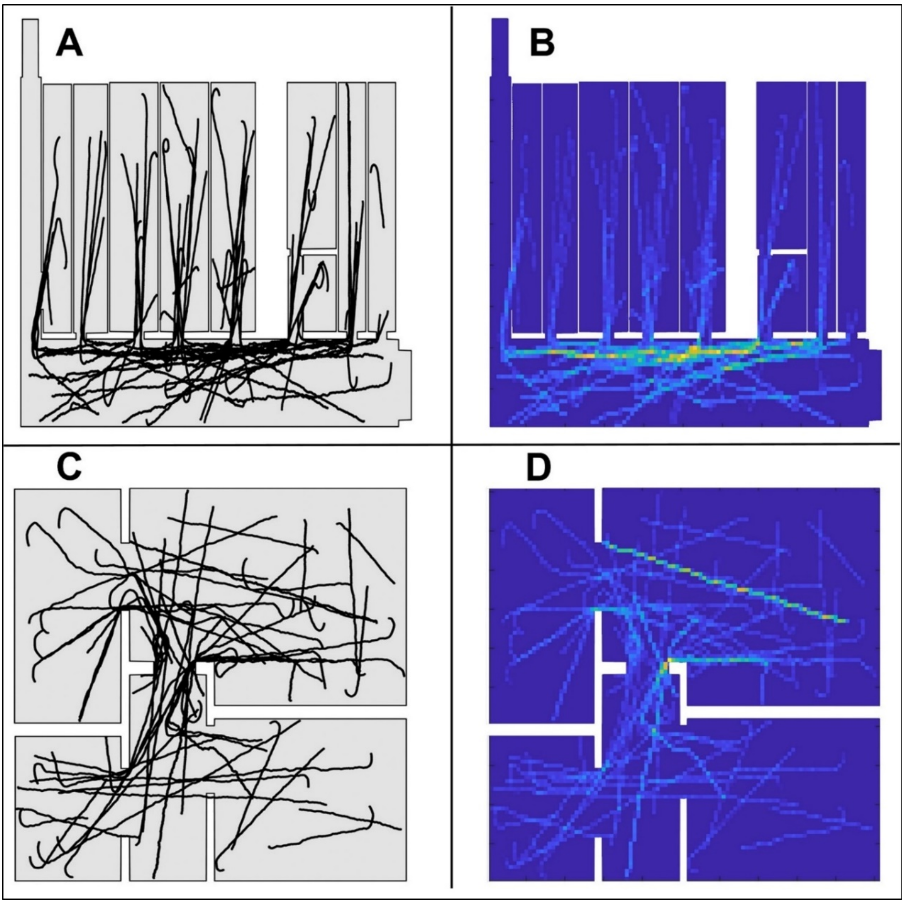

Figure 21. Movement simulations plots. Subfigures A and C are movements inside example layouts, while B and D show heat maps of movements inside the same layouts

4.2.2. Indoor body exposure - Results

The casted results of movement into the CFD results enable the indoor exposure data to be probed. The parameters of the CFD simulation performed followed steps similar to those presented by Aganovic et al. [109] The direct data sampling ball-plot with a colouring of the simulated thermal distribution is shown in Figure 22. The source of SMs for probing the information was provided from a real-case scenario, where one residential room (living room) was selected to investigate the occupants' thermal exposure. A two-occupant group participated in this experiment. To calibrate the simulation and obtain adequate results, it was necessary to use some additional measurement devices during the investigation trial. The calibration setup had three thermocouples, two anemometers (TSI VelociCalc multi-function ventilation meter 9565-p) and a thermal imaging camera (FLIR E60). The depth registration camera was placed in a corner of the room. The placement made it possible to cover the whole room area. The purpose of the trial was to show typical spring/summer days without additional heat gains.

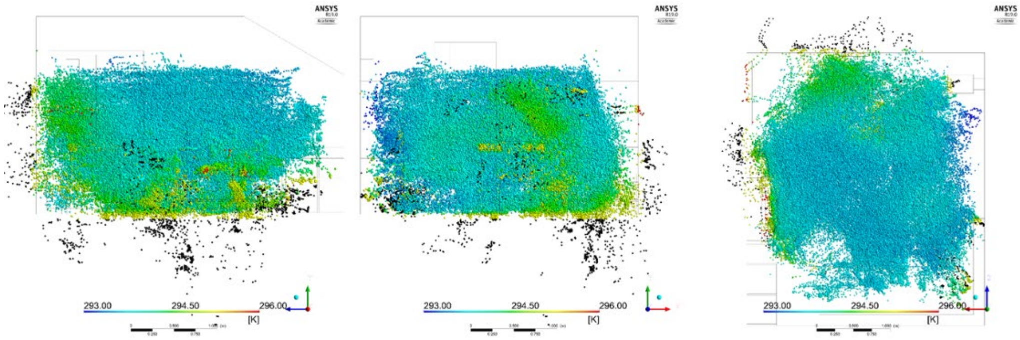

Figure 22. Composition of all records of SM joints projected into the room geometry. Each point probes the information from CFD simulation, and its colouring depends on a probed variable value

To show partial joint exposure, it was necessary to extract the data from the simulated volume of air, and this data extraction required the variables to be specified. To show the ability to perform data extraction, only the temperature variable was selected. The movement of the occupants was registered throughout the monitoring campaign (48 hours). Displaying the whole set of data in a readable form would require the use of at least 120 plots. To avoid this issue, it was decided to show the example results of one hour of human body exposure from one of the monitored occupants as presented in Figure 23. The blue line shows exposure at the position of the base of the spine, and the red line represents the position of the head.

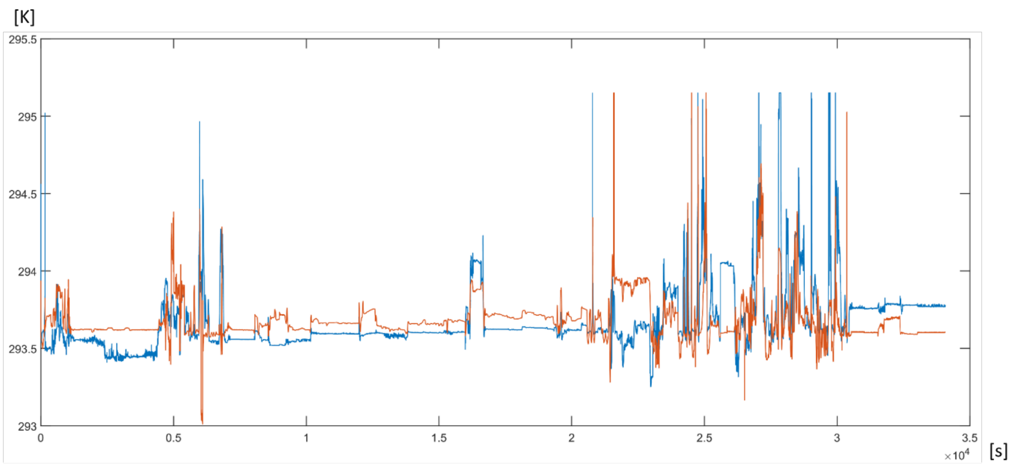

Figure 23. Example plot of SM information used to export information about thermal properties from CFD simulation

4.2.3. Layout import and its simulator - Results

Layout exploration is necessary if there is no digital (vectoral) drawing of the investigated space. If vectoral information exists, it can be directly implemented in subsequent simulation steps. Otherwise, the bit map must be vectorized. To implement the drawing in the system, it is necessary to detect all the layout edges. Before this can be done, the investigated raster picture has to be binarized, where each pixel belonging to the floor layout has to hold a positive value and the rest of the data are translated into a negative value. The next step consists of identifying the layout currents and connecting the points in a polygon. A format with connection to a polygon requires chain identification, which is a vector variable (1xn+1), where n is the number of points included in the vector. The extra spot is reserved for the initial point. The vector variable defines the order in which the edges of the polygon must be connected. Before this step, it is necessary to check whether all the corner points belong to the same class. The direction of these features is performed using the density-based scanning (DBSCAN) technique. This technique is an unsupervised classification method that provides data segregation based on their spatial distribution. Once the number of separate edges is defined, it is possible to generate a vector of polygon connections. If there is more than one detected edge, then this result indicates the existence of a hole inside the layout, for example, a column or other construction object. Sorting by the size of the polygon will help in distinguishing which polygon represents the default floor layout and the holes inside it. It is expected that there will be no unconnected part of the layout. Therefore, no sophisticated method for detection is necessary. Each hole must be subtracted from the main polygon area using Boolean, subtraction operations. Once this procedure is performed, it is possible to simulate the distribution of appliances.

The description of the layout digitalization is essential for the appropriate operation of the proposed ABM simulator. Importing the layout does not produce results that can be differentiated from its initial state if the importing is done properly. The next necessary step consists of distributing a set of appliances that fit the room category to the virtual layout. If the test case is already furnished (post- design phase), the layout can be added manually via the editor of the application. In other cases, the layout is simulated via a probabilistic map of the distribution generated from previous studies. Each appliance has its own map, and the order of placement is decided based on the results of the survey regarding the importance of specific appliances in a selected room category. The example results from the survey are displayed in Figure 24. Each device has its own orientation and properties designed in a manner similar to that in building information modelling (BIM) software, and it allows agents to immediately identify an object and interact with it if necessary. If the object is being used, it will generate a virtual output of its usage by consuming energy or by producing internal heat gains.

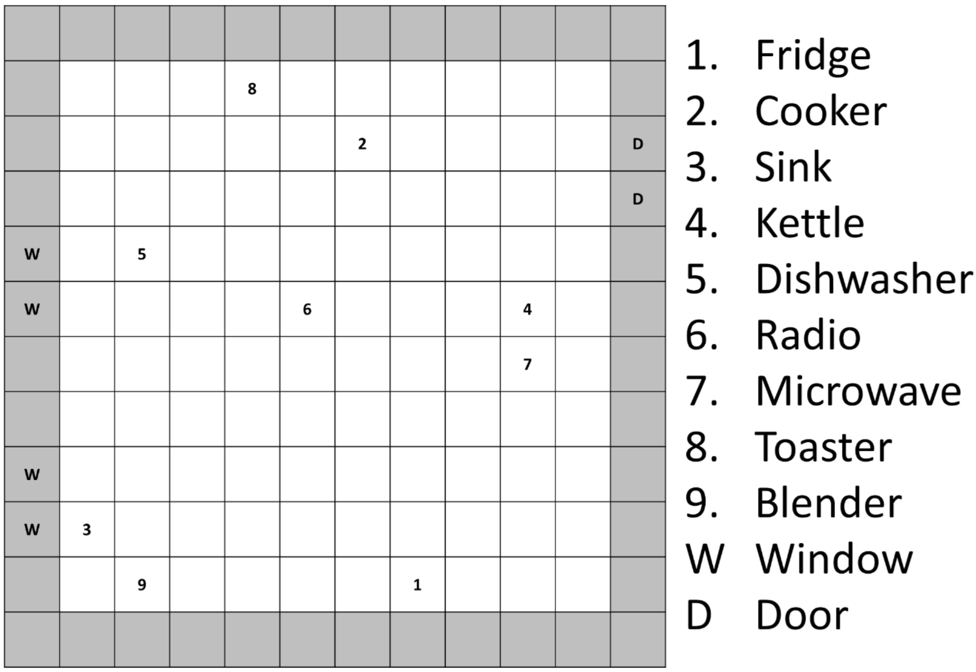

Figure 24. Example of the layout simulator results

4.2.4. Action associations - Results

To drive occupants to one specific task, it is necessary to implement an activity association solver. The core solver distributes the activities in a defined order to finalize the activity. The activity association is semi-random. Each simulated occupant has his or her open slot for the action association, and based on a group hierarchy, the actions are distributed. The simulator considers the occupants' preferences and their focus on and commitment to the activity. The simulated scenario shown involves a procedure in which a four-agent group is engaged in the activity of preparing dinner. The description of the activity made it possible to perform several parallel activities at the same time, and there was a disturbance factor of phone use. Occupants one and two were parents, while occupants three and four were children. Through the system of social hierarchy, the agents representing the parents are the first to pick their specific activity. Consequently, occupants may select any available task in the activity description. The activity description is shown in Figure 16, layer 3. Activity regarding the use of the phone is not included in the main activity description, but such action is always associated with each occupant, and it can be considered a source of disturbance. The simulations performed were conducted with the use of agents that were not exposed to any disturbance factor, and their well-being status did not influence their task. The results of the activity interaction simulation are shown in the chart in Figure 25.

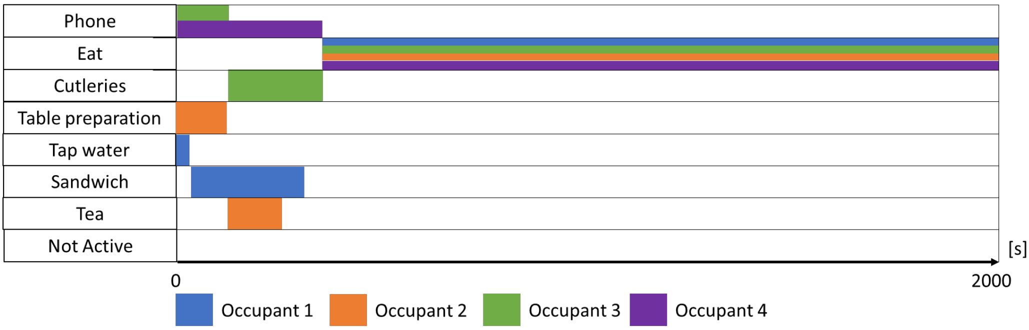

Figure 25. Summary of simulated activity composed of several pre-defined actions taken by agents resembling occupants

5. Discussion

5.1. Occupant tracking - Discussion

Through the development of a series of standalone modules focusing on one occupant-related phenomenon, it is possible to obtain a good overview of indoor OB. The specifications of the depth registration camera can provide extensive information about the occupants with a sampling rate that can capture any visible interactions with an indoor appliance. The SM of each occupant grants a significant view of the occupants' habits, which can be used to build a knowledge base to monitor occupants' resource utilization. Using the SM, it is possible to track the body ratio index among the occupants and to indirectly detect their activities. Depth registration with a minor use of a video camera does not enable direct identification of an individual. Each occupant will be represented by the SM and CLO identification, which does not allow us to directly specify the observed person's identity. The closest that we can get to such recognition is a formulation of the occupant's identity number, which is used only internally. A direct connection to personal information can be established only if someone deliberately breaches and gains access to the internal monitoring system, which itself is an illegal act. The modular structure of each component of the detection system enables various levels of data monitoring. Therefore, if a specific feature is considered too invasive, it can be suppressed, which will reduce the effectiveness of the occupant monitoring system; however, the system will still be able to provide a significant amount of information. On the other hand, all the potential information that can be obtained from the proposed monitoring system does not allow insights such as those produced via contemporary smartphones.

Tracking occupants individually can contribute to formulating the profile of their use of space and appliances. It can highlight the differences in thermal preferences that exist among observed users, and it offers a vision of a new kind of building automation control that aims to achieve fit-for-purpose application. The differences in preferences identified can be addressed by implementing various strategies that aim to maximize occupant satisfaction or optimize resource utilization. The use of the depth registration camera has applicability for model predictive control due to the possibility of formulating OB profiles. If such a monitoring system is introduced in a specific space, it will be possible to observe the daily utilization of that space, which can lead to certain forecasting. Furthermore, the introduction of such a system would highlight the monitored space occupant routines, which can lead to appropriate energy utilization. For example, if the monitored space is a residential building with multiple rooms and all the rooms included belong to a certain category, we can conjecture that certain rooms will be visited daily, but other rooms will not. While analysing the pattern of visits to those rooms, it will be possible to introduce a control for thermal zoning that is set based on the needs of the zone users. Additionally, the proposed system can be used for a supportive feedback machine. With the use of a secure human–machine interaction interface, it will be possible to attach an energy tag to a specific action or activity. Occupants can be informed if a specific behaviour promotes low-energy patterns or if it increases energy use. With such ability, it will be possible to propose strategies to reduce the energy use in buildings. Such a system can be considered an educational feedback machine but, it is an advisory tool. Ultimately, whether a proposed modification of their behaviours is acceptable is the decision of the occupants. Regardless of the outcome, this system will allow us to attach an energy price tag to a certain behaviour and show what is an achievable energy standard.

The ability to record SMs makes it possible to formulate various modules that focus on a specific phenomenon of energy-related OB. From the perspective of existing modules, an occupant indoor profile can be built from modules that focus on movement, occupant identification, activity estimation and the CLO insulation level. There is no minimum number of enabled modules to allow the profiling, but the fewer the modules being used, the lower the resolution of the occupant profile that can be achieved. For example, without an identification module, the whole detection of the individual will be less accurate, and the system might tend to generalize the whole group being monitored. This effect of disabling various modules is difficult to estimate and it is hard to define how it will influence the generation of individual indoor occupant profiles.

Figure 26 presents a sketch of the data processing pipeline showing the existing modules that are operable; however, this does not mean that there is no room for improvement. As presented in the last paragraph of subchapter 4.1.4, further extensions are possible without a significant modification of the monitoring source code. Once the extension of the activity labelling is appropriately tested, it can grant access to additional modules that will allow us to define occupants from the qualitative perspective. Implementing an indoor occupant profile can contribute to the supporting formulation of a more precise description of occupants' indoor activities. Beyond all the applications listed above, the use of a depth registration camera can help with monitoring occupants who require constant feedback about their well-being or special care. For example, with application in nursing homes, it will be possible to detect certain body positions and limb activity (via the SM), which can indicate a sudden fall or cardiac arrest.

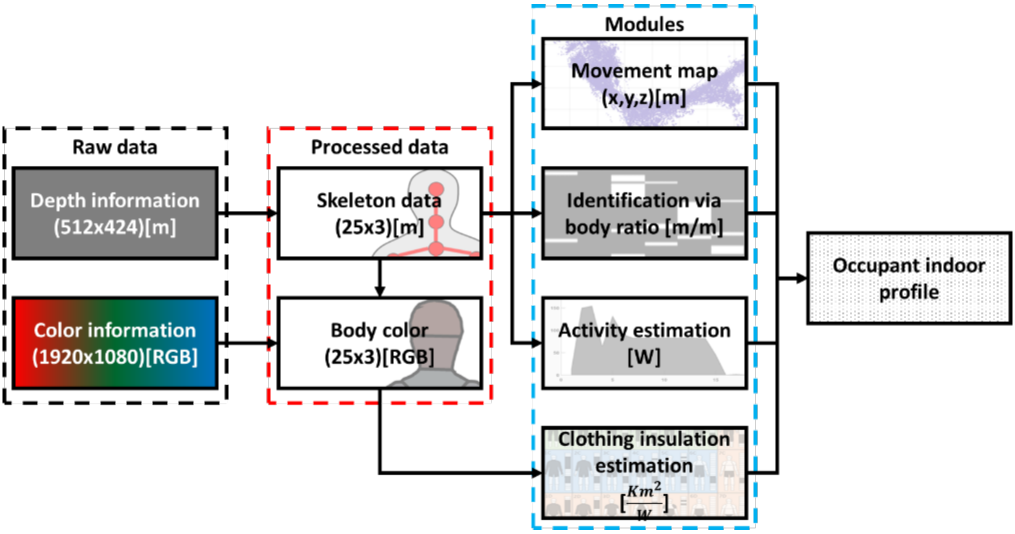

Figure 26. Structure of the data outputs used to compose an indoor occupant profile

5.2. Measurement accuracy - Discussion

Based on presented applications (in chapter 3) and achieved results (in chapter 4), it is legitimate to claim that the depth registration is a useful monitoring technique for OB research. This thesis explores usage of the depth registration in four different applications focusing on some central aspect of occupant indoor behaviour. Each of the four applications was tested only in terms of the internal accuracy of the device. The performance of each of the applications was tested through comparison with manually labelled data designed for application validation. The simple validation included distance measurement for movement patterns registration, metabolic rate estimation and manual description for CLO-value estimation and activity labelling.

The hypothesis and the research questions pointed out the direction of the conducted research. The first research question examines the possibility, the second scrutinizes potential gains, and the third focuses on the implementation of solutions. These specifications limited opportunity for comparative studies with other, similar measuring devices. Therefore, the device comparison relays on the literature review presented in subchapter 2.1.2.

The accuracy of each of the applications depends on the general accuracy of the device. All applications have their own richness of content that could be explored further, but such approach was not the target of this research. Instead, the presented work shows an overview of depth registration applicability in OB research. A summary of achieved accuracies for each of the applications is shown in Table 4.

Approach	Highest archived accuracy	Unit
Movement registration	0.01	[m]
Dynamic clothing insulation estimation (D-CLO)	98,01	[%]
Dynamic metabolic factor estimation (D-Met)	0.05	[m]
Activity labelling	97,41	[%]

Table 4. Summary of archived accuracies per approach

The “Movement registration” and “D-Met” applications are strictly dependent on the device built-in properties. If it was conducted the same research, but using a different device than Microsoft Kinect V2, the results might be different. On the other hand, “Activity labelling” and “D-CLO” can be considered as a derivative of the data obtained from the measurements. The achieved accuracies for these two applications are impressive, but the number of investigated cases does not cover all of the applications potential. The “Activity labelling” includes twenty-two actions, while the advanced “D-CLO” includes thirty-nine clothing setups. The presented applications and their accuracy are showing the potential to reach a highly accurate description of indoor OB.

Therefore, the presented work should be considered as an opening chapter for the OB research using the depth registration monitoring technique. Based on achieved accuracies, it is possible to extend the applicability of each of the applications. For example, the “D-Met” approach is currently using averaged body acceleration for estimation. An improvement of this application should aim towards calculations of direct estimation of metabolic rate based on the dynamics of each limb and classified activity. Conducting such a study would require access to the climate chamber, which allows for a precise measurement of the heat gains and has an option of adjustable layout to simulate various activities. Under such conditions, it would be possible precisely to investigate estimation of the metabolic rate. Also, such study would have to include the usage of advance biometrics of tissue composition and blood flow similar to the study conducted by Wolki [110], and a large and diverse population of occupants. Such study could have contributed with its findings to improvement of ASHRAE standards or REHVA guidebooks.

5.3. Modelling of the BOT-ABM - Discussion

Access to precise information about OB profiles has made it possible to formulate a comprehensive model that can be used to recreate occupant activities on an individual level. Based on the data provided, it was possible to propose a model framework for a BOT-ABM. Further explanations of the framework itself can be found in Paper no 6. The proposed model is defined by the composition of sub-models, which can be called modules. Each module represents an essential element that is necessary to perform a highly granular OB simulation. It considers aspects such as dynamically changing positions indoors, the influence of an indoor environment, occupants’ individual habits and activity preferences and their status in the social structure. Each occupant is simulated as a separate agent. Formulating the model in this manner makes it possible to run simulations of multiple agents without significant increases in the iteration time step. Combining these co-dependent modules aims to simulate the deterministic re-creation of building user behaviour. It tries to reduce the randomness to the more unmeasurable scale of the human thought process, but at the same time it promotes coordinated action control. It shifts the numerical perspective due to the accessibility of the new, more precise information about the cause and effect of each action. Based on the registration of each action performed, it is possible to capture a more deterministic picture of the simulated activities. Therefore, with such an input, it is possible to build a chain of evidence that will be reproduced by the sequence of actions or activities. The randomness is transformed into the occupants’ commitment to an activity and their focus. Using the survival modelling technique, it is possible to define the means of focus and to comment on activities.

The proposed model does not have a specific target group of users. Similar to the range of specialities of scientists who focus on energy-related OB, the proposed model is structured to cover each speciality. It takes into consideration mechanical and civil engineers, architects, physicians, psychologists and social scientists. The BOT-ABM aims to be useful for each scientific branch that focuses on the well-being of occupants. A broad range of specialities that takes OB into consideration requires a platform (software) that enables communication and direct collaboration on the same issue. This is similar to the BIM design philosophy, where access to the building design process is granted simultaneously to each member of the design team. Due to the early stage of model development, not all the necessary resources are available, and there is still a need to develop a database of various personalities and activities. Once the database has a significant volume of inputs, the use of the tool will not require a significant number of specialists or time to conduct the OB simulation. This tool is intended to be implemented and used during the building design phase, but it may also be used as an activity forecaster. The main difference will be that the actions and activities are not predefined by the specialist but are self-reported through the formulation of the indoor occupant profile.

The current stage of the model allows its basic operation to be simulated, and each module can be simulated as a standalone application. (Figure 27). To harness its full potential, it is necessary to combine all its features together in a way that enables simultaneous calculation. It is possible to conduct such simulations at the current stage but doing so will require a significant amount of manual labour. Therefore, it is not yet ready for industrial applications.

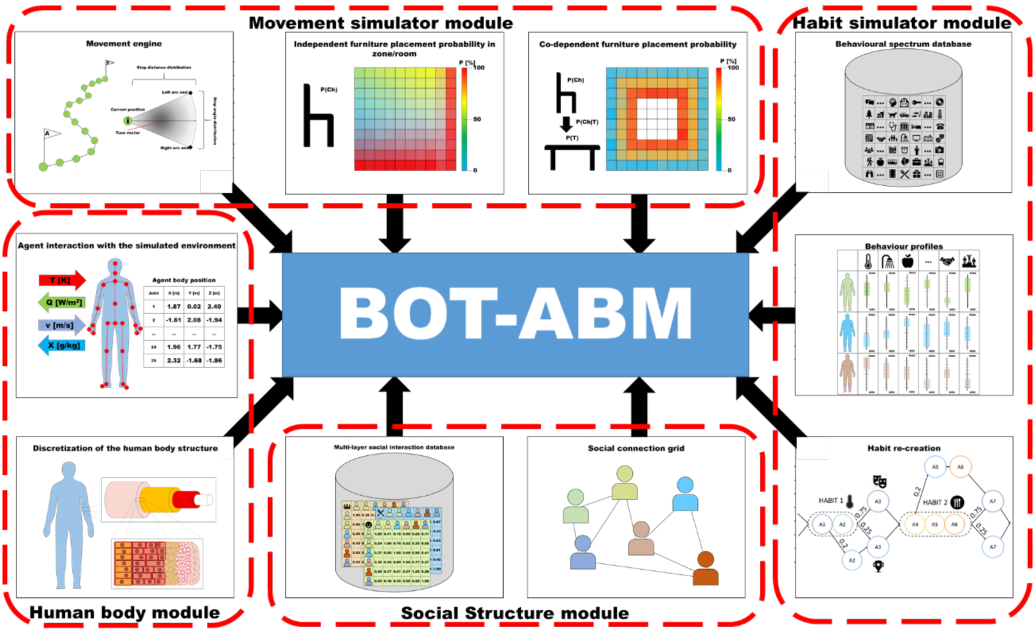

Figure 27. Development framework of Building Occupant Transient Agent-Based Model

The debatable feature of the agent-based modelling is the validation process. The more complex the model structure that is proposed, the less predictable the simulation result becomes. This does not mean that the whole simulation provides uncertain results. The action or series of actions that an agent is required to conduct will be fulfilled, but the way of doing it might differ between simulation runs, generating opacity [111]. Testing the influence of each separate part (functionality or implemented rule) on the general performance of a model requires the use of the performance matrix. The number of separate model parts defines its size, where each column represents one specific model part.

It is a binary matrix, where each row represents a setup of enabled (positive cell value) and disabled (negative cell value) model parts. If the model part is enabled, it follows the description implemented in the model. If it is disabled, these model part variables use random values to perform. The performance matrix is composed of all potential model functionalities setups. Each setup should be tested to check its performance.

There are two levels of model evaluation if the performance matrix is used. The first level is to cross-check all cases with a setup case, where all the model parts are disabled. Such a case can be considered as a baseline case, where all the functions are operating on random numbers. The second level is a setup of specific boundaries that an agent cannot cross. For example, an agent cannot walk through the wall or use private space when it is occupied. If a specific setup passes both levels of the evaluation, it scores an evaluation point. Conducting proper evaluation requires the testing of one specific setup from a performance matrix several hundred times. Specific errors might not emerge in each simulation run. After such a procedure, it is possible to check the influence of each separate model part on the general model performance.

Each developed piece of the model was tested in such a way, and its functional performance was examined under validation measures. The way an agent-based model can be validated does not provide a quantitative output to compare. There is no optimisation target or series of activities that promote a specific solution, especially if the simulation has a brief narrative to follow for agents. The main objective of ABM is to perform and enact rules that are imposed on it. In the worst-case scenario, it may produce a fatal error of simulation. In other cases, if the ABM is pre-trained correctly, it will reach the requested target or fulfil it. It must be stressed out that the function of any ABM is to simulate a complex phenomenon of interactions. Since it operates in a virtual world, it is possible to register its every conducted action and the reason behind it. Therefore, it is possible to conduct in-depth investigations of a complex phenomenon, like occupants' behaviour, where each person is represented as a separate agent. The real challenge is answering the question about the actual model validation. As it is mentioned in subchapter 2.2.2, the validation process of ABM is challenging, and ensuring the quality of the model requires cross-validation within a data from different observation.

Acquiring proper data in most of the cases request the existence of the independent research that focuses on a similar phenomenon. The solution for this challenge, concerning further development of BOT-ABM, is a promotion of the Indoor Occupant Profile generation (subchapter 4.1, and 5.2). The ability to automate profile generation and data annotation will bring a tremendous boost towards development of the referential database. Most of OB ABM studies [48], [64], [87]–[91] are pointing out that extraction of the crucial information can be considered as a cumbersome process. Once this issue is by-passed development of the referential OB database will be achievable within a considerable amount of time.

5.4. Next steps

The formulations of both the indoor occupant profile and the BOT-ABM are state-of-the-art applications that do not have a competitive comparison among other models. The closest application that has an extensive focus on OB is the OB functional mock-up unit (OBFMU), which is included in the Energy Plus software [11]. Such a comparison can be considered unfair due to the different core operation solvers. The Energy Plus sub-model focusing on OB is a time-series model, whereas the BOT-ABM is an ABM. In terms of comparison with other existing OB-related ABMs, most of them focus on one specific phenomenon, such as opening windows or user preferences. Each specific model can be implemented in the existing framework, but it must be rebuilt to match the simulation perspective of the BOT-ABM. In other words, if the model describes a specific phenomenon, it has to be re-forged to become an action or activity conducted by an agent who represents an occupant.

The development of a comprehensive indoor occupant monitoring system that operates based on depth registration is still an ongoing subject. In 2016, when the work on this measurement technique was introduced to monitor occupants, the most popular device that had a preinstalled depth registration camera was Microsoft Kinect [99]. For this reason, it was decided to purchase a few of these devices to begin developing software that would focus on OB monitoring. However, in the last quarter of 2017, the manufacturer of the device announced that its production would cease. As a consequence of this decision, during the first quarter of 2018, all these devices were pulled from the commercial market. At the end of the same year, another manufacturer (Intel) announced that it would launch new depth registration cameras on the market [112]. The new products arrived on the commercial market at the beginning of 2019. This story reflects the development of this thesis. During the first steps of development and while becoming familiar with the device, the market was saturated with equipment that was still not tested. While the first few trials showed promising results and the measurement technique was ready to be implemented on a larger scale, the devices used were not available on the market. Consequently, further studies were blocked. Once the new device was introduced to the market, it was too late (from the perspective of the development of this thesis) to focus on recrafting previous methods. Therefore, future steps of development should aim to transition the proposed monitoring technique toward the use of different devices that operate based on the same monitoring principle.

The development of the BOT-ABM should continue to enable all functionalities into a user-ready level, and its major function should focus on merging all the modules listed above into one functional model. Beyond this, it is necessary to introduce the cross-platform usage of the BOT-ABM in the BPS software. To harness all that the potential BOT-ABM application has to offer, it should be introduced into BPS platforms as an advanced plug-in application. This is a challenging task, but due to the modular structure of the BOT-ABM, each module is defined as an object-oriented program. Therefore, communication between modules takes place without sub-dependent variables, which accelerates the process of merging and implementation. This object-oriented programming treats each defined part of the software as a “box” with inputs and outputs. The meaning that each input and output represents is important, but the solver inside the “box” operates internally, which allows a more robust manipulation of the entire software. Therefore, due to the proposed programming methodology, implementing the BOT-ABM should not be an insurmountable undertaking. An additional task that must be taken into consideration is the development of the libraries for the individual modules. A comprehensive model capable of recreating a normal behaviour library of preferences, daily habits, activities and actions must be developed and defined. This task can be performed partly through data from observations, but to accelerate the process of BOT-ABM development, it must be performed through manual definition. Beyond these tasks, the next step should focus on an investigation of an appropriate graphical user interface (GUI) that will smooth the process of running the simulation process.

6. Conclusion

The main hypothesis of this thesis was that an increase in the spatial and temporal monitoring resolution of indoor activities can provide valuable insights regarding OB and building energy use. As presented, the ability to capture OB when specific actions are happening opens a new dimension of analysis. Access to the spatial identification of the occupants' action enables the personalized control. At the same time, with such a detailed description, it is possible to learn about occupant habits and ways to utilize energy resources. This opens a wide range of application possibilities that can support energy forecasting, and better understanding of the energy processes. These functionalities are an offspring of the increased insight about indoor OB. They will support the answering of fundamental questions regarding the minimal threshold level of energy use reduction in buildings. This level will highlight which practices and habits make the greatest contribution to reducing energy use. Finally, this will pinpoint the price tag attached to the activities of occupants and connect to their footprint, which might lead to more responsible resource utilization.

To summarize the thesis, it is necessary to answer all the research questions initially specified.

6.1. Answers to the research questions

Research question No. 1: Is it possible to increase the temporal and spatial resolution of OB sensing?

It is possible to substantially increase both types of resolution. The current stage of technology improvement makes it very difficult for infrastructure to keep up with it. This might be the reason why certain types of technological solutions, like depth registration, do not appear to have received proper attention. Depth registration cameras already have a few other industrial implementations, such as drone avoidance control and facial recognition systems, but it is surprising that these devices have not been used in the building energy performance sector. It is conjectured that the underlying reason is a lack of available tools for handling such big data. In other applications, such issues are appearing due to the differences in functionalities.

As presented in chapter 4.1, the use of depth registration cameras allows a wide spectrum of detection that can more precisely define occupants' activities without crossing important boundaries with respect to their privacy. None of the obtained inputs can be used to directly identify a person without merging them with external sources of data.

Research question No. 2: How can the new type of information contribute to current knowledge about OB?

The data streams from the device can be used to obtain new insights into OB. The depth registration camera enables the transitions, activities and CLO patterns of occupants to be captured. All these parameters are crucial for the proper design and control of HVAC systems. Once this information is translated into model application, it can be used for simulation purposes. Additionally, a constant stream of these parameters will allow the definition of the preferences and patterns of behaviour of the observed occupants, which can be useful for building management systems and model predictive control. The proposed monitoring solution provides an observational perspective because it is one of the first applications to make possible the analysis of indoor OB without treating it as a derivative of the monitored phenomena. Most previous studies do not directly track occupants while they are performing activities. Previous monitoring rigs were mainly focused on the interactions of the occupants with a specific piece of equipment or appliance, and activity tracking was conducted via self-reporting, which leaves room for social desirability bias. The proposed monitoring technique provides an unbiased, in-situ tracking of occupants, which means a higher likelihood of capturing representative information.

Research question No. 3: How can the increased insight into OB be implemented in existing building performance simulation (BPS) tools?

The new and more precise information about OB can help in the development of new tools that can be integrated with existing simulation applications. The key issue is the ability to handle the information exchange between OB simulations and BPS software. According to the assessment conducted, there is no simulation tool that can handle such precise inputs regarding OB. Therefore, we proposed to design a new model structure that will concentrate only on the simulation of OB. With the use of object-oriented software design, it will be possible to implement the knowledge about occupants collected as a standalone application. Such a solution can be considered beneficial for model development because it does not require a focus on an implementation but, rather on the definition of the most crucial inputs that are necessary to run the model. Object-oriented design allows the existence of such a software structure, and it can be used as leverage if the proposed application has to operate with many and various other types of simulation software.

In terms of details, one of the important findings is an update of the movement solver. Due to the detailed observation of the occupants, it was possible to investigate the relations between movement speed and transition angularity. Previous models, as is shown in the literature review in subchapter 2.2, did not take into consideration such relationship or were using rather more simplistic solutions development on a base of GPS data. Ability to re-creates an artificial pathway is a crucial parameter for reactive simulations. Without it, it is impossible to simulate the occupants' reactions in a local indoor condition, such as exposition to sunlight, glare or local drafts. If simulated exposition of occupants towards such phenomena is desired, it is necessary to localise simulated occupant precisely.

Moreover, once the significant amount of the data is collected regarding CLO- estimation [subchapter 3.1.4] and Activity labelling [subchapter 3.1.6] that considers indoor thermal conditions, it would be possible to implement new reactions towards proposed OB model [subchapters 3.3.4 and 3.3.6]. Both methods have an accuracy detection above 95% (for CLO-estimation [subchapters 3.2.2.3 and 4.1.2], for Activity labelling [Paper No.11]), which makes both methods highly reliable. Therefore, it is possible to assume that after accumulating a proper amount of investigation data, it will be possible to discover new findings of occupant behaviour that could be implemented towards the proposed model.

6.2. Implications for the practical work

6.2.1. Implications regarding design

The energy-related occupant behaviour is a complex phenomenon, and to include it in BPS, requires specific knowledge and skills of involved specialists. Therefore, the usage of OB simulation tools is still scarce in a typical building design process. To increase the number of designers that will use OB in BPS, new sophisticated software has to be developed. The main challenge is to formulate the software that does not require complex operations and still can provide elaborate simulations output. Proposed BOT-ABM application was designed to fill in this gap. The BOT-ABM is crafted to support a building design process. Its operational goal is to provide functionalities allowing designers to perform advance OB simulations without further sociological or statistical training. It provides an output about artificial occupants' actions that where triggered by their programmed daily routines and thermal preferences.

Access to all these features could be compared to the transition from standard CAD drawings towards BIM in the design pipeline. Designers will have a possibility to test the impact of the proposed design with referential occupants. Additionally, the platform provides tools that enable a partial quantisation of the qualitative data. Therefore, the comparison of various design decisions can be performed without a need for an advance numerical background.

6.2.2. Implications regarding control

The proposed, novel approach for in-situ measurements of occupants' indoor activity has the potential to become a new standard application for buildings ICT. As it was shown in subchapter 3.1, the use of this monitoring technique allows formulation of indoor occupant profile. The formulated profile can be utilised for the evaluation of occupants' activities or adjustments of the building control system.

The access to the personalised record of each incremented indoor action can tag each action with an energy bill. The knowledge about a specific way of resource utilisation can be used to educate occupants, or at least provide quantitative information about their impact on a building energy use. The outcome of such feedback might be various because it is strictly dependent on an individual character. However, if such observations are continued for an extended period, they can provide a comparative analysis that can advise for energy use reduction. Therefore, the decision regarding energy use will be fully dependent on the building user. Additionally, such application of indoor occupant profile can help to educate occupants that are interested in the low energy use lifestyle, but they are not trained for such behaviour.

6.3. Implications for research and development

6.3.1. Implications regarding BPS development

Proposed model application is still not on a level of the full implementation, but the current stage allows a partial merge of functionalities. Current development stage permits extracting information about occupant's indoor exposition and artificially arches their reactions. The whole process independent of the schedule of activity. This means that specific steps of OB simulation are taken by the software. The main advantage provided by the implementation of ABM in BPS is a possibility to track the software "reasoning" behind each action. It is a significant advantage, compared to other existing solutions using stochastic methods.

Currently, BPS tools do not support a significant connection with agent-based models. Therefore, the future development of BPS tools should focus on the implementation of the functionalities that would cater for the straight-forward co-simulation. Another solution is to embed the ABM features inside the BPS software directly.

6.3.2. Implications regarding OB studies

Presented work comes up with great promise for OB studies. It provides a novel method for monitoring occupants. Also, it introduces an innovative way for simulation of occupants where new sources of data can be implemented. In terms of future studies, presented work opens new direction in OB studies, which integrates the OB related specialities under one platform. Further OB studies will focus on holistic observation of the individuals inside indoor spaces. Additionally, it provides the ability to unify all scientific domains that focus on the OB and creates a common ground for further discussion.

Additionally, the current development stage of the occupant database for BOT-ABM requires further studies to be fully operational. This points out directions that should be taken towards new research topics focusing on filling up the missing datasets. The proposed model can simulate each occupant individually.

Each virtual individual is following its own routines that could be disrupted by various events. Development of virtual individuals and their actions database are subjects that are not yet well covered by the state-of-the-art research, but with currently available monitoring technique, like depth registration, it is possible to extract these features.

6.4. Depth registration as a functional tool for OB research

Based on presented results and number of applications that can be implemented through data streaming from depth registration camera, it is possible to claim that this technique has its own niche for OB research. It has the unique properties that make it stand out among other OB monitoring techniques. The depth camera can be used if the study aims towards a high precision depiction of the OB in a small area like flats, homes, and non-open focuses. In a larger area, it is also feasible (if the devices are set in arrays) to use this technique, but such precision might not be crucial. In comparison to other techniques, like CO2 sensor, PIR sensor, ultrasonic sensor, the device has much higher precision in describing the occupants' actions. On the other hand, it does not compromise as much privacy like with a solution using only colour cameras. It can describe occupant precise position, clothing setup, activity and label the actions.

Proposed monitoring techniques can be rich in delivered content, but it has to go in pair with monitored occupants' acceptances, which sometimes might be hard to achieve. Additionally, despite applied efforts in software development that was a significant part of this thesis, the use of the device requires specific data processing skills to operate the depth registration camera. If further work that focuses on data processing automatization of these measuring techniques will be conducted, the device could reach the level of a commercially available OB monitoring solution. The use of the depth registration camera can be considered as the right way forward in OB research. It does not discredit the use of other techniques, but instead, it is recommended that it should contribute its unique features to market available solutions.

6.5. Final remarks

Investigation and development of the novel OB monitoring technique have brought forward a new discussion topic. It provided access to the unique quality of data that not only extends the resolution for measurements but allows for the further progress of the OB models development. Based on an implemented solution and richness of the accessed data, it is possible to speculate that there is still room for further development. It requires further testing in larger setups with data fusion of multiple sources.

In the comment to the BOT-ABM development displayed progress covers only part of the necessary developed modules. Beyond that, it still requires proper implementation as an independent application or co-simulating software. Despite the current development status, it is possible to claim that once the application is fully functional, it has the potential to be a very advanced platform. To reach that goal, the research must be continued bearing in mind that the best is yet to come!

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Paper No.1 J. Dziedzic, D. Yan, V. Novakovic; Occupant migration monitoring in residential buildings with the use of a depth registration camera; Procedia Engineering 205; 2017; 1193-1200. Conference Paper

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 00 (2017) 000–000

Procedia Engineering

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10th International Symposium on Heating, Ventilation and Air Conditioning, ISHVAC2017, 19-22 October 2017, Jinan, China

Occupant migration monitoring in residential buildings with the use of a depth registration camera

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Abstract

Energy performance of residential buildings depends on geographical location, building design, occupancy status/level, culture and many other factors. Until today, there have been no applicable measurement methods that would be able to describe occupant behavior without exceeding ethical borders. This paper discusses the use of a depth registration technique (surface scanning) to monitor movement/migration of one occupant residing for 48 hours inside the ZEB Living Lab dwelling, located in Trondheim, Norway. The recorded data and the obtained results may validate the accuracy of the existing models or become foundation for developing a new occupant behavior model – the Building Occupant Transient Agent Based Model (BOT-ABM).

Peer-review under responsibility of the scientific committee of the 10th International Symposium on Heating, Ventilation and Air Conditioning.

Keywords: Occupant behavior; Occupant movement; Data mining; Pattern recognition

1. INTRODUCTION

Building Performance Simulations (BPS) solutions currently available are able to perform multi-physical transient simulations, which allow predicting (with low error margins) a building's physical reactions to various environmental conditions, and estimating energy loses and gains in the perspective of a year. High performance computers or even desktop workstations have the computing capability to perform this kind of calculations in a relatively short period (depending on the scale, geometry and the applied equations). Nonetheless, energy consumption calculations

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Peer-review under responsibility of the scientific committee of the 10th International Symposium on Heating, Ventilation and Air Conditioning.

frequently do not correspond to the on-site measurements. The discrepancy may come from imperfections in the installation assembly, proper-ties of the used building materials or unpredicted stochastic behavior of the building's occupants [1]. These phenomena have been observed previously and they point out the human behavior as a component significantly affecting the overall building energy performance. Hence, monitoring and simulating the occupant behavior inside residential buildings is one of the most important factors to improve prediction of energy usage in any study related to buildings' energy performance.

Occupants' activities and their behavior modelling has become one of the most rapidly developing branches of BPS. Several models related to this topic were developed only last year. Most of them were focusing on one particular activity performed by occupants, such as e.g. opening the windows, moving the blinds, CO2 emission etc. Several research platforms have been created to capture human interference into the performance of all building features (facilities). The main role of these platforms is to combine the best performing models and use them in the process of developing simulation software, e.g. Energy-plus, IDA-ICE or DeST [1-2]. The joint effort of scientists from all over the world has borne fruit in the form of the project carried out by the International Energy Agency (IEA) and the Energy in Building and Communities Programme (EBC) called Annex 66: Definition and Simulation of Occupants' Behavior in Buildings (https://www.annex66.org/). The aim of this project was to develop an international, interdisciplinary study aiming to create a holistic approach de-scribing occupants' energy-related behavior in buildings.

All the measurements which have hitherto provided data for developing models were monitoring effects of occupants' actions without capturing their causes. Current thermal comfort identification and interpretation of an occupant action in each room/building with that level of data were flawed by low accuracy. At this level of development, personalized setting of indoor environment seems to be still unachievable. Without violating ethical issues related to direct video recording of occupants performing their daily routines, which would only aggravate the difficulties in data interpretation, it appears impossible. Lack of information stream leads to generating only case studies of investigated buildings or developing unverified models. If it is wanted to achieve a situation in which a person will have the option to adjust the indoor climate to their personal needs or preferences, it is necessary to identify each occupant directly, follow/study their actions/habits and adjust the indoor air climate accordingly. Due to the ethical issues related to storing personal information that may serve direct identification of persons, it is forbidden to store or use such information, even for scientific research. The only way to be able to collect that kind of data is to obtain an approval from the ethical committee. It is only granted if additional data randomization and an adequate encryption process and information distribution across investigated building are ensured. This limitation prevents the use of video recording devices for monitoring a building occupants' actions. The only way to comply with the requirements is using equipment that does not allow direct identification or infringe on the occupants' privacy [3].

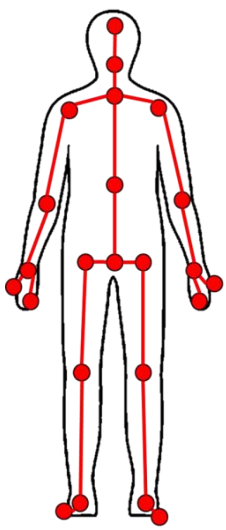
In order to by-pass this obstacle and deal with the troublesomeness related to obtaining and storing of personalized information, it was decided to use Microsoft Kinect [4]. This study was dedicated to investigating the possibility of using this device to capture occupants' migrations inside residential buildings. The explanation of how the device was used, how it worked and what was the aim of the research is to be found in the chapter on methodology.

One of the most important factors in simulating or modelling occupants' behavior is the ability to correctly measure/model the occupants' location (the current room occupancy) and their transition between rooms. An artificial representation of each occupant's location will be a trigger for the next steps in simulations of their actions. The collected data will be used to build a simple discreet Markov-chain transition model, which will be the first milestone in developing The Building Occupant Transient Agent Based Model (BOT-ABM). BOT-ABM will constitute a new approach in simulations and in modelling occupant's energy-related behavior in the field of building performance simulation. Using advanced machine learning and big data mining techniques, it will try to quantify and recreate occupants' habits and preferences treating them as personal triggers. If a level/value of some habit/s decreases, it will open a spectrum of possibilities that will depend on the occupant's personal preferences. The objective of each action will be to increase the level of habit on accepted value. The overall goal of the BOT-ABM will be to generate a platform on which to recreate different behaviors and energy consumption needs, dependent on environmental conditions and personal preferences, for model predictive control or annual simulations. The ultimate aim is to enable generating different profiles of occupants' behavior based on low-input, publicly available statistical data, such as the cross section of the population demographics or employment. Once BOT-ABM is connected with the information from the geographic information system (GIS), it will enable developing bottom-up simulations of energy demand of whole neighborhoods, districts or even cities.

To achieve this big picture goal, it is important – first – to gather a significant amount of reliable information and – secondly – to process it correctly. This paper demonstrates the process of gathering information about occupants' location and explains how to differentiate each occupant. The study presents one case study of measurement procedure in occupant behavior laboratory ZEB Living Lab. This is a multipurpose experimental facility built by the Research Centre for Zero Emission Buildings in Trondheim, Norway (www.zeb.no). It is a test dwelling that was occupied by a real person while measurements were performed. Its main goal is to study new technologies and design strategies. The overall plan of building is shown in Figure 3 [5]. Two Microsoft Kinect devices were used in the measurements. Location of these devices is shown as red dots in Figure 3. The measurement session was set as a 48-hour exposition period with one college-age male occupant during a normal working week.

2. METHODS

The device selected for investigating occupants' movements is Microsoft Xbox One Kinect [4]. The choice has been determined by the device's ability to stream sufficient information to enable description of occupants' movements regardless of lighting conditions. It has the function of scanning surfaces as a depth camera. It projects a grid of dots in the infra-red spectrum and, with a built-in camera, analyze the distance from each projected dot. Owing to this technical solution, it is able to measure the depth of the observed field. Commonly used video cameras deliver pictures in tree layers: red, green and blue (RGB) with various resolutions; e.g. 1920 x 1080 for high definition (HD). Each mentioned layer has the same resolution and each pixel may have the value from 0 to 255. The depth camera used for the measurements delivers information in resolution 520 x 480 with a speed of thirty frames per second (FPS). It streams a one-layer picture, but each pixel has the value ranging from 0 to 5120, which represents the distance of the observed point from the device in millimeters. It means that the effective range of the Microsoft Kinect device is a 45o radius of about five meters, which is enough for measurements of close distances, such as in residential building's rooms or corridors. The Microsoft Kinect device has a built-in software for linking a human body shape to a skeleton model.



	[X]	[Y]	[Z]
SpineBase = 1;	0.1066	-0.2272	2.3211
SpineMid = 2;	0.0990	0.0792	2.3576
Neck = 3;	0.0903	0.3762	2.3800
Head = 4;	0.0832	0.5278	2.3588
ShoulderLeft = 5;	-0.0939	0.2785	2.3739
ElbowLeft = 6;	-0.2182	0.0450	2.3635
WristLeft = 7;	-0.3324	-0.1487	2.3171
HandLeft = 8;	-0.3879	-0.1982	2.2953
ShoulderRight = 9;	0.2749	0.2756	2.3563
ElbowRight = 10;	0.4278	0.0628	2.3095
WristRight = 11;	0.5774	-0.0988	2.2356
HandRight = 12;	0.6207	-0.1409	2.2146
HipLeft = 13;	0.0210	-0.2271	2.2906
KneeLeft = 14;	-0.0017	-0.5919	2.2254
AnkleLeft = 15;	-0.0485	-0.8850	2.1211
FootLeft = 16;	-0.0264	-0.7374	2.1179
HipRight = 17;	0.1888	-0.2196	2.2758
KneeRight = 18;	0.2266	-0.5835	2.2297
AnkleRight = 19;	0.2552	-0.8882	2.1656
FootRight = 20;	0.2160	-0.7434	2.1606
SpineShoulder = 21;	0.0926	0.3032	2.3768
HandTipLeft = 22;	-0.4402	-0.2368	2.2771
ThumbLeft = 23;	-0.3892	-0.1488	2.2181
HandTipRight = 24;	0.6720	-0.1895	2.1962
ThumbRight = 25;	0.6357	-0.0864	2.1534

Fig. 1. Skeleton model hitch points.

This feature enables tracking twenty-five joint points of a bound skeleton, and monitoring its activity as shown in Figure 1. Information about each joint point position is delivered in three-dimensional data stream. Each Microsoft Kinect device delivers distance information based on its local [0,0,0] point located in a mass center of the device. While working with more than one device, it is necessary to calibrate positions of each device to the main device and the remaining proxy devices. To accelerate the analysis procedure, it is mandatory to measure distances between devices, determine the offset vector and recalculate the delivered measurement results. Additionally, each measurement device is capable of tracing up to six persons in one exposition range.

Examples of using Microsoft Kinect in many different scientific fields, including also building energy performance studies, may be found in relevant literature. Typical applications of this device comprise simultaneous localization and mapping (SLAM) in computer/machine vision solutions [6] bio-medical solutions, such as e.g. monitoring of a rehabilitation process, body shape registration and many more [7-9]. Microsoft Kinect is one of the lowest-price surface scanners available on the market. First attempts to use it in building energy performance studies were made by [10]. Most of the above-mentioned example studies used Microsoft Kinect to investigate occupancy in an office building [11-13] or to develop a pedestrian corridor movement model [14]. There have been some studies related to occupants' behavior which used depth cameras, but they were aiming at solving problems connected to elderly people by detection of their daily routine. Depth registration technology is relatively young compared to other solutions, and this may explain why there are so few publications on occupant behavior studies and this measurement technique. This paper focuses on analyzing occupants' migrations inside residential buildings with a future aim of developing a mathematical model describing the same phenomena. No record of any similar study has been found in literature. This paper contributes to energy-related occupant behavior inter-disciplinary studies by investigating a new technology that may accelerate progress in development of high accuracy models for building performance simulations.

The device has been chosen because of its impressive performance and because it offers quick access to the streamed data. Microsoft Kinect developers have published full support in a software development kit (SDK) to extend the usability of their design. Bound together with Matlab software (Imagine Acquisition Toolbox), it becomes a powerful tool for occupant behavior studies. Software developed inside Matlab environment was responsible for recording the captured skeleton data. In order to obtain this information, it was necessary to initialize the recording procedure by a trigger. Each time recording was triggered; it would last for a fixed number of frames. The captured information was stored inside the central processing unit (CPU) and then transferred to the hard drive. Once this procedure is completed, a new trigger launches another recording. The recording software also saves data from each minute of measurement exposition. This protocol repeats itself in an infinite loop. If there is no registered movement, the software saves an empty matrix that has always the same memory size, less than one kilobyte, which is an upside because these files can be easily filtered out. The downside of this solution is that there is a small, time gap between the end of one recording and a new trigger. To achieve the best recording fluency, the FPS value had to be optimized. A short performance test was conducted to do that.

Different sets of frames per trigger were tested. Normal performance periods that should take three minutes of recording, based on basic calculation, were compared with the run time of the software. Multiplication of the number of triggers and the frames-per-trigger number, divided by the real run time, gives the real medium value of FPS. A value closest to multiplication of thirty FPS should be used as a fixed value for future measurements. Five different sets of FPS (80, 90, 100, 110 and 120) were tested during trail registration. Tests have shown that the software is stable for 80 and 90 FPS. This may have been caused by absence of proper code optimization or stricter (CPU) limitations. Measurements were per-formed with a set of 90 FPS. Although each sampling time is set to optimal performance, measurements may produce a "lag" effect. Whenever the occupant enters the measurement zone and stays there for a period longer than one trigger, its sampling treats him/her as a new observed human. In this case, the software sees no direct link with the previous skeleton data. To recreate complete sets of movement paths, it is necessary to identify each observed skeleton separately in time. Without connecting the recording, it would be impossible to track all the transitions together with the correct amounts of time they took. Recognition of migration will depend on the established range of detection at the entrances into the monitored zone. During the measurement procedure, there is a chance that the monitored occupant may disappear/appear in the reading, because he or she will be heading towards the exit of the monitored zone and this may combine with the above-mentioned lag effect. To capture their transition between rooms correctly, it is necessary in such case to extrapolate their next steps by calculating their movement speed and the direction in which they were heading. When all of the missing connections in pathways are found, it will be possible to pro-duce a timetable of migrations and occupancy.

It is very important to distinguish between occupants while monitoring their migration in-side the investigated space. To do that, it is necessary do develop differentiating filters. The Microsoft Kinect device provides information about distances of certain points from the device. The first layer filter is the shoulder width to height ratio. Any other ratio, like hips to shoulder are also applicable. If the first layer filter is not significant, it is necessary to recalculate directly the monitored occupant's body dimensions. When all the occupants are identified, it is time to record the migrations of each of them. To capture their movements correctly, the obtained raw data are transferred and projected on a surface representing the physical floor. The mean value point (MVP) of two skeleton model joints (Neck and Spine Base joints) is projected on a surface of the floor. MVP can be treated as drawing points for representation of movement corridors or pathways inside residential buildings.

The proper placement of the device, usually in the living room or the main corridor, is essential as it may affect the accuracy of recording migrations across the whole apartment or residential building. Because each skeleton model is recorded with time information, it is possible to estimate the occupant's movement speed, direction and the time they have spent in each room or zone. Such accurate data allow developing a model of an occupant's "typical" usage of the residential building space. Even if there is no significant movement across the observed field, occupants enter/leave this field at the same or close points. This may indicate that there is a doorway or some other entrance in a nearby area, which forces occupants to use the same pathways. Additionally, the same technique can detect obstacles located in the exposition zone, such as a table or a chair. Occupants will naturally avoid them by extending their pathway. If crossing of obstacles is registered, it may indicate that they were not big. If pathways patterns change their shape, it may indicate furniture reorganization inside the room. Focusing on entering/leaving zones information, combined with estimation of directions of occupants' movement enables monitoring their migrations and the time they stay in different rooms. Linking the information on the occupant's identity, enables to describe where occupants are at an exact moment, e.g. in the living room, bedroom etc. The only assumption needed to achieve this description, is that the occupant cannot leave their apartment without crossing the exposition zone.

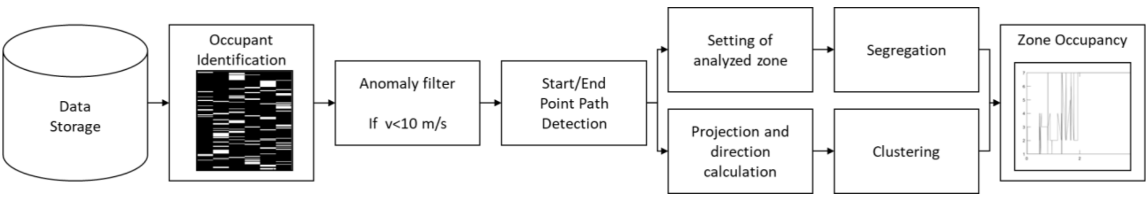


Fig. 2. Data processing flow chart

The collected data were processed and analyzed by two different methods (semi-automatic and automatic). Consecutive steps of data analysis performed by the relevant software are shown in Figure 2. The semi-automatic method required that the boundary areas (BA) of the analyzed pathways had to be set up manually. The role of the BA was to capture the moment (position and time) when the monitored occupant ends his/her movement inside the designated areas, such as the entrance to the kitchen or the living room. This method requires, at the initial stage of measurement, that the description of the analyzed space/flat must be done correctly: it must be determined where the BAs are situated in relation to the Microsoft Kinect device. The automatic method was able to process all of the collected data and detect the entrances/exits. It looked for the starting and ending points of the registered pathways and projected these points onto the boundary line of the analysis. The boundary lines were set outside the registration zone, and, when combined, they created a rectangular shape. The point was projected in the direction consistent with the one it was targeting, in the direction towards the end of the pathway. After all pathways had been projected, the points were clustered by the k-mean clustering method, where k is the number of entrances/exits of the analyzed area. Once the collected data were set in order and segregated, it was possible to recreate the schedule of occupancy in the monitored building.

3. RESULTS

The data collected during the measurement trial are shown in Figure 3. They present all the pathways taken by the occupant during the trial. To differentiate between various kinds of activities, each pathway was given a different color and overlaid on ZEB Living Lab dwelling floor plan. To highlight the pathways, the floor plan was faded. The choice of the path-way color was not dependent on time.

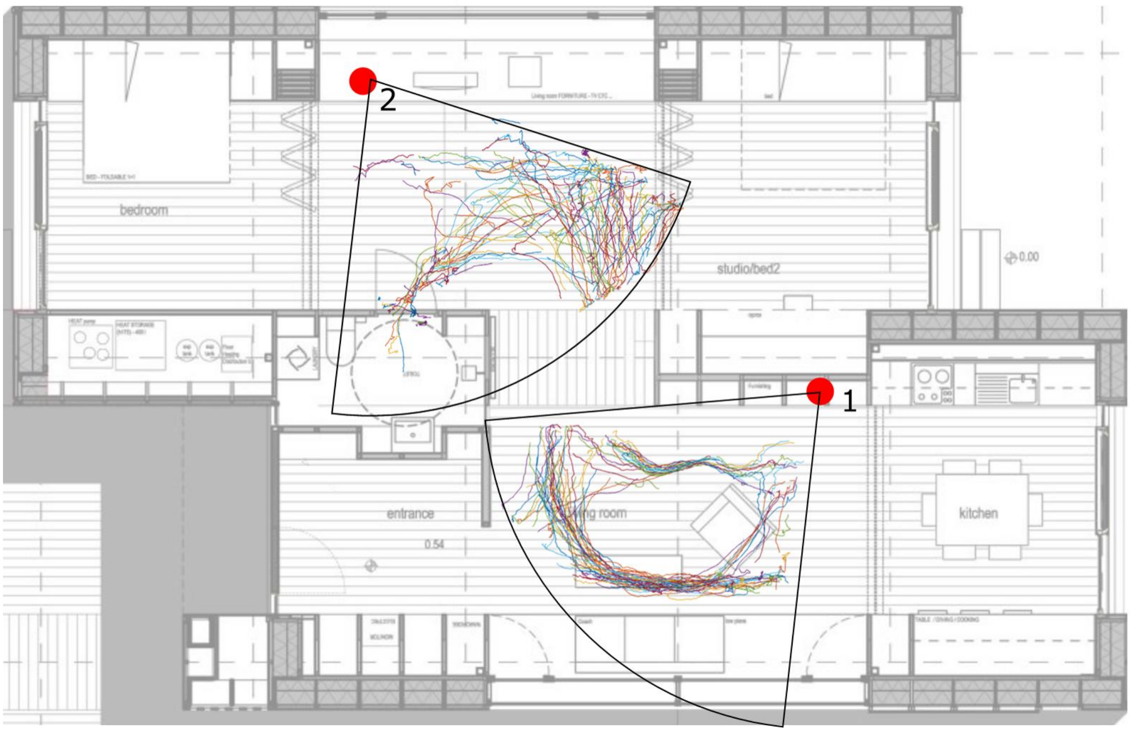


Fig. 3. Living Lab layout with registered path of migration

Pathways registered by device no. 1 indicate the existence of some obstacles, different from these indicated on the floor plan. The path signal shows that the occupant had to follow orderly route to migrate between rooms. Judging from its dimensions and location, the obstacle could have been a large piece of furniture, such as a table (approximately 3 m wide). It is also shown by the data collected from device no. 2 that occupants' movements were more varied in an open space. Both methods used for analyzing the collected data offered similar information, but each of them had its pros and cons. The semi-automatic method requires setting up boundary areas, which involves employing trained personnel on-site to conduct the calibration process. However, owing to this procedure, it is known which area represents the kitchen, the living room etc. The automatic method offers data that have been segregated automatically, and because of clustering, it each time has to be determined, which area is being currently described by the cluster centroid. This method was also tested in the aspect of its reliance. In 200 trails of clustering, there was only one incident of significant movement of cluster centroids. The automatic analysis method also captures the movement inside the monitored area and treats it as an escape from the device vision field. It is considered as an error and requires extra data filtering. Due to this reasons, the semi-automatic method was chosen for the final data fragmentation. The segregated data were processed to calculate occupancy in each room. Once this procedure was completed, the results were displayed on a graph Figure 4. where Y-axis represents the room/zone number, and X-axis is time, in seconds [s]. It is possible to see the first signs of living patterns in Figure 4. such as periods of being outside, sleeping etc.

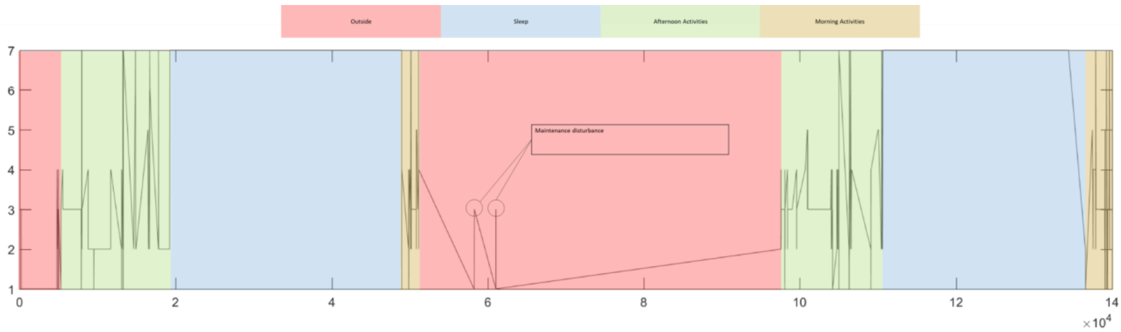


Fig. 4. Zone occupancy graph

4. DISCUSSION

The conducted measurements proceeded without any major disruptions which would potentially affect data collection. The only problem that occurred twice was caused by a poor cable connection between the device and the computer. No registration errors appeared after the problem had been fixed. The procedure was performed with only one occupant making data filtering easier. To fully understand the registration potential of this device, it is necessary to test it in a case involving more occupants. Additionally, to increase accuracy of the monitoring, it is suggested to increase measurement area to cover whole “corridor” area.

The obtained results prove the great potential of using depth registration cameras for occupant behavior studies. The Microsoft Kinect device used for occupant behavior monitoring may be applied in any kind of facility with access to a power grid and Wi-Fi. This measuring method offers information required for the validation process of the existing simulation models. It meets all the newly imposed requirements of occupant studies and opens a new chapter in further studies. The processed data provide direct information on spatial occupancy in time, which can be used in development of new models able to support annual simulations of building energy performance. This measurement technique may be used in advanced control systems for HVAC installations. By discovering the patterns of building usage and capturing the migration habits, it may support adjusting energy requirements for indoor air climate.

Additionally, the collected data may support not only researchers interested in the field of construction, but they can also support scientists studying the fields of behavioral psychology or anthropology. They may also provide feedback to architects about how spaces in buildings are used.

5. CONCLUSIONS

Depth registration is an interesting technique that may play an important role in the future occupant behavior studies. It avoids violating ethical codes related to tracing and video re-cording/streaming of humans and their daily migrations inside a residence. Because of the low cost of the device, it is possible to monitor a relatively large area thus acquiring high quality information. This measurement technique must be explored further.

Acknowledgements

The authors are not sponsored by any private company. The choice of device and measuring technique was done on the grounds of its potential and accessibility. This publication does not aim to promote any specific producer.

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Paper No.2 J. Dziedzic, D. Yan, V. Novakovic; Measurement of Dynamic Clothing Factor (D-CLO); Proceedings of the 4th International Conference on Building Energy & Environment 2018; 208-212. Conference Paper

Measurement of Dynamic Clothing Factor (D-CLO)

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SUMMARY

The conducted study was aiming to explore the potential of a new innovative measurement technique, using a depth and colour registration camera, to quantify the CLO-factor. Microsoft Xbox Kinect was selected as the measurement device. The device selection was based on the criteria of cost and market availability on the market. The whole procedure was a trial test with just one participant who was instructed to follow a prescheduled clothing pattern. The main aim of the study was to check if such a measurement technique is able to capture correctly the patterns it was exposed to. A combination of this technique with a previously developed database on the CLO-factor will offer a powerful tool to be used in building performance evaluation and simulation studies. Additionally, it may increase the level of accuracy of the existing models of energy related occupant behaviours in buildings.

INTRODUCTION

Human thermal perception and comfort is a complex issue that still requires further study/research. Due to individual nature of the objects under study, it is difficult to understand and interpret it properly. (Hong, et al. 2016) Achieving this goal would accelerate the development of personalized air conditioning systems. It would also benefit other branches of science, such as e.g. building performance simulation (BPS), by delivering more accurate occupant behaviour description and increasing the accuracy of developed numerical models (Yan, et al. 2015)(IEA -EBC Annex 66). Recording actions performed by occupants and their reactions to changing conditions is a step on the way to accomplishing this goal. First, the most common way of adjustment to achieve thermal comfort is regulation of occupants' thermal insulation, by adding or removing layers of their clothing. Observation of such actions could deliver significant output that will support understanding of occupants' intents, which is essential.

Estimation of clothing types and their insulation properties is a well-known research subject in the scientific community (Mustapa, et al. 2016)(Xue, et al. 2016)(Newsham, 1997)(de Carvalho, et al. 2016). It has been quantified by measuring heat resistance of clothes used by humans. Each garment was subsequently described by a CLO-factor value, which is directly connected to its insulation level. The developed tables have helped to approximate the level of an occupant's thermal insulation. (ASHREA, 2013) It was one of first steps in realisation of the importance of occupants' behaviour in building performance. The type of worn clothes depends on many factors and can be used to express social status, identity or culture, it can be relative to a dress code or regime. Nonetheless, it is directly connected to and influenced by weather conditions. A combination of the above factors enables development of comprehensive models that can simulate the overall situation in a building. The most common way to do that is establishing a fixed value of the CLO-factor with included standard distribution that can be interpreted as a difference generated by various types of fabric. To increase the accuracy of CLO-factor modelling, it is necessary to develop a new approach that will be able somehow to measure or approximate the dynamics of the building occupants' CLO-factor.

Monitoring a building occupant's actions that are related to adjustment of indoor air quality is a well-known procedure in science and industry alike (Parsons, 2014)(Mahdavi, 2012). The above-mentioned actions are usually connected with the use of various appliances and their performance can be relatively easily measured. However, such a solution only delivers a general description of the occupied zone. The performed actions are not bound to a specific occupant, so it is difficult to estimate individual occupants' preferences and action sequences if there are more than one person within the monitored zone. Additionally, without tracking individual occupants' actions, there is a hazard that if a set of occupants in one zone changes, the new set will be described in compliance with the previously observed rules. Lack of occupant's identification entails that BPS studies can only offer energy consumption specifications for various zones within a building.

The ability to identify individual occupants under observation has always been a challenge. To bypass lack of existing data about occupant's movement different models were developed using random walks (Ahn, et al. 2015) or statistical data (Wang and Hong, 2016). Most limitations stem from ethical concerns related to privacy issues and the willingness of the individuals under surveillance to have their privacy compromised. It is a particularly important issue if occupants' behaviour is to be registered in a residential building. To by-pass this issue, it was necessary to find an optimum solution that will deliver reliable data with minimum invasion of occupants' privacy, while still being able to identify occupants and bind them to their actions. A device that is able to meet these requirements is the Microsoft Kinect device (Xbox One, Microsoft). It is a three-dimensional scanner that is currently most easily available on the market. This device is usually used for entertainment that requires the persons using it to perform physical movements. Its main designer and manufacturer has decided to publish its software development kit (SDK) and thus reveal it to third-party developers with the view to extending its usability. The device provides access to a powerful function that enables capturing the "skeleton model" of a monitored person (Xbox One, Microsoft). The usability of this device was tested in previous study related to monitoring occupants' movements inside Living LAB, a laboratory resembling a residential building (Dziedzic, et al. 2017). The successful usage of Microsoft Kinect encouraged to explore its possible application in building occupants' behaviour studies. It has been found that it is possible to perform measurements aiming to monitor dynamic changes of occupants' CLO-factor. To evaluate the results correctly, such mode of recording has to be supported by additional hardware capturing the thermal properties of indoor air, to provide a basis for evaluation of occupants' actions.

The research investigates the possibility of CLO-factor changes evaluation. To reduce potential errors, it was decided that, in the first trial of measurements, only one occupant will be monitored, and he will change his clothes according to an agreed plan. The main purpose of this research was to check whether it is possible to notice the difference between various items of clothing. If the proposed measurement method delivers the expected performance, it will be possible to conduct more advanced tests, with additional persons. The person participating in this research has been given comprehensive information about the performed measurements and decided to do it voluntarily.

METHODS

In order to collect suitable data, it was necessary to develop software that enables capturing the desired data. It was done with the use of the Matlab environment with an image processing toolbox. The first step in developing the monitoring method was aimed to access the "skeleton model" data. It is a representation of human body movements. The body is represented by twenty-five connected points that are able to register the move of each body limb in a flow. Each point of the "skeleton model" holds information about three-dimensional information about the distance from the mass center of the Kinect device. Each dimension has the same operating unit as a meter. Each point is measured simultaneously and it is sampled with a frequency up to 30 frames per second (FPS); the device can register up to six people at the same time. The sampling time depends on the computer setting. Data frequency sampling is shown in a graph. Information on collecting data on occupants' movements can be found in our previous paper (Dziedzic, et al. 2017).

While recording movements, it is possible to project the observed points onto any surface. It can be projected onto a video camera recording surface. While observed, the occupant is connected with a bundle of points, and each point can be treated as a sampling point on the video recording surface. While probing colour from each "skeleton model" point, it is possible to collect data necessary to establish the skin tone colour. This information will lead to developing the dynamic clothing factor (D-CLO-factor). Due to the fact that the sampling points meaning (it always represents same limb) does not change in time, the position of the points is determined. Points representing the head, for example, will always follow the observed head, while it remains within the measurement radius range. Some of the information sampling may be done with an infrared video camera surface. Once data is sampled, it produces a matrix of three columns and twenty-five rows. Rows represent measurement points and columns store information on three selected colours: red, green and blue (RGB). Visualization of sampling has been presented on a mapped drawing of a human body (Fig.1)

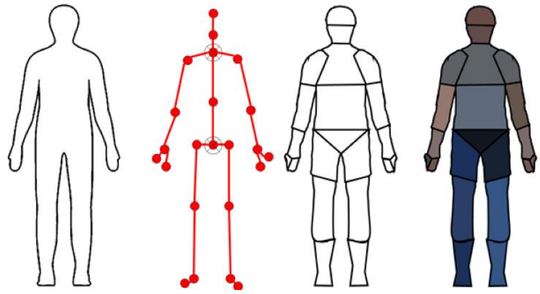

Figure 1. *Development of clothes colour model, based on SM and human body outline*

The collected data has to be reorganized to make it easier to handle and interpret. Each observed occupant generates one 3x25 matrix. To make it more workable for processing, the collected matrices were transferred into a one-dimensional row with four hundred fifty columns. The first order of segregation is done by the number of maximum observed occupants, and the second order sorting is based on information from each basic colour channel. Clock information is added after the last row of the sampled colour data. It is necessary input that allows using more than one device during the experiment.

After the data, had been recorded, the next step was skin colour analysis. Due to the fact that the whole analysis is highly dependent on the lighting conditions, it was decided that the reference for skin tone detection will be internal for each occupant. The colour spectrum to be used for the analysis was taken from two head points of the "skeleton model". The established reference colour was then used to differentiate the skin colour from the colour of the worn clothes. To make the estimates more precise, a reference matrix was created. It contains all outcomes of the monitoring that may be captured by these kinds of measurements. The main assumption of the study was that all the observed persons would dress symmetrically in relation to the skin. Adopting such a scenario has helped to divide different possible settings into three major groups. The first one (green colouring Fig. 2) represents the possible setting of skin that can be found in such places as an office type building, where people work. The blue colouring (Fig. 2) is a group of clothing variations that seem to be more casual. This group also contains people that may be dressed like someone from the fist green group. It depends on style, social circle and weather conditions. The last group (the red one, Fig. 2) represents a group of possible settings that are not socially accepted or can be worn only in specified areas, like a pool or beach. Such segregation accelerates monitoring of CLO-factor dynamic changes as it narrows down the number of possible outcomes, according to the type of monitored building or area.

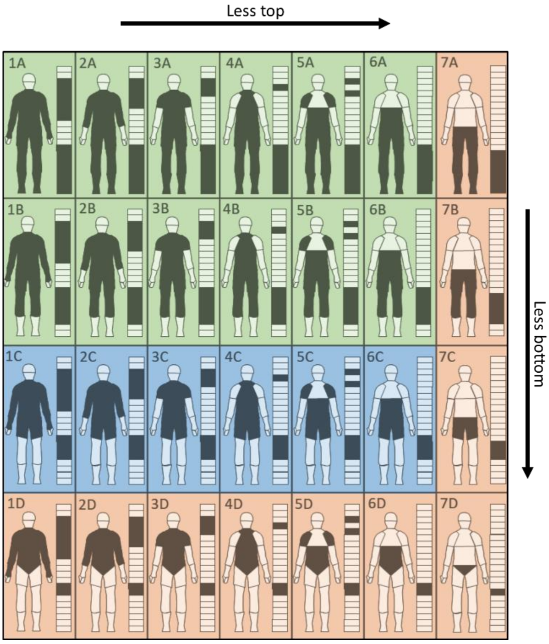

Figure 2. Matrix of all available records that Microsoft Kinect device is capable to detect

Skin tone recognition allows forecasting the first step towards conservation of the CLO-factor dynamics. In order to enhance the analysis procedure, different colour maps have been introduced. The standard picture provides information about RGB of each pixel of the raster. Such solution has certain advantages, but it is not sufficient to completely evaluate clothing adjustments of the observed occupants. Hence, it has been decided to use a hue, saturation and value of lightness (HSV) colour map model to support the analysis process. HSV allows capturing the lighting conditions of the observed area. It can detect variations related to the hue of the sampled colours. In other words, in can provide feedback about a number of significant different light sources. Each artificial lighting source has its individual temperature, from cold (bluish) to warm (reddish), and it has direct influence on the hue value. If hue recording is homogenic (in the context of the whole possible spectrum), it means that the sample was probed in an environment with one type of artificial light. When the measurement indicates the existence of more than one lighting sources, the main source has to be identified, which is the one with the highest number of occurrences in one frame. The rest of the samples from one frame have to be recalculated to the dominant lighting condition. The vector of recalculation was set based on the difference between hue values of different lighting sources.

The measurement trial was conducted with the use of one Microsoft XBOX ONE Kinect device supported by a PC connection cable. A high-performance computer was used for both the recording and data analysis procedure. Exact settings of the used computer can be found in the acknowledgment section. The performance test of the frame recording speed it shown that mean value of recording it is 25+/-1.5 FPS. It has to be mentioned that during measurement, there were no background processing and unit was running only measurement code in Matlab software. Such a value of recording was stable no-matter how long sampling was took over.

Main trial procedure was planned to have a trial detecting different clothing patterns. Based on a figure 2 it was planned to collect samples on cases in scheduled order: 7D-7A-1A-7A--7D. Detection test was based on colour sampling from SM joint representing head positions (No. 3 and 4). Measurement procedure was conducted in an artificial lighting to simulate typical operating conditions. Results will be compared with expected detection, according to the planed schedule of skin coverage. After data from all of the colour channels (RGB +HSV) and each reference point (No. 3 and 4) was connected, it was possible to start analysis process. Whole analysis process was shown in a graph (Fig. 3) In the last step of analysis, if there was correct guess among all highest percentages of detected possible cloths setting, it was considered as a success (positive value).

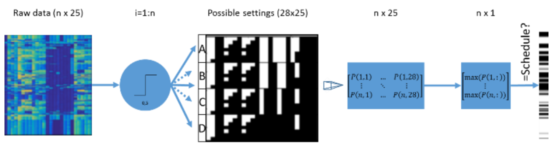

Figure 3. Each step of data processing

RESULTS

Results of overall trail were displayed in a summary graph (Fig. 4). To make it easier to display, all of the records were turned horizontally, in such an orientation columns are representing one bundle of samples from whole SM. Such a set allows to displays information for graphical analysis. All of recorded data from performed experiment were displayed in "raw records" section. In generated graph, a picture from “raw records” represent 63 rows of data colourised by their value. Each three rows represent three colours channels, from 23 measurements points of SM. Used color map was not related with sampled colors from experiment.

Registered schedule of clothes change was shown based on a "schedule" line. Participant of the experiment was instructed to follow planned clothing pattern, but it was not determined when occupant should change it. It was established that clothing pattern had to be followed in prescribed order but it was up to participant when detection starts and, ends. Detection begins while participant maintain in move, and it stops analysing when no move forward was detected. Once participant have stopped moving, it was requested that he has to change his clothing according to schedule. Such a design of experiment accelerate analysis process by generating clear boundaries for analysis. This detection conditioning, created more natural situation of detecting clothing patterns. In normal conditions (outside laboratory) occupants will move around monitored zone without being cautious about conducted measurements and analysis. Positive detections were marked as a positive (white) value.

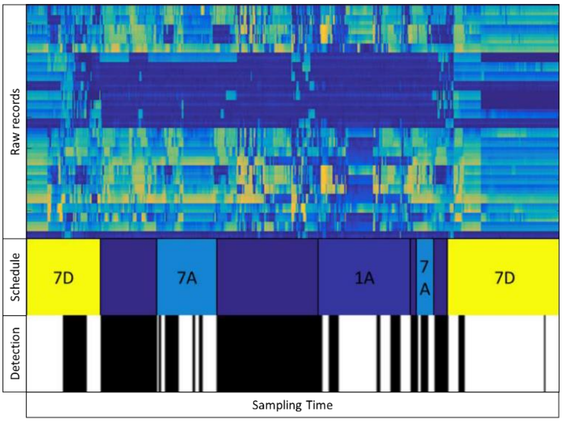

Figure 4. Overview of collected data, with a comparison of aim goal and reached detection.

This approach of data filtering and selection delivers positive detection with range of 74,29%. If all of the debatable detections (were more than one clothing setting gets highest value) were not included, positive detection value decrees to 67,78%. It has to be mentioned that detection precision was calculated during time of scheduled order of cases. Time gaps between dressing and undressing were not included.

To understand how clothes detection influenced the description of CLO-factor values, all of detected clothing states were calculated and compared with a reference values. If there was more than one detected clothing state in a same time, its values were averaged. The results were shown in a plot, were blue area was a detection target, and red dots represent detected values.

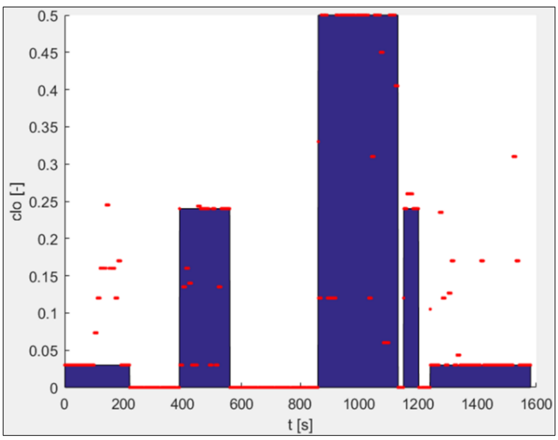

Figure 5. Comparison between target CLO-factor value and results of detection

DISCUSSION

No significant errors were encountered during the sampling trial in terms of hardware issues. Using the Kinect device has proved to offer more options than was expected at the beginning. The device is not only able to capture the movement of humans but it has potential to conducted study that it can also automatically detect changes of the monitored occupant's clothing. Gained results of 74,29% of correct identification it is not satisfying and its accuracy value has to be increased. However, it has to be stated that basic random selection, based on clothing scenario matrix has only 1/28 (3,57%) chance of success. Currently reached accuracy do not allow to investigate, approximation of clothing layers. Additionally, this approach requires further investigation that will include more than one subject to be captured within the monitoring zone.

The obtained contextual comparison between expected and recognized values shows that, this measurement method has an issue while detecting low CLO-factor values. Additionally, analysis of reference skin tone colour readings, shows that its value is not stable as it was suspected. Probing point No.4 form SM delivered lower readings which may suggest that this point was gathering its values from colour of subject's hair.

The main problem related with the use of depth registration techniques is connected with a lack of understanding of the nature of collected data. Combined with serious concerns about occupants' identity and privacy, it may lead to misconceptions about the study and, as a result, potential participants may eventually drop out from the project. The depth registration camera is a relatively new technique that requires more publicity and education among both the general public and the scientific community. Especially so that it finds ever more applications in various areas, such as e.g. in automotive industry, entertainment and even retail trade.

Detection of building occupants clothing heat resistance will deliver new dimension for building performance simulation studies. It will allow to monitor user's preferences and demands for thermal comfort. Additionally it may lead to estimation of occupant's thermal needs, by monitoring energy effects of building users. Actions connected with adjusting thermal properties of indoor air like opening the windows or adjusting thermostat, can be easily detected by measurement devices. But such a data do not allow to capture full picture of taken actions. Monitoring of occupants CLO-factor state can support estimation of their actions reasons. It will help on establishing their thermal preferences. Implementation of this measurement solution will directly visualise influence of occupants living style on their energy demand. Additionally it can be a source of behavioural information about their willingness to passively adjust their thermal comfort (by extending clothing resistance) or actively trying to increase thermal properties of indoor air. Finally it can become a basis for behavioural forecast that will support control of building management system.

CONCLUSIONS

Further research with more participants is necessary to make the use of the Microsoft Kinect device more suitable for building energy studies. Tests with real-life data will ultimately verify its usability for measuring the CLO-factor. Additionally, more data may provide a basis for building a test model. The developed potential clothing matrix (Fig. 3) can be used in the future as a reference matrix. Such a solution, combined with previously developed knowledge about the CLO-factor, may lead to a dynamic on-time measurement of this factor. Once the observed conditions are monitored, it can be used to build a non-homogeneous Markov chain model for simulating CLO-factor changes of different occupants triggered by various sources

Standard approximation and selection based skin-tone colure it is not sufficient enough to reach high accuracy of detection. To increase accuracy, it is seems that is necessary use of a machine learning technique. Additionally, it has to be tested if it is possible to input different pantones of skin colour to have a resource to apply detection matrix training. Such a solution could be applied with a geo-positioning technique and it will increase detection ration by reacting on typical, local skin pantone.

Additional step on development for increasing detection accuracy will aim on extending existing SM on extra probing points. They will be localized on mean positions between already existing SM points. Because of that its localization will dynamically respond to actual detected occupant position, issues connected with additional points sampling should not occurred. Such a solution will increase volume of recorded data. It will also decrease general importance of previous reference points from SM by adding few new points in head area. Extension of points will influence clothing matrix (Fig. 2), but it may lead to develop more reliable matrix of clothing detection. (Fig. 6)

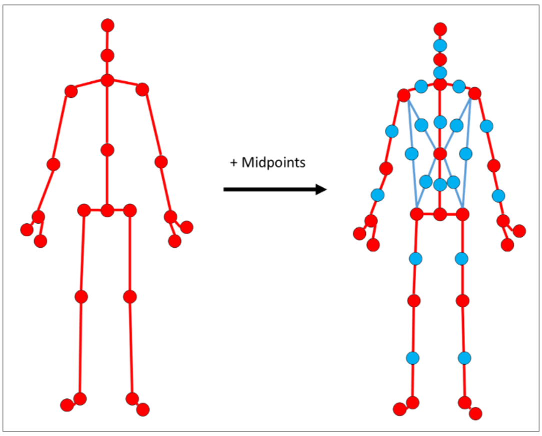

Figure 6. Evolution of SM model

After further development, will reach higher accuracy, this measurement technique will open new possibilities of various behaviour studies. The collected information can be used not only in the occupancy and energy related studies. It can also be used for research in social and cultural fields as joint, interdisciplinary studies in which CLO-factor values can be used as markers indicating various aspects going beyond the ones related to thermal comfort. Such a solution can be used to describe occupants' dressing patterns and habits in different social groups. This solution may accelerate development of new, more accurate numerical models that will represent real-life scenarios more precisely.

Achieved results shown that, there is existing possibility of online, in-situ estimation of occupant's Clo-factor. Once detection accuracy will be increased (probably with a use of machine learning technics), it will become a powerful tool that will allow to track occupants clothing pattern preferences. Previously, (Newsham G. R. 1997) such a data could be obtained by performing expensive and time consuming observations. Other, previous solution for accessing this type of information was connected with modelling (de Carvalho P. M, 2013) approach that simplifies description of clothing patterns (clo-factor values) by connecting them with a type of investigated zones. Tuned up performance of clo-factor detection will allow to track individual clothing preferences and will include them as a set of rules or patterns for control settings. Final effects of such a precise measurements are hard to estimate in current state of development, but suggested solution holds great potential for deeper understanding of occupant's behaviour inside various type of buildings. Which can eventually leads to more precise and accurate buildings performance simulations.

The usefulness of the Microsoft Kinect device cannot be denied, and due to its low price (compared to other occupants' behaviour measurement devices), it has a high chance to find application in the building monitoring sector. Accessibility of this data gives it a huge potential for use in building management systems (BMS) solutions. The use of this device has to be explored further to fully describe its applicability in the field of construction science.

ACKNOWLEDGEMENT

Computer setting for the measurement procedure: Intel® Core™ i7-6700HQ with a CPU of 2,60 GHz: 16 GB DDR3 ,1600 MHz; NVIDIA GeForce GTX960. Using different hardware settings for the purpose of measurement may influence the sampling time.

The authors do not indorse usage of any specific brand or device developer. The study has not been sponsored and influenced in any other manner by private companies. This publication does not seek to promote any specific product..

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Paper No.3 J. Dziedzic, D. Yan, V. Novakovic; Real-Time Measurement of Dynamic Metabolic Factor (D-MET); Cold Climate HVAC 2018, Springer Proceedings in Energy; 2018; 677-688. Conference Paper

https://doi.org/10.1007/978-3-030-00662-4_57

Paper No.4 J. Dziedzic, V. Novakovic; Occupant behavior modeling based on migration registration technique; ENERGODOM 2018, IOP Conf. Series: Materials Science and Engineering 415 (2018) 012044. Conference Paper

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To cite this article: J W Dziedzic and V Novakovic 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **415** 012044

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IOP Conf. Series: Materials Science and Engineering **415** (2018) 012044 doi:10.1088/1757-899X/415/1/012044

Occupant behavior modeling based on migration registration technique

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Abstract. The building occupant energy related behavior modelling is a key factor for building performance simulation that supports realistic forecasting of energy consumption. The current state of development of this topic delivers partial knowledge about occupant's behavior, but information about transient thermal comfort of each occupant is still, beyond the reach. Access to such a data would visualize outcome of the proposed HVAC design. With a use of proper measurement technique, it is possible to develop virtual bot that will recreate typical energy related behavior scenarios inside designed building and gather consistent information regarding thermal properties of the indoor environment. Such a tool will display potential faults of the design regarding occupants thermal comfort and point out potential paths of adjustment during design phase

1. Introduction

Re-creation of a building's occupant behavior has always been a challenge. The main reasons are the diversity of personal preferences among building users and various acceptance conditions. The above factors make modeling of occupant's behavior a troublesome subject. Since there are no significant input data, they have to be replaced by individual behavior approximations. Behavior models can be applied to all human-related scientific topics. They may even be used as a tool for monitoring and forecasting of energy consumption inside buildings. Several methods aiming at description of energy-related human behavior were developed in the past [1] [2]. They opened a new chapter in the research on indoor environment quality since they allowed evaluating sensation of comfort on a fundamental level. It was an essential step towards improvement of indoor air quality (IAQ) control and optimization of energy consumption for heating, ventilation and air conditioning (HVAC) systems.

The next step should lead towards personalized comfort detection. Reaching this goal will open a new space for automation in buildings. Without synergy of accuracy and reliability, it is impossible to reach the level of personalized simulations that could support preferential HVAC control. The current state-of-the-art instruments enable detecting occupants inside offices/zones with a low error margin [3]. It was possible to distinguish between two types of office/zone users: average daily users and guests. This simulation approach ensures accurate results, but it can only define behavior of occupant groups and does not offer a precise picture for a personalized indoor air model. This obstacle concerns both office and residential buildings. Occupants are described as a mass. It is difficult, within this solution, to distinguish individual actions of an occupant from occupants group. Insufficient accuracy has been emphasized in Yan's general review of occupant behavior modeling in buildings [4]. The results of his research indicate that if higher simulation accuracy is to be achieved, it must be connected with detection of occupants' personal needs.

To improve energy simulation accuracy, input information about occupants behavior has to be more accurate/transparent [5]. With registration of each occupant's actions, it is possible to develop a pattern of their behavior. Organized chronologically, it will tell a "story" of their thermal sensation. Such data will generate a range of possible interpretations concerning an occupant's thermal needs. The collected feedback can later be interpreted as a habit or standard practice of each occupant. In order to reach the required level of detail in description, there is a need to improve the measurement accuracy. The collected data has to allow distinguishing each occupant's position and action in time. At the same time, it may not go as far as to cross the important boundary of recording data that can be considered sensitive from occupants' point of view. It has to provide sufficiently meaningful information so that all the future recordings could be attributed to a given person (for example Occupant A). The collected data has to provide specific metadata that enables interpretation of all the occupant's activities.

If all of the above requirements are fulfilled, the obtained data will allow taking the next step in development for personalized control for IAQ. With direct identification, it will be possible to build models that will support identification of occupants' needs based on actual thermal conditions. With this holistic approach, the accuracy of building performance simulation (BPS) results may reach the acceptable level. It may minimize the difference between the simulated and measured energy consumption of the building. This goal may be achieved with the use of the transient occupant behavior model. The first step towards its goal should aim at discovering patterns of occupants' movements that could later on be used to create simple yet robust movement model.

Improvement of the gathered data quality requires selection of a new measurement device or/and technique. To make them more reliable, measurements have to be conducted with the use of an in-situ method. This means that all solutions that require using a device, such as a wristband or smartphone, have to be excluded from this study as potentially leading to measurement errors with reference to some occupants. The errors may occur if some occupants lose their device or leave it in the monitored zone. Similar effects of under/overestimation of some occupants may appear if the system counts door opening as input data. It is hard to link the number of times when the door was opened to the number of occupants using it. Moreover, this solution give us no information on the direction of migration.

Other solutions – like infra-red (PIR) detectors – provide information on crossing its monitoring point. This measurement method can sometimes produce results that come close to the description of occupants' activity. However, this method does not allow capturing anticipated information. Using these detectors produces binary output. It can be enough for the lighting control or presence detection but the accuracy and resolution are not significant enough to support the development of personal thermal comfort sensing. The method has a great potential when it comes to the detection of CO2 concentration. Unfortunately, due to the response delay in this measurement technique, it can only be used for areas, like an auditorium, where occupants stay for a longer period [6]. For residential solutions, such measurements can deliver only brief information regarding the occupancy state. Occupants activity and their degree of freedom is higher in residential buildings.

In order to obtain higher quality data, it seems that it is necessary is use video recording data. Supported by Kalman filtering or pre-trained model, it can map the paths of movement. The registered movement will be only a projection on an observed surface. The absence of perspective from the recording can be re-calculated. Unfortunately, applicability of video recording is limited due to ethical issues. It is most unlikely to be used in monitoring of residential buildings, but it can be used to track movement in wide, open areas, such as halls or lobbies. The only other solution for the measurement of occupant behavior that bypasses all of the obstacles is depth registration camera. Collected data do not allow direct identification of the monitored occupant, but it can provide information about the movement of each limb. Additionally, it can detect the outline of the observed body and thus identify individual persons. The main issue related to this type of observed depth recording is its limited range. The range boundaries are defined by the limitation of the power of signal amplifier and the price of the detector. There are many different producers currently on the market who are focusing on manufacturing this kind of devices. Most of them find applicability in the automotive, personal aviation (drones) and entertainment sectors. Previous investigation into these measurement technique has shown promising results, and that is why using it will be explored further. [7] [8]

2. Aim

The aim of the presented work is to investigate the use of data collected in previous studies. The collected data offers high-resolution information, and its potential has not been fully used. With high-quality data, it is possible to produce an occupant behavior transition model that accurately recreates their movement. The developed model will become a foundation for building an occupant behavior simulator for model predictive control or annual simulations during the design phase. However, it is necessary to discover patterns of transition to reach this goal.

It will have to be seen if the already available data is sufficient to build a behavioral model. The first step towards development of a building occupant transient agent-based model (BOT-ABM) has to focus on observation regarding occupants' movement itself. The goal is to develop a self-sufficient model that will recreate pathways of transitions inside the investigated area. In the current state of development, drivers of occupants' actions regarding their transitions will be not investigated.

3. Methods

3.1. Measurements

Measurement data will be obtained with the use of a depth registration camera. For the purposes of this research, the Microsoft Xbox One Kinect device will be use. The choice of the measurement device was determined by the desired quality of the data to be collected, the sampling time, price and availability in the market. The selected device is capable of registering up to six people at one time and has the detection distance limitation of five meters. Regardless of these obstacles, this type of measurement can be successfully used in close spaces like corridors, entrances, small offices or residential buildings. Access to the full measurement device potential was obtained from the software development kit published by its manufacturer. Collection of this data is done with the use of a grid projected by a beam in an infra-red spectrum (to avoid discomfort of the observed occupants). Once someone crosses the observation spectrum, his or her transition/activity is registered. The obtained data is a skeleton model (SM) that has representation of twenty-five common points in three dimensions. Each SM is connected to an identification number, from one to six, by a semi-random procedure. During measurement, the device registers movements of each joint with the frequency up to thirty frames per second. A more detailed description of the measurement technique may be found in manufacturer webpage [9].

The whole recording was conducted with the use of self-developed software in the Matlab environment. The choice of the programming language was based on the availability of the existing library, the available third-party support and personal preference. The registered data will recreate paths of movement taken by each monitored occupant. Two Kinect devices were used during the measurement procedure. To make data more coherent, it was necessary to establish one common global coordination system .One device has to be selected as a 'master' device, and rest as a 'salves'. All recordings from the 'slave' devices has to be recalculated via referential 'master; device. It was done by measuring distances between both devices and setting up a translation vector to recalculate readings. Streamed information from SM provides three-dimensional data. The devices were placed so as to cover the whole office area, from one end to the other.

It was detected that there were certain specific points within the monitored area that were more actively used. All of these points on this surface can be treated as nodes of communication or points of interest (POI). POIs have to be understood as being limited by boundary spaces/zones which can be defined as points. POI location was detected with the use of the Pareto filter. While "typical" enterers were exposed, it could be used to generate a hidden Markov chain model. This part of study regarding occupancy modeling was put aside for future investigation. At the present current stage, movement inside the measurement zone and discovery of its patterns was treated as a priority.

IOP Conf. Series: Materials Science and Engineering **415** (2018) 012044 doi:10.1088/1757-899X/415/1/012044

3.2. Raw data

The recording process produces a vast amount of data. Each minute of recording generates an 1800x457 matrix. Each row of the matrix represents one frame, 30 frames per second multiplied by 60 seconds give 1800 rows. In one exposition, the Kinect device can capture up to six occupants standing within the device's range. Each registered occupant provides information about the movement of 25 points in three dimensions, 75 columns in the registration matrix. Based on this information, the recording device has to reserve recording space for six people – six multiplied by 75 gives 450.The last seven columns are reserved for the clock data that gives information about the year, month, day, hour, minute, second and frame number.

The software built into the device is unable to distinguish occupants directly, and it does not link any observed occupant with the same SM number. After it loses track of a specific person, it may link it to the same SM, but the odds of this happening are one to six. The process of connecting the SM with an observed human is semi-random. It links an occupant with the next available SM number. Once the software reaches the SM number six, it resets numbering and starts from SM one. That is why it is necessary to record all the possible SMs simultaneously. During the registration procedure, each of device's clocks was synchronized. Recorded data packages provide an overwhelming amount of data, far too much to process it manually, so it was necessary to develop software to do it automatically. It is essential to develop filtering and linking software that will transform the acquired data into a suitable form enabling its correct interpretation

3.3. Processing

The first step of data processing is initialized during recording. To save the hard drive space and improve performance of the recording software, minimization of the file size was required. To discard rows with zero activity, all empty rows have to be deleted before saving the data on the hard drive. The developed software was checking the sum of the first 450 columns from a row and deleted it if it was equal to zero (no movement detected), so that it would not be included in the saved matrix. Because the reporting (saving) protocol is resolved every minute, most of the saved files are entirely blank, due to the absence of movement inside the observed field. If there is any detected action, it immediately provides a significant data stream. It makes the files with recorded activity stand out, regarding its file size, from the rest of the files, which are blank. Simple filtering of files by their size allow quick determination which file has data with registered activities.

Afterwards, the data is successfully connected and calculated by the transition vector to one global coordinate system. The collected records require extra processing steps to identify whether there exists any POIs. The merged data still requires connecting pathways because of the existing discontinuities caused by the following two factors:

- The devices lose track of an occupant;
- The second source of discontinuities in the recorded data is dependent on some characteristics of the device used in the experiment.

Each device binds SM data by itself, with no communication between them. It is highly unlikely that both devices will link a monitored occupant to the same identification number of SM. To connect detached paths, it is necessary to sort records by time and calculate the velocity of each step. The next step requires investigation of the SM body ratio.

Each SM provides a complete set of information about the movement of each monitored limb. It can be used to distinguish each occupant regardless of the connected SM identification number. Registered occupants may differ from each other regarding their body dimensions, height, width etc. They can be distinguished by their body ratio factor. For example, the value of height divided by the horizontal distance between shoulders. The choice of the representative ratio or ratios will be based on its reading stability and transparency. If this layer of filtering does not provide a reliable sorting criterion, limb data can be applied to use its swing (pendulum) movement analysis. Each limb has its own specific harmonic move during walking. Observation of its repeatability can also provide some "marker" information. Frequency and deviation angle of limb movement can provide significant support in the personal \\\identification process.

3.4. *Moment knowledge*

Post-process data allows displaying all chosen pathways separately. All of the pathways were projected

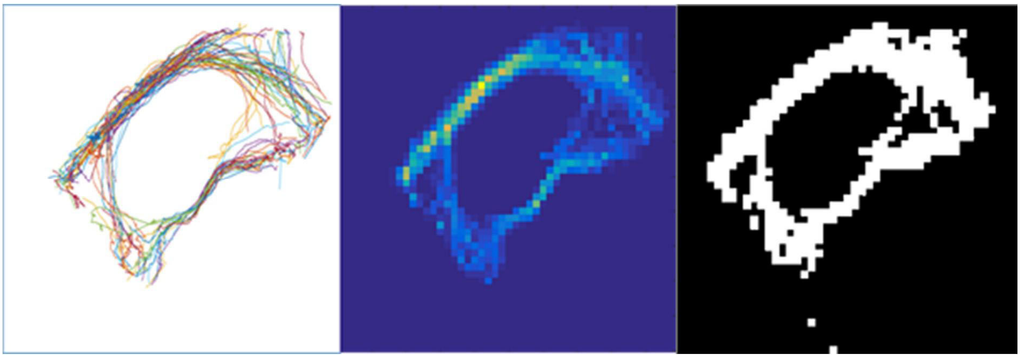

Figure 1. Pathway registration, the Heat map of space usage, transition outline plots

on a heat map to discover the frequently used tracks. Displaying these results allows swift identification of the monitored area layout (Figure 1). Based on ground truth, the uncrossed area represents the position of the table and chairs. It shows that the transition model has to take into account all possible connotations of the layout of the building. It is impossible to achieve it with just an overview of the transition and that is why the next part of the analysis has to focus on each separate step of the transition. As has already been mentioned, all monitored pathways have to be plotted on a normalized shape, where it is possible to discover patterns of transition from point A to B. Conceptual analyses of the movement were presented in Figure 2. It shows the possibilities of transition from point 1 to point 2. Transition steps and the angularity of consecutive steps are unequal. The probability of the step selection was illustrated by a gradient cloud, which represents the density of the selected steps from the starting to the end position. To understand the whole transition phenomenon, all of the movement transition has to be observed separately..

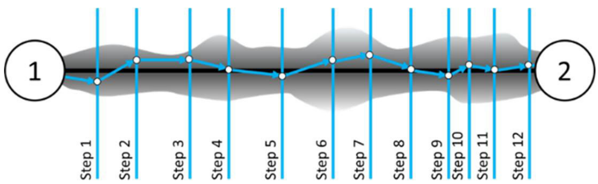

Figure 2. Movement pathway distribution illustration

3.5. *Movement model*

Investigation into the transition patterns requires to include all of the recoding inputs in the scope. The most interesting observation, regarding the model development potential, was the distribution of step lengths and its angularity, which is understood as an angle between the previous step and the next step turn. The distribution of the step lengths and angularity was displayed in histograms (Figure 3). Both of the graphs show that each value is characterized by natural distribution in a limited range. It demonstrates the existence of actual patterns that can be explored further. The displayed data shows a

IOP Conf. Series: Materials Science and Engineering **415** (2018) 012044 doi:10.1088/1757-899X/415/1/012044

Gaussian semi-bell-shaped curve. Both distributions were investigated, and distribution data, such as range and peek, were used to develop a movement.

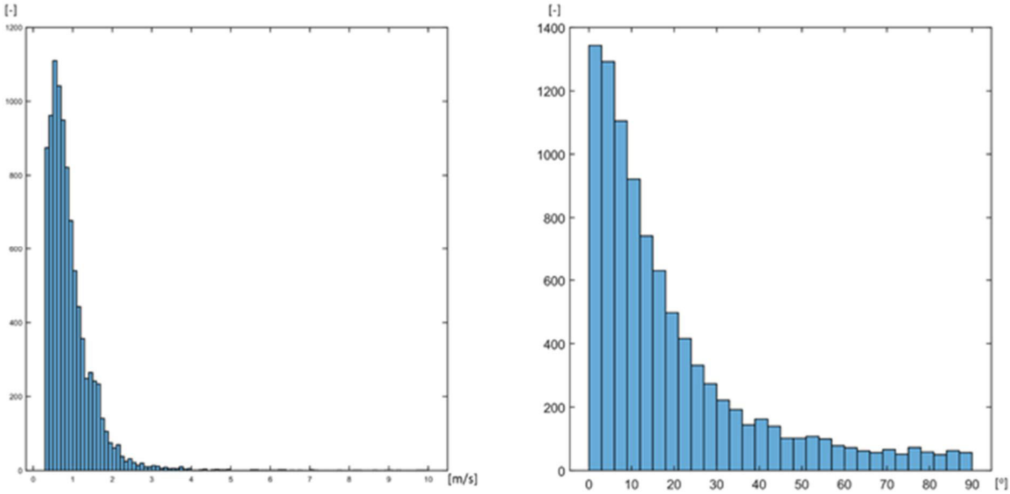

Figure 3. Histogram of movement speed and angle difference between steps

For the development of the Agent-Based Model that will recreate a selected pathway, all of the necessary data has been obtained. The essential model parts are the current location, the step length distribution, the step angle distribution and the turn vector (Figure 4). The step length was directly translated into the natural distribution model, where its metadata, such as the position of the semi-bell peek, range and standard deviation, were used in its description. Each step has been resolved with a random number that indicated the step deviation from the natural model. The step turn, was resolved in the nearly the same fashion as the step length. Data from angular distribution was re-calculated to absolute values to take into account all possible changes of the angle. It produced a semi-bell shaped natural distribution curve which includes data on step angle differences and the maximum difference between all the necessary statistical values. The maximum angle difference allowed locating the left and right arc ends. The turn vector always followed the general turn of the simulated agent from the previous step, and that is why the whole distribution arc was continually updating its step turn per time. It seems that the angular distribution was split into two semi arcs (the left with a red outline, the right one with a blue outline). For each step, it is necessary to decide which part of it will be taken into account. Selection of the semi arc part was made by measuring the distance from the intended goal to the arc ends. The smaller distance has always been selected. If both distances were even, selection of the semi-arc was random.

The designed movement model has been tested, and it has produced similar pathways in a normalized transition scenario. That is why it has been decided to test its capabilities in a virtual environment. For this purpose, four different layout cases were investigated. The developed movement model requires information on the transition towards the intended goal. If the randomly generated start and end point

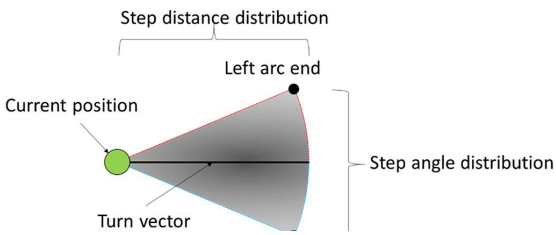

Figure 4.Drawing of principal element of the transient movement simulator

have some obstacle between them, the developed model will not be able to compile it. The model requires more information regarding the specific position of the investigated case. That is why test layouts have to be supplemented with additional information on local transition points. The points play the role of navigation points inside the tested cases. Location of navigation points was detected with a use of self-designed software. Each corner of the layout has been taken into account. During that phase, it was tested if other currents are also visible. If so, each pair provides one middle point between the visible corners. All middle points on the layout outline were discarded. Next, all the middle points identify connections between them. From now on these points are called orientation points. The identification process uses once again visibility analysis. Once the matrix of connection is established, the layout is ready to be tested for movement simulations. Each layout had one designed purpose of the testing. Scenarios naming is adequate to the figure included in results (Figure 5).

- Scenario A was investigating behavior in close corners;
- Scenario B was a testing transition between rooms in cross-like connections;
- Scenario C was focused on testing transition in an advanced room connection;
- Scenario D has tested the reaction of the model to the occurrence of possible circular patterns in the simulated space.

Once the location of beginning (A) and ending (B) of the pathway is established, the shortest pathway algorithm is used to describe the step of the agent. The procedure prescribes a schedule of the points that the agent should reach to achieve the end position. For example, it describes that to reach goal (B), the agent has a scheduled vector [A,1,3,6, B]. It means that from point (A) it should be focused on aiming towards and reaching orientation point no.1. First of all, in each step, the algorithm checks if end point (B) is reached. If not, the software movement procedure is initialized. While progressing towards this orientation point, it will detect that orientation point no. 3 is visible. From that event, the aim of the agent is updated to reach orientation point no. 3. This procedure continues until the end of the pathway has been reached. To avoid extension of the simulation time of the agent movement, if endpoint (B) is within reach of the agent, it finishes the movement simulation with a transition towards it. If during the simulation procedure the next step taken by the agent will cause over-crossing the space outline, it resolves the step selection once again. In critical condition, if it is not possible to resolve a movement without crossing the layout border, the simulation software cancels the last step, and it is resolved once again. To check the frequency of appearance of such situation, a specific counter has been applied in the code. Once all of the monitoring systems have been set up to track all the potential misconducts of the movement model, it is possible to initialize simulation procedure.

4. Results

For the model test trials, four different layout scenarios were designed in a black and white bitmap. Once all the necessary assumptions had been formulated, each layout was tested for generation of fifty pathways. The start and end points were generated at random. Due to that reason, it was impossible to predict if all of the selected areas layouts will be visited by the designed agent. The results of the simulated pathways were displayed in Figure 5.

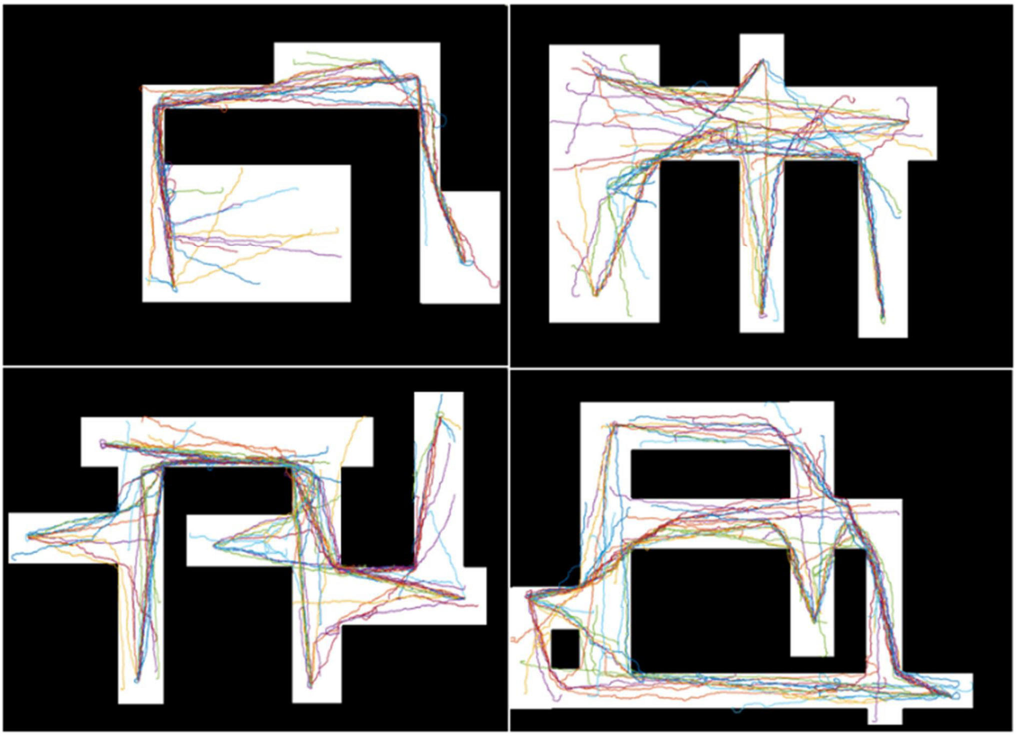

Figure 5.Movement simulation results on selected floor layouts

5. Discussion & Conclusion

The performed simulation test shows that the suggested modeling approach has its potential applicability in building performance simulation. This study has to be treated as the first step towards transient occupant behavior modeling. The results of simulated pathways show that a few parts of occupant transition have to be improved. The next improvement steps should aim at a transition from the raster to vector data. Re-calculation of the whole matrix into a raster matrix can be overwhelming, for CPU or GPU. That is why it is important to deliver this calculation switch. Additionally, all of the designing software uses vector drawing as its basis. If the potential designers are to support their work with such a tool, it is critical that their workflow will not be disturbed by additional unnecessary tasks. Simulation of the transient occupant behavior has to reach the level of a complementary feature. During the simulation trials, none of the monitored errors were observed. The movement simulator respected the limitations imposed on all the four test scenarios.

With continuous work aimed at improvement of this method, it will eventually be able to obtain more precise data regarding occupant thermal sensation. With the use of this method, it may be coupled with a converging CFD simulation. If it holds information of the indoor air thermal condition, it is possible to track the history of an occupant's exposition to local conditions. Such asset can be used for evaluation of the already existing local thermal comfort models. Once the accuracy of the previously developed comfort models is taken into account, it will be discovered what their transient accuracy is. It can indicate the potential direction for future improvement towards development of the personal transient thermal comfort model. To reach that level of confidence, the proposed approach has to be put to more extensive trial. To do so, it is necessary to conduct a new series of measurements with wider spectrum of occupants included in the study. It has to be checked what are the pathway decision-making factors which influence the selection of a specific pathway. This knowledge can be obtained from investigating simple movement scenarios. Each future scenario will have to include the choice of at least two different pathways. Additionally, it will have to be checked how the beginning position influences the selection of a pathway. Once the above-mentioned parameters have been investigated, data collected in those experiments may be used for improvements in the movement model. The current state of development shows promise of a potential breakthrough in building performance simulations. If all the missing parts of the knowledge are verified and receive positive feedback, it will mean that this model could be treated as the first milestone in development of the Building Occupant Transient Agent-Based Model (BOT-ABM).

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Paper No.5 J. Dziedzic, D. Yan, V. Novakovic; Indoor occupant behaviour monitoring with the use of a depth registration camera; Building and Environment; 148; 2019; 44-54. Journal Paper

Building and Environment 148 (2019) 44–54

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Indoor occupant behaviour monitoring with the use of a depth registration camera

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ARTICLE INFO

Keywords:
Occupant behaviour
Building energy performance
Depth registration
Pattern recognition
Big data

ABSTRACT

Registration, identification, and re-creation of an indoor occupant's actions are challenges in the field of building energy performance. Commonly used measurement technologies are capable of capturing partial information regarding the occupants' activity. However, the combination of all existing inputs cannot grant access to a satisfying description of occupant behaviour that allows capturing profiles of occupants' intentions and habits. It seems that there is a missing type of data that could be used as a connection platform for already existing inputs. To connect existing data sets, there is a need to deploy a monitoring method that can identify particular individuals; however, it must do so while still providing a certain level of privacy among the monitored occupants. Fulfilment of these standards can be achieved through the use of the depth registration technique. The entertainment industry popularized this registration technique, but this registration method has many other applications in the fields of medicine and computer vision. The most commonly used device (Microsoft Kinect) delivers high-frequency sampling (up to 30 Hz) and a moderate measurement range (up to 5 m), which allows its usage in the monitoring of medium-sized indoor spaces. The delivered input data do not allow for the direct identification of the monitored person, and it does not require any interaction from the occupants to initialise the monitoring procedure. Due to these reasons, the potential of this measurement method was explored in terms of becoming an *in situ* indoor occupant behaviour monitoring technique.

1. Introduction

A recently published report of the International Energy Agency (IEA) shows that more than 27% of globally produced electricity is consumed by the residential sector [1]. In the 70's, the electricity expenditure of this sector amounted to 23% [2]. Despite a significant improvement regarding energy efficiency in the use of resources, the global consumption of electricity in the residential sector is still rising. This increase might be caused by the widespread use of electricity powered appliances in the population. Additionally, this trend might be enhanced by the introduction of new products that further contribute to the overall usage of electrical power (e.g., electric cars).

Even with the continuous improvement of energy use in all kinds of industrial sectors, our society has been unable to slow down the rise in energy consumption per capita. Despite the fact that numerous efforts and regulations have been undertaken to reverse this trend, the demand for energy in the residential sector still increases, fuelled by the growth of the world population [2]. Therefore, it is necessary to search for possibilities that may lead to a reduction of electrical energy consumption or an increase in the efficiency of its use. To reduce energy consumption, it is necessary to obtain a proper forecast of its demand and thus avoid overcharging of the grid. It is crucial to detect the peak of the energy demand with high accuracy to achieve this target.

Many approaches have been applied previously to achieve this goal, e.g., a statistical approach based on observation of the whole network [3] [4] and observing trends and trying to predict the grid's performance on the basis of the collected data. Such "top-down" approaches did not reach their required goal, but they have contributed to an idea for future improvement: the increase of measurement and modelling resolution. The boundary of this advancement was set on the level that would reach the expected forecast quality.

At present, the approach regarding the simulation perspective has been reversed. The majority of the conducted research in this field by now is done using the "bottom-up" approach [5]. From this perspective of simulation, occupants and their actions are treated as part of the system, and the collected data are used for the description of the population. Each individual part of the system has meaning. This approach may prove successful if the sum of records and the number of

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https://doi.org/10.1016/j.buildenv.2018.10.032
Received 13 July 2018; Received in revised form 16 October 2018; Accepted 17 October 2018
Available online 19 October 2018
0360-1323/

cases achieve statistical significance. The approach was aiming at the development of a database of typical buildings. One of the research trends that has led to an increase of modelling resolutions was aiming at modelling energy behaviour by the development of a model that would describe most common buildings types [6]. The whole building stock in the investigated area was classified by their types. The next step involved an investigation based on energy consumption within each group, and then typical characteristics of each building type were discovered. Despite the fact that the approach seemed reasonable, it did not deliver a high-quality solution. The solution was considered a hybrid, a trade-off between two modelling approaches. Currently, the accuracy of this method is still at the stage of being developed [6].

The reduction of energy demand requires improvement of cooperation between the building and its users. All energy sources used by building occupants should be considered a limited resource. A real improvement of energy management systems is required if this limited resource is to be used with the highest possible effectiveness. The scope of the deployed system has to include the needs and demands of each user. For this purpose, researchers started to examine the concept of building users' comfort. Collecting information on occupants' comfort desires helped improve the management of energy use [7].

Comfort can be described as a state of physical ease and freedom from pain or constraint [8]. This definition aptly describes also the ultimate objective of any energy management system that includes the occupants' thermal comfort. The first milestone of its definition was delivered by Fanger's approach [7]. The methodology gives rise to a relatively simple method for evaluation of the thermal comfort parameter. It includes a human-related factor in energy equations. Currently, it is considered to be fundamental for building performance simulations (BPS). The methodology proposed by Fanger was introduced in the 1970s. The research related to occupant thermal comfort was continued, and over time, it delivered a few more sophisticated methods. A good overview of the developed BPS models is presented in the book [5].

Despite the undertaken efforts, a more accurate understanding of general energy flow inside buildings has not been reached. The reason is the insufficiently advanced state of occupant behaviour models in BPS [9]. Absence of this knowledge is blocking improvement of control systems for buildings. The summary of the current BPS software performance and the development condition, which includes the occupant factor, can be found in Yan [10]. Yan has noted [10] that it is necessary to increase the resolution of occupant-related data collection. The development of proper sensing techniques that will grant access to high-resolution data on building users is required. The collected data will lead to the development of a knowledge base about an occupant's living style. If such a knowledge base is created, it will lead to improvement of control systems.

A few initiatives have sprung up in the process of working towards achieving the set goal. Several scientific work groups were formed that were focusing on the description of real building energy use [11]. The recently completed project IEA-EBC Annex 66 was focusing on the definition and simulation of occupant behaviour in buildings. The initiative included scientists from various backgrounds, and it was trying to develop a coherent description of the occupants' behaviour. The exchange of experience and knowledge has led to certain conclusions about the current state of development and pointed out directions for further improvement. Hong's [12] findings demonstrate that the progress of future modelling techniques should be connected to capturing the motivations of the occupants' actions.

An understanding of the origins of the occupants' actions may be built by establishing a collection of relevant metadata. The combination of all collected information has to generate a space for possible interpretation of the occupants' preferences, although collecting such information is a challenge. The data collection procedure has to find a way to overcome the problem of disturbance of privacy that occupants may experience. The current state of data collection accuracy fails to deliver a satisfactory resolution [10]. This situation prevents development of more precise models that could deliver feedback for designers during the stage of the building design. The study conducted by Turner [13] demonstrates that only in 30% of buildings, the energy consumption simulation accurately predicted the actual energy consumption in the building after it had been constructed. It shows that there is significant room for improvement and that the currently available tools may be insufficient.

If the situation continues, it may affect occupants, and they will lose confidence that the system they are using is capable of delivering the expected indoor air conditions. Generation of such negative feedback may lead to an increase in energy consumption. Typical solutions do not allow detection of the occupants' identities or movement vectors that could be used as tracers. These, in turn, could be used to link the input of occupants with their thermal preferences. Devices that allow identifying occupants usually require being carried around (Fitbit or smartphone). Access to such input data can offer reliable support for BMS. Unfortunately, this solution has an important limitation — it can only be used in public buildings or offices due to privacy issues. Additionally, it will not include people who forget the carry-on device. On the other hand, most of the devices that are used in a fixed position are incapable of precisely detecting the presence or tracking the occupancy state in the monitored zone. The only available solution that is capable of tracking the occupants' activity (a video camera) encounters the same obstacle as a carry-on device — it may not be accepted in residential buildings because it can harm their privacy standards. It seems that there is a technological gap regarding monitoring techniques. Occupant sensing techniques, its limitations and potential outcomes are presented in chapter 4 of the book [9]. Additionally, in Arief-Ang, et. all work [14] each presented sensing technique explores in detail used processing algorithms and overall accuracy.

The missing element is information about the occupants' personal thermal comfort needs in residential buildings. Currently used technologies for sensing human presence and actions can grant access to the partial information regarding the occupant's behaviour. The usability of the obtained information cannot be forgotten; however, its quality of sampling time and data resolution cannot capture the full dynamics that influence occupant behaviour [10]. The lack of a direct trace of each occupant activity leaves a gap of uncertainty that blocks potential interpretation of the occupants' needs and desires. Typically, used occupant-oriented measurement techniques cannot bind data with a particular person in the monitoring zone. That is why the kind of expectations occupants have remains unknown. The designed solution grant access to the necessary data while respecting the occupants' privacy. It is necessary to develop a tool that will collaborate with other measurement techniques and contribute to the general view regarding energy-related occupant behaviour. Based on an existing overview of used occupant sensing methods [9,14], there is one promising measurement method that is still underdeveloped. Based on the used measurement technique it has the potential to deliver the expected support. It is the depth registration technique. The literature review has shown that the selected measurement technique was not explored enough in building energy-related studies. Further on, due to the market availability, price and required programming skills, it was decided to investigate applicability of the Microsoft Kinect [15] as the depth registration device and to discover the benefits that it can provide.

1.1. Aim of study

Access to information about occupants' actions inside buildings can bring a new quality to the identification of indoor environment quality. It has the potential for increasing the accuracy of the existing energy models. With the use of this technique, it is possible to register occupant's activities in *in situ* methodology. This study will investigate most of the measurement capabilities of the depth registration device. In particular, how much information can be obtained and how it can be a

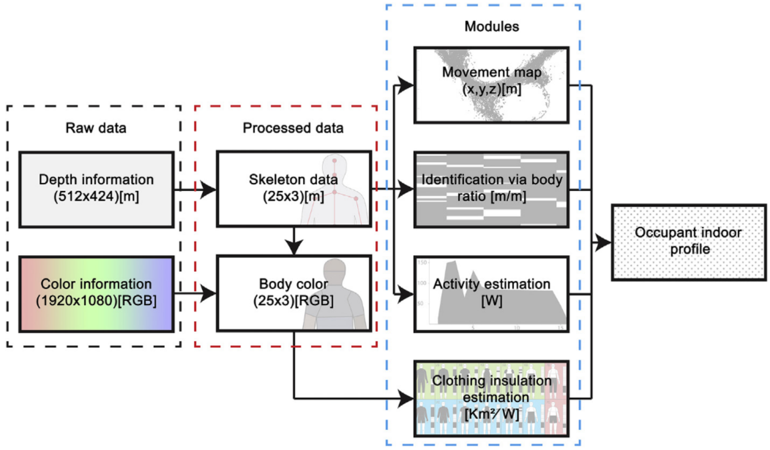

Fig. 1. Flowchart from raw data to occupant indoor profile.

benefit in the building monitoring systems will be analysed. Each step towards the development of occupant indoor profile will be explained in the following paragraphs (Fig. 1). Use of the selected measurement method goes beyond the suggested spectrum of spatial, temporal and occupant resolution, according to the methodology proposed by Melfi et al. [16]. Recent studies are still capable of delivering new findings with use of the lower sampling resolutions, with use of the surveys [17] or environment monitoring (CO2 or RH) [18–20]. Extending measuring range might support the development of the understanding of energy-related occupant behaviour in buildings. It might also be used as a referential technique that could evaluate already existing finding. The potential output gains, as well as the device's measurement limits, will be put to the test.

Use of the suggested device can grant access to a new measurement approach that will track occupants' motions. Collected data combined with the space layout (furniture and device placement) may allow tracking occupant daily routines. With this feature, it would be possible to describe behaviours and habits regarding usage of the space. Moreover, investigating which patterns of activities have a significant impact on energy consumption would be possible. Additionally, it will be checked, if with an assessment of whether it is possible to extend the description of occupants' thermal comfort in buildings with the use of this measurement technique. If this goal is reached, it will be a significant signal that this measuring technique has scientific and commercial potential. If the data collection technique grants input for direct validation of the existing energy-related behavioural models, it could give a foundation for new mathematical models.

2. Measurement and methods

2.1. Depth recording introduction

The depth recording technique is an enhanced video registration and monitoring solution. It overcomes previous problems generated by background analysis, which were usually related to typical video post-processing. It adds an extra dimension to the observed field. Such goals can be achieved by combining a typical video camera with a projector (a laser beam) that displays information in the infrared (IR) spectrum. The installed projector displays a known grid (cloud) of points, and the reflection of it is captured by the camera. When data is captured, the installed software recalculates the distance, and by this operation, it is possible to capture depth. After depth data are collected, they are resolved as a raster picture, but each pixel holds information about the measured depth. Registration boundaries are directly related to the quality of the used hardware, mainly the capacity of the projector and of the imaging amplifier. Such measurement methods are gaining popularity in various branches of industry (industrial scanning, automotive sensor, entertainment, etc.). The most popular application of this technology is the Microsoft Kinect device. The producer of this device was aiming mainly at the entertainment sector, but with the release of the software developer kit (SDK) [21], it has become a dominant low-cost tool for various types of depth measurements. Due to its popularity, the device can be considered to be of low or moderate cost. Currently, it is one of the most inexpensive scanners available on the market. Its designers were aiming at developing it as a game controller that requires players to move or exercise. That is why this device is capable of detecting people in a medium range, within the distance of up to 5 m in radius and an angle of 46°. It is sufficient for monitoring small offices and residential buildings.

Due to the selected device's primary use, its core operating software had to be upgraded with a skeleton model (SM) that links the observed human-like shape with a moving limbs SM. Each limb is connected by joint points, as listed in Table 1. Whenever a person crosses the exposition zone, it connects the human-like body movement with the SM. Due to this solution, it is possible to measure the dynamics of the human body. It can be done by exporting information about the position of joint points. This device is capable of registering up to six people at the same time (captured frame) while they are inside one and the same exposition zone. That means that it is possible to capture a large number of people, but the observation area has to be relatively small (approximately 10 m^2) and without significant crowd movement, such

Table 1
Skeleton model joints list and numbering.

Number	Joint name	Number	Joint name
1	Spine Base	14	Left Knee
2	Mid Spine	15	Left Ankle
3	Neck	16	Left Foot
4	Head	17	Left Hip
5	Left Shoulder	18	Right Knee
6	Left Elbow	19	Right Ankle
7	Left Wrist	20	Right Foot
8	Left Hand	21	Spine - Shoulder Level
9	Right Shoulder	22	Left Hand Tip
10	Right Elbow	23	Left Thumb
11	Right Wrist	24	Right Hand Tip
12	Right Hand	25	Right Thumb
13	Left Hip		

as in a corridor. Seer's experiment shows that during 1 h, it was able to track the movement of 1682 pedestrians [22]. The main disadvantage of this device is its lack of autonomous performance. Each unit requires a computer that will be used as the software carrier and for data storage. Setting up more than one device per computer is not supported in the published software development kit. This is caused by the significant data stream from one device. In addition to this issue, the device offers high-quality sampling, with a frequency up to 30 Hz. The real-time frequency of probing depends on the capabilities of the used computer [23]. In addition to depth registration, it is also possible to register a regular video with high definition quality. The selected measurement device has four installed microphones which allow estimating directions of oncoming sounds. Sound recording and the following pathway re-creation via sound will not be included in this analysis. Currently, depth registration devices find applications in various technical solutions. They are used in research projects related to medicine [24–28], ergonomics [29–34], computer vision [35–38] and many more [39–43].

For medical applications, most of these devices are focusing on reinforcing the rehabilitation process, post-stroke activity and evaluation of post-surgical effects in posture (scoliosis). Due to its mapping capabilities, this method is also used for evaluation of the effects of various types of plastic surgery. The most typical use of depth registration is in computer vision techniques. Due to its sensing capabilities, it allows furnishing developed robots with an additional module. Being able to sense the surrounding geometry enriches their performance by delivering the sight depth [44]. Such an application offers an extra push in the development of robots in a new era. Identification of the surroundings with the use of a beam surface allows analysing the “observed” field and delivering correct responses to the stimuli from the environment. For walking machines, it allows forecasting changes of balance. Autonomous driving stations can optimize their track by avoiding obstacles. The same application can be used for drone technology, where the drone can avoid an obstacle or limit pilot control when it could lead to damaging the machine. The closest application to building science that uses the depth registration is building ergonomics. This technology supports evaluation of interference between humans and their working environment. Being capable of delivering direct feedback about the observed area instantaneously, it can quickly detect weak points of the interior design. This type of response system can have a direct influence on an employee's productivity. Examples of depth registration cameras regarding occupancy status can be found in the relevant literature. However, most of the publications were made before the software development kit (SDK) was available. Therefore, most of these scientific approaches were not using all of the device capabilities. The reason why there is no trace of using the device's full potential is also because the previously used computers were much less advanced than current computers. A good example of using this device was presented by Ref. [45], where data from the depth registration camera was used as an input for CFD studies. Another field of potential use of depth registration is welfare technology. The research conducted by Ranyz shows observations regarding monitoring the position of elderly people living in a nursing home with the objective of checking whether they fell or had some injury [46]. That approach allowed tracking their activity without the need of examining each room. It delivered information about occupants' actions during the entire day; therefore, it could detect if a person was in an emergency without affecting their privacy.

2.2. Data collecting

This paper aims to show a method that provides access to the data that will fill the information gap preventing development of new numerical models. Direct monitoring of occupants' actions will support defining their thermal comfort needs. Because the chosen device allows obtaining precise information about occupants' locations, it can be treated as a resource for developing new models regarding energy-related behaviour. Previously conducted research allowed determination of serial types of behaviour among occupants [47], but the selected data did not allow precise identification of individuals within the group of investigated subjects. The behaviour of the investigated group was described, but it was impossible to separate data down to the level of defining each particular occupant's thermal comfort. The measured data do not allow precise identification of behaviour of each particular occupant, which is why the designed control system was only capable of operating with data on the energy-related behaviour effect. Such limitations appear in all kinds of buildings where occupants are allowed to tune up IEQ. Based on such data, it is difficult to accumulate knowledge about the monitored subjects. Without an understanding of causes of occupants' actions, the control system might act against their needs. An additional issue appears in regard to solving the identification of regular space users and distinguishing them from guests. Occasional visitors to any space (residential building, office, etc.) may influence the registration process, and when their appearance is not correctly marked, registration may lead to an incorrect conclusion. The influence of such readings grows with the frequency of a visitor's presence and their relations with regular users. Regardless of the measuring technique used, the influence of visitors, cannot be ignored, and their reactions regarding IEQ have to be separated from the signals of regular users. Visitors' behaviour may be different from the one exhibited by regular space users. Their thermal preferences may not correlate with regular users. They could view the visited place as remaining outside their thermal comfort acceptance area. Their actions should not be considered as a resource for the control system; however, they should have the possibility to adjust it.

Regarding spatial distribution, each building zone can be described either as a destination or a transition room/zone. Transition rooms/zones, in addition to offering space for various appliances, have the additional functionality of providing passages to other rooms/zones. The destination type of rooms/zones does not have this functionality, and without the transition room/zone, it would be impossible to reach them. The placement of the recording device depends on the type of studies. To monitor general movement and transitions inside the investigated facility, the device/s should be placed at a location that allows monitoring occupants' transitions. Because each measurement device has to be connected to a separate computer, the number of devices has to be kept at a minimum in relation to the maximum possible coverage area. Importantly, it should be noted that it is necessary to cover all existing transition zones inside the area under observation. It is necessary to ensure coverage because it eliminates potential uncertainties about the occupants’ location.

Access to the data that allows detection of indoor occupants' actions and positions will benefit a wide range of buildings applications. The usability of these applications can influence sectors such as building energy performance, healthcare, energy markets and many more. The profiling of each separate occupant will grant direct feedback for development of thermal zoning inside the monitored space. Daily occupant activity data can be correlated with a study regarding public healthcare. Development of an occupant's profiles could be shared during routine medical examinations. It could help with the estimation of the development of diseases such as cardiac arrest or diabetes. It could also be used for a wide range of applications that can support monitoring of nursing homes. Knowledge of the occupancy schedule can also benefit the estimation of a peak load and the management of the energy grid. Once a significant amount of the profiles are obtained, it will be possible to investigate what kind of strategy can be applied to balance daily energy consumption.

2.3. Accuracy & calibration

As the position of occupants is constantly changing, it is necessary to investigate how the obtained data is influenced by the original fitting to the SM. This model works with the identification of the human body position. If some parts of the body are invisible to the detector because they are shaded by other parts of the body, SM estimates their position. Therefore, it is required to run a series of test scenarios to estimate the influence of the monitored occupant's position on the accuracy of data probing. The accuracy test was performed with the use of a pre-scheduled pathway of movement back and forward, with a similar walking speed regime. The test was divided into a series of events. Each event took the same amount of time. The main difference was related to the angle between the pre-scheduled pathway and the position of the recording device. Studies were conducted with a fixed position of the camera (Kinect 1) on the floor. Because the camera height position may vary in each measurement case, placement at different heights was investigated [0.6 m from the floor, 1 m from the floor, and 1.8 m from the floor]. To facilitate following the selected pathway, lines representing each angular scenario were drawn on the floor. During this calibration study, three different angular positions were investigated (0°, 45° and 90°). The turn of each investigated case was related to the surface of the position of the recording device. The angle value 0° represents a pathway that is perpendicular to the device reference surface, whereas the angle value of 90° represents a pathway that is parallel to the device reference surface. The second camera was used in ratio readings comparison. The drawing of the calibration test setup is shown in (Fig. 2).

To check the probing accuracy of all scenarios, the position of the device at 1 m above the floor level and the 0° pathway angularity were used as the reference. This scenario was selected because no part of the human body is being shaded by another while performing this movement, so the SM fitting depends only on the recording. During the calibration process, each joint of the SM was subject to investigation.

After capturing data for each scenario, each record for each joint was projected perpendicularly onto the local reference surface to investigate the pathway turn in each case. Each data package captured during calibration was compared to the archived result from the reference case. The comparison was made with cloud point analysis. Data on each joint collected during the reference trail were analysed regarding the generated cloud point boundary and the heat map of sampled points.

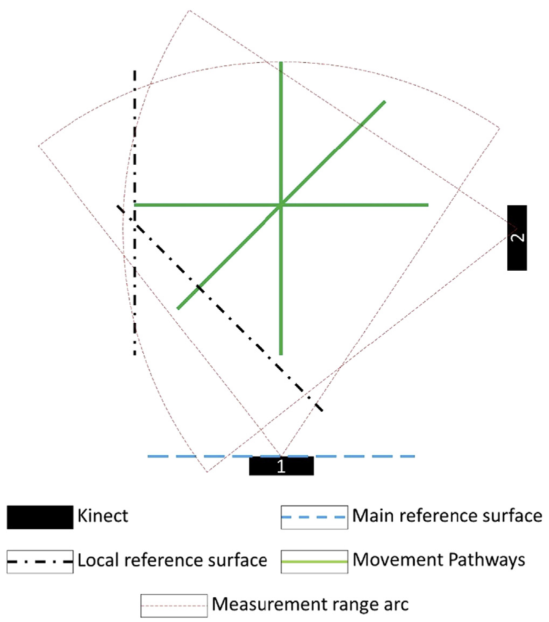

Fig. 2. Calibration test setting, view from the top.

Next, in each case, the joints were analysed regarding their fitting into the reference boundary, checking to determine what percentage of all points, from all joints, fit into it. The result of this operation generates a response surface which describes all the values by the percentage in which they fit into the generated boundary. A series of analyses was conducted to check the accuracy of data probing against the reference measurements. How the degree of accuracy rises while the reference boundary buffer (outline) increases was tested. In each test step, the boundary was increased by 0.01 m. During the whole procedure, eleven buffer states were investigated, from 0 m to 0.1 m. The result of the calibration test is shown in the heat maps (Fig. 3). The horizontal axes of all of the graphs represent SM joints, and the vertical axis of each graph represents each step of increasing the buffer boundary size. The highest results show the percentage of fitting into the reference boundary with no buffer boundary. The lowest records show the percentage of fitting into the reference boundary with 0.1 m of buffer boundary.

The collected data shows that there is a significant shift in accuracy connected to the height of the measuring device position. Fig. 4 shows that in both lower positions of the measurements device (0.6 m and 1 m), the satisfactory percentage (above 90%) of fitting into the reference boundary was reached with the buffer of 0.05 m. The highest position of the device reached the same accuracy level with the buffer of 0.09 m. This lack of precision was overcome by using the calibration matrix based on the calibration test. The calibration matrix was used to re-calculate the collected data in the following experiments. Additionally, the calibration test shows that the SM model fails to simulate positioning of the "unseen" parts of the human body correctly. All body parts that were not in the sight exhibit a sudden drop in accuracy (compared with the reference state). Bypassing this condition, the movement of an "unseen" limb can be re-created with the use of the data from a registered body part and by generating the counter phase of pendular movement of each body part.

R - is the spine length to the shoulder span ratio, i - is the sampling frame, x represents the x-coordinates of investigated SM joints, y represents the y-coordinates of investigated SM joints, and z represents the z-coordinates of investigated SM joints. Additionally, an investigation of the ratio output data that can be produced by two depth registration cameras monitoring the activity of the same person was conducted. Both devices were recording data at the same time. The test setup was displayed in Fig. 2. The data collection with the suggested method can be obtained only the use of different computers. Therefore, the maximum frame rates of recording that various devices can handle are unknown. How the frame rate setting will influence the data collection procedure was an important consideration. For this experiment, the first device was set up to perform with a maximum frame rate of 30 Hz, and the second device frame rate was set to 15 Hz. Obtained information from both devices was processed with Equation (1) and compared with the histograms. Both frame rate values were not even; therefore, it was necessary to re-calculate the histogram choices to the absolute values. Each step in the histogram (on a horizontal axis) represents a 0.1 m value. The comparison of both histograms is shown in Fig. 5.

$$R_{1,i} = \frac{\sqrt{(x_{head} - x_{spine\ base})^2 + (y_{head} - y_{spine\ base})^2 + (z_{head} - z_{spine\ base})^2}}{\sqrt{(x_{shoulder\ left} - x_{shoulder\ right})^2 + (y_{shoulder\ left} - y_{shoulder\ right})^2 + (z_{shoulder\ left} - z_{shoulder\ right})^2}} \tag{1}$$

Occupant identification equation to body ratio proportions.

Both of the recordings note that the most commonly occurring ratio value is 2.2 m. The blue histogram shows ratio values from the device that was sampling data with a frequency of 30 Hz. The ratio values from the orange histogram were collected with a rate of 15 Hz. Despite

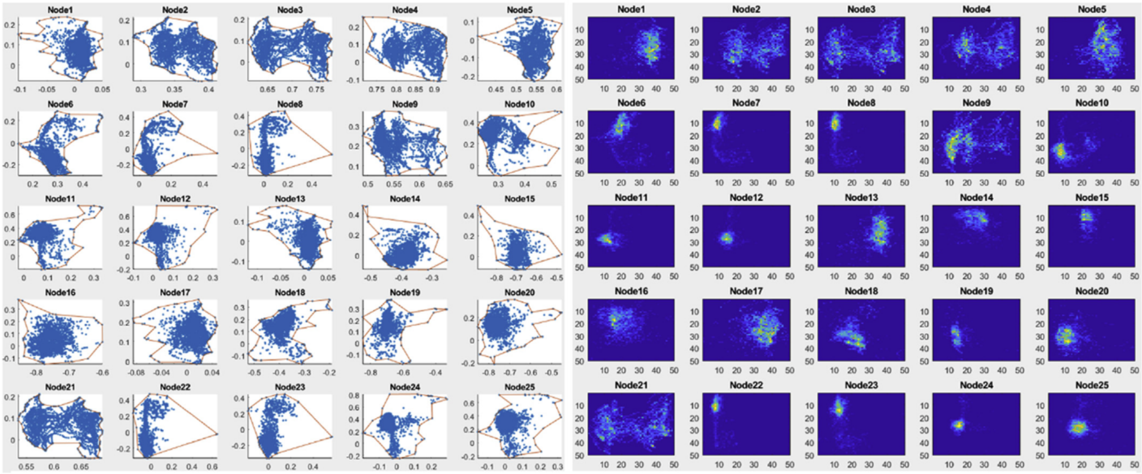

Fig. 3. Sample of calibration reference data. Nodes are numbered as in Table 1 with the SM joints list.

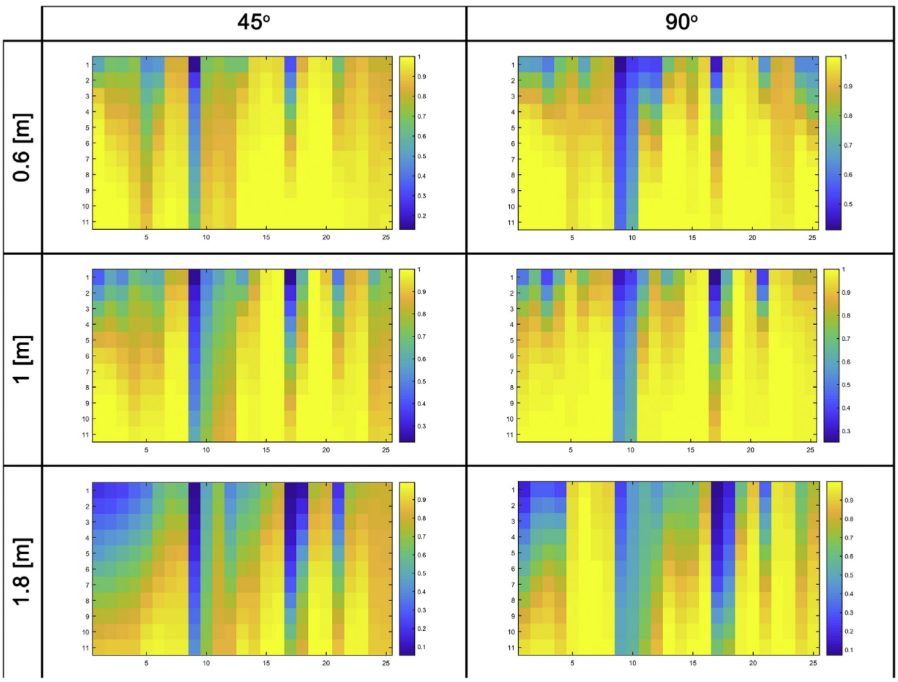

Fig. 4. Calibration test results.

different camera positions and different sampling frequencies, it is possible to define the default ratio of the observed occupant. In addition, it is possible to claim that the location of the device has a no significant influence on a ratio reading.

2.4. Identification

Typical measurement techniques that are widely used in building performance registration should by supported by an occupant identification system. The suggested use of the depth registration camera will offer the possibility of identification of occupants and still leave space for occupants' privacy. The identification process should respect their privacy limits, and it should be passive. With direct support from the SM, occupants can be distinguished by measuring the ratios of their bodies. The most stable body ratio is the value of the distance between the spine base and the head divided by the distance between shoulders (Equation (1)).

The numbering of operators is based on the SM described in Table 1. A sample of the ratio is registered at the same probing frequency as the complete records, which makes it possible to register it dynamically and distinguish occupants on the basis of this factor. The distance ratio between these four points is stable in a function of time and space

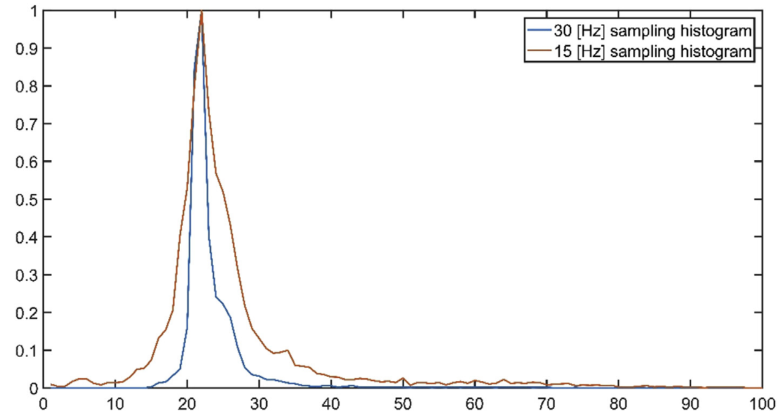

Fig. 5. Histograms of ratio readings from both devices.

because the SM linking software has a basis to detect these points. The values of other ratios created with the use of other points can also be useful, but their reading does not provide such precise identification. It is possible that two persons will have similar body ratios, but it is still possible to differentiate between them on the basis of some additional factors. The simplest is the measurement of height; occupants may have the same body proportions, but their height may be different. If this measurement fails regarding identification, it is possible to collect statistical data about pendular movements of each limb. If this identification is still insufficient, the occupant can be distinguished from others by their typical zone occupancy, type of clothing or patterns of their activity. Identification based on occupants' clothing will be described later. Once an occupant has been described, the description can be connected with those metrics (identification data) to generate an identification profile. There is an option for the occupant to consciously participate in the identification process. It can be performed with the use of an "identification mode" where all the typical users are separately asked to perform a series of actions inside the registration area. This approach allows generating a metric body profile that can be enriched by an active profile afterwards. Such an approach produces valuable data from the beginning of the registration process, but its applicability depends on the zone type. If it is an area where occupants' replacement is small, it is reasonable to use this solution in registration. On the other hand, if the monitored area is a space with a vast migration of occupants and where the amount of visitors is high, prescheduled identification may cause data handling difficulties, and it will be impractical for space users.

2.5. Access to raw data

Access to the essential movement data was granted by a self-developed recording code in the MATLAB environment. The created application was responsible for holding the device in an infinite loop, where all joints from the SM were registered. During standard performance, the device is capable of registering up to six occupants in one frame. The process of bonding the observed occupants is semi-random. It means that selection of skeleton numbers (from one to six) is uncontrollable. It is a semi-random process because it starts with skeleton number one, and when another person appears, it is linked to skeleton number two. The same happens when it loses track of the person that was connected with SM number one. If SM number six is being registered, the next person coming into the view will be linked to SM number one. The process repeats in a cycle until the registration process is stopped. It tries to keep the same skeleton number connected to the same person by analysing the differential state of the movement from the depth registration source. The software built into the device does not have an advanced system of recognition, so it is better to register all potential SMs that may appear. If one SM is lost, and the same occupant is linked to another SM, it will be easy to detect it with the use of identification data. If an SM is not in use, the data from it is always equal to zero.

One sample of data is distributed as a vector of four hundred and fifty-seven columns of records. Each SM holds three-dimensional information about twenty-five points, so complete information on one SM is stored in forty-five columns. Because it is unknown which SM will be selected for an action, it is required to store all six SMs. The last seven columns are designated to hold information about clock data. While conducting measurements with more than one device, it is crucial to collect clock data because it enables synchronization of all the used devices and re-creating the use history. Because of the device's high sampling frequency, it is necessary to delete rows of recording that do not hold information about any activity. Otherwise, it would be difficult to process large recording matrixes. The collected data is stored in a 1-min interval, and afterwards, the next collecting event begins to be executed. If during the whole recording event (1 min of recording) no activity was registered, the file was saved with the symbolical zero value. This procedure allows defining data efficiently for later processing.

2.6. Movement pathway re-creation

Previous investigation with the use of the depth registration technique shows great potential in tracking occupants' movements, and the research has been extended to include more cases [23]. After data is collected, it is combined in files representing a one-day recording from all used devices. It is essential to connect all of the recordings with recalculation vectors if more than one device was used in that measurement trial. Once the data are connected, sorting must be done by time of recording and divided by separate occupants with the use of the identity matrix. Post-processed data allows re-creating the pathways of their movements. By analysing the shape of the pathways, it is possible to estimate the current layout of the monitored zone. It also enables detecting points of connections with different zones.

To correctly define the existence of zones, it is necessary to combine all the movements from all typical occupants. Connected data on all the entries and exits from the monitored zones has to be selected. Highlighted areas have to be classified or segregated. One of the simplest approaches to apply is the k-means clustering technique [48]. The value of k represents the number of entrances connecting rooms/zones in reference to the observed zone. Establishing the location of these areas is necessary. In addition, it is necessary to link the location of these points to the basic figure shape, such as a rectangle or ellipse. The choice of figure strictly depends on the effect of the shape optimization, and its dimensions are selected based on the criteria of the maximal hold of points and minimal coverage area. The centre point of each figure will be the centre of each cluster.

A similar observation can be made by analysing start/end points inside the registration range. This post-processing step has to be made after identifying entries into the registration zone, to avoid including those points in the analysis. If there are some parts of the zone that occupants will use the most (such as a chair), their pathways will be likely to start and end at the same place. If there is a difference between zone entries and exits, those points can be detected by using the heat map of the whole registered movement. Generating the heat map is done by location of start/end points in the registration area, and the located point adds one unit to the observed space. This operation is repeated until all the starts/ends are included. A typical occupants' point of interest (POI) in that area will be highlighted by the highest value in the observed space. Afterwards, all the data that is left is information about occupants' activities and movements that can be used later. Observations about an occupant can be used to develop knowledge about occupants' ways of using the observed zone. It can show their everyday habits in using the space.

2.7. Clothing patterns recognition

In the process of gaining a better understanding of occupants and their thermal comfort needs, it seems a necessity to learn about their clothing preferences. This is a sensitive subject because it requires access to data that might be considered private. Scientists addressing this topic use, most of the time, the RGB camera for recognition, with a sustained use of the conventional neural network [49]. This approach is still in development, but it delivers promising results. It requires access to a direct video stream, which may be a sensitive subject to most of the private apartment users. Additionally, such an approach has a small database. It should be noted as well that most published papers regarding clothing detection describe experiments conducted outside, where privacy issues are less rigorous.

Use of the depth registration technique and depth registration camera as well as the SM model are competitively advantageous to the RGB camera and avoid the problematic issues related to the privacy of participants. Access to the SM may be overlaid with colour video. These points become locations for colour probing. This approach requires temporary access to the RGB recording, but after the data are probed, all the recorded video data is deleted. The only stored data are probed colour values from their corresponding joint of the SM. In this approach, the most valuable data in regard to defining occupants — the clothing factor — is captured, and without obtaining access to the whole picture. The first trial using this approach has shown promising results [50].

Whether the extension of numbers of probing points has any impact on detection accuracy requires testing. Additionally, the method used in Ref. [50] was capable of identifying clothing patterns without the use of machine learning. In that study, only one-pixel from each SM location was used. It seems that turning to the machine learning technique in this part of the measurements is inevitable. The primary challenge in this next step is access to the necessary database that can be used for training of the model. Such a database can be developed with the use of code that can explore clothing producers' webpages and probe colour information from pictures of models wearing different clothing in the same fashion as SM. It can collect information on the existing metadata, such as the type of fabric or the type of garments.

2.8. Activity level measurement

Access to a complete set of movement recordings makes available an analysis of their typical activity level. Proper data processing can show occupants' movement frequency and their usual movement velocity regime. With access to data representing movement of all of the limbs, it is possible to directly estimate the amount of energy that is required to perform a given action. It is an approximate estimation, but it allows developing an activity profile of each separate occupant. Because occupants' activities are recorded only within the registration area, the collected recordings will show short samples of movement unless the monitored persons are highly active in the data sampling zone. Despite this downside, identification of different zone features allows direct estimation of the heat generated in such a zone. The point of reference for each zone can be collected from previously established tables [51] [52]. The previously conducted studies show that this way of approximation of activity delivers a valuable input for interpretation of occupant activities [53]. It not only shows how the activity level fluctuates over time but also shows how such an approach can provide grounds for forecasting heat gains.

This part of measurements has to be treated as supportive due to its current level of development. A series of measurements has to be conducted for measuring all types of zones in different scenarios. This type of measurement would show movement and activity as a process that can be done inside a specific zone, such as cooking or doing laundry. This approach will allow forecasting activities outside measurement zones, based on an occupant's location at which they exited the monitoring zone and the time spent outside it. This estimation will work as a hybrid of the survival model, where the time spent will be determined as a metadata activity that can later be represented as a heat value of the activity. The estimation of heat generated by occupants inside any kind of space is dependent on space "opportunities" to the activities. A set of possible interactions is limited to the appliance located in an observed zone. It means that any kind of activity has its termination period that can be acquired, and later it can be treated as a compound for generating survival models.

2.9. Data security

The collected data via the use of the depth registration camera can be considered as fragile. Each data package holds information that could be potentially used against monitored occupants. To prevent such an event, an encryption of collected data was deployed. Each time the data package was gathered, before transferring it from temporary memory, all data was encrypted and secured with a fixed password. Due to the recording of security reasons, this part of the algorithm was not included in this paper.

2.10. Case descriptions

The current approach to data collection and processing is focused on passive, non-invasive data collection. The primary goal is to explore the obtained data afterwards, during the post-processing period. The depth registration technique has the potential to become the common measurement device delivering dynamic feedback, based on its records. It is a new approach to measurement of occupants' behaviour inside buildings, and therefore this way of measuring activity has to be tested in various cases to reach a dynamic feedback level.

During this study, two cases were investigated. The first case was focusing on general monitoring of the whole apartment. In that case, one camera was sufficient to cover the whole transportation artery existing in the apartment. The transportation artery is a space in the apartment that is used only for transition between different rooms or zones. This case study was conducted in a private apartment occupied by two adult persons. The second study was focusing on the description of one local zone. In that case, it was the kitchen during pre-holiday preparations. In this study, only one camera was used as well. During that period, the monitored zone was used extensively. There was a certain period at that time when the kitchen held up to six users

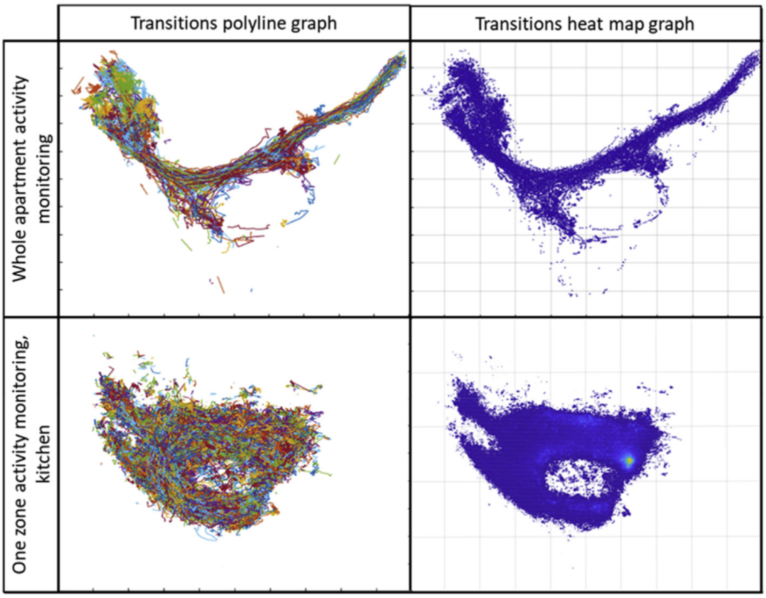

Fig. 6. Results overview. All of the graphs are plotted on a projection of the observed apartment floor surface. Both of the axes are in the range from 0 m to 5 m.

simultaneously. Both studies were conducted within a trial period of 24 h of monitoring.

3. Results

The monitored movement data is displayed in the form of plots (Fig. 6) in two fashions; each transition is represented by a polyline and a general heat map of activity. Each polyline represents one signal event of the registered movement. The colouring of the heat map was dependent on a frequency of the place usage. The colour map of the heat map was set on an automatically linear colour distribution.

4. Discussion

Access to occupant's movement data in real-time scenarios is a valuable asset for future development of new buildings and validation of the existing occupancy models. The passive system of monitoring their behaviour shows their usual, natural way of using the space. Traced pathways can be used as a basis to understand how monitored occupants use their space and what kinds of functionalities are delivered from it. Additionally, with access to the scanning capabilities of the devices, it is possible to measure the monitored zone dimension. Combined with a drawing of the whole layout, it is possible to estimate furniture placement and their functionalities, such as the placement of a chair, table or drawers. Such information can be used as an additional asset while conducting advanced CFD studies.

Measurements carried out for a long period of time can provide a meaningful input to the development of an occupants' transition model. Once the amount of collected data allows describing space use habits, it seems possible to track occupants' expectations from the space and approximate their desires and needs. Such a tool will be made available if the amount of collected data reaches the level of statistical significance. Such data have an implication for energy use in a building because these data have the potential to define occupants' thermal comfort expectations and their acceptance regarding changing it. In addition, such data can provide information about occupants for developing strategies of controlling and adjusting indoor environment quality.

Based on the collected information about transitions in time and space, it is possible to link functionalities and appliances inside different zones without adding any input data, such as electricity consumption. For example, if occupants spend in one zone approximately 5 h out of 24 h, it is most likely to be a bedroom. An additional indication of location description can be supported by the detected occupancy/activity during the daytime. An auto description technique can be supported by developing a matrix of typical occupancy patterns in different rooms. Reaching that level of detection requires conducting a series of measurements that will confirm the accuracy of event descriptions. Data prepared in this way can be treated as a knowledge base that can be extended with each session of measurements.

5. Conclusion

Investigated measurement method delivers access to the new type of data. It can grant access to the new dimensions of analysis connected with energy-related occupant behaviour in buildings. This measurement technique grants access to the data describing:

Information from each of the modules can be obtained independently, or it can be collected as a bundle. Once the registration procedure is initialised, any captured information is enriched with a clock data. It allows to position collected information in chronological order. Time information is necessary to capture the dynamics of observed values, but it is essential for the calculation of the module number four. Without time information it would be impossible to estimate the metabolic rate value.

Output data from the described modules (Table 2) can be coupled with information of observed building/floor/zone to locate the position of used depth camera/s. Correct placement of the devices may increase the spectrum of potential obtained information. Once the information from modules (Table 2) is connected with output data from a typically used measurement device (thermometer, CO_2 sensor, electric meters, weather station, etc.), it is possible to increases the accuracy of the detection of occupants activities. Proposed measurement method should be threaded as a supportive means for describing energy-related

Table 2
Modules available with use of the depth registration technique.

NR	Module	Measured value	Output
1	Occupant position and their posture	Twenty five points in three dimensions [m]	Information about occupant distribution in the monitored area
2	Partial identification of observed human body	Specific body ratio readings [−]	Indirect identification of the observed occupant
3	Skin exposition to the environment	Sampling colour information from specific points of the video stream [R,G,B]	Estimation of the clothing insulation value $\left[\frac{Km^2}{W}\right]$
4	The activity level of each observed occupant	Differential state between positions of each corresponding body limb [m]	Estimation of the metabolic rate value $\left[\frac{W}{m^2}\right]$

Table 3
Case detection spectrum for evaluating occupant thermal expectations.

A	B	C	D	A	B	C	D	A	B	C	D
0	0	0	1	+	0	0	1	–	0	0	1
0	0	+	0	+	0	+	0	–	0	+	0
0	0	–	0	+	0	–	0	–	0	–	0
0	+	0	1	+	+	0	1	–	+	0	1
0	+	+	0	+	+	+	0	–	+	+	0
0	+	–	0	+	+	–	0	–	+	–	0
0	–	0	1	+	–	0	1	–	–	0	1
0	–	+	0	+	–	+	0	–	–	+	0
0	–	–	0	+	–	–	0	–	–	–	0

A - signal change from module three (skin exposition).
B - signal change from module four (activity level).
C - signal change from IEQ-related values.
D – dose the IEQ matches with expectations?.
A,B,C – no change (0), decrees of the value (−), increase of the value (+).
D – yes = 1, no = 0.

occupant behaviour. As a single source, it can deliver valuable output, but its usage can be extended while combining it with data of other origins.

Most basic description of occupant actions that can be obtained with a combination of all this outputs is an occupancy time and activity level. For example, if the device is placed in a zone that can be treated as a "distribution" corridor, it is possible to monitor the occupancy state beyond the direct monitoring spectrum. In the monitored zone, entrances will be highlighted as a start/end points of the movement. Monitored time differences and the module two output (Table 2), can be used to generate a profile of typically used zone/rooms by the specific occupant. Use of this method allows highlighting usage of monitored space. It could be a support for introducing thermal zoning of the monitored area. It can be achieved with an only data source from depth registration.

Developed profiles of the occupancy could be connected with information about used plug load. Combination of this information allows describing the activities of the monitored occupants. It is possible to detect periods of the day when occupants are performing activities such as preparing a meal (by usage of the kitchen appliances), appreciating leisure (low electricity consumption with low movement activity or watching TV) or sleeping (low electricity consumption during night time). All of this activities could be detected with use of the plug load analysis, but it will not be possible to detect who is conducting certain activities. Combination of the module one and two (Table 2) with a plug load allows to bound occupant with specific actions. If the monitoring of such activities is prolongated, it can be used to define occupant's habits.

Similar to the previous plug load analysis, it is possible to define what acceptable thermal conditions of indoor air are. Combination of the all introduced modules (Table 2) coupled with the information about indoor and outdoor thermal conditions allows defining occupants preferable thermal conditions. With the use of the modules three and four is possible to observe dynamically status of occupant clothing insulation and activity. Data from module three and four can be used for filtering. Coupling it with information of any adjustment that influences IEQ directly, allows detecting conditions where occupants are satisfied with the thermal environment. Records from module three and four can be segregated by the following principle: constant value (0), decrees of the value (−), increase of the value (+). The same filtering can be done with the general observation of adjustments of IEQ-related values. Each of three segregated outputs has three different states (-,0, +), that is why it is possible to detect a spectrum of 27 different cases ($3^3 = 27$) describing the interaction between occupant and indoor environment. Cases where each user had direct interaction with adjustments of IEQ-related values (like adjustment of the thermostat or opening a window), can be used as a marker that can imply that occupants are unsatisfied with IEQ. Marked regions can be treated as a bracket that binds data in a timeline for investigation of the preferable conditions that occupant are expecting. (Table 3).

Each time the thermal conditions are not reached it is possible to trace back the history of previous set points and check what kind of indoor thermal parameters were set. It is possible to investigate how long such conditions last without adjustment of the thermal state of the indoor air. Also, it will be possible to examine if "preferable" conditions are matching or not. Bundle of this information can generate a profile of what kind of desirable thermal conditions observed occupant has.

Amount of possible information that can be collected with use of the depth registration technique is noteworthy. According to the given examples, it is possible to claim that continuation of the energy-related occupant behaviour study with use of this registration technique will enrich the understanding of occupant thermal expectation in buildings.

Acknowledgements

The data collection and storage method do not allow identifying the participants of the study. Therefore, this study does not require certification by an ethics board. The authors declare that they have no conflict of interest. For this type of study, formal consent was verbally delivered by the participants of the study. The authors do not endorse any specific brand or device developer. The study has not been sponsored or influenced in any other manner by private companies.

The computer setting for the measurement procedure was as follows: Intel® Core™ i7- 4785T with a CPU of 2.20 GHz: 16 GB DDR3 RAM; Intel HD Graphics 4600. Using a different setting of hardware for the measurement purpose may influence the sampling time. This publication does not seek to promote any specific product or brand.

The authors of this paper received funding from the EU-China "IRES-8" Mobility Project under EU Contract Number No ICI+/2014/347-910. The contents reflect only the author's view, and the European Union is not liable for any use that may be made of the information contained herein.

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Paper No.6 J. Dziedzic, D. Yan, V. Novakovic; Framework for a transient energy-related occupant behaviour agent-based model; REHVA 2019/5, 39-46. Conference Paper

Framework for a transient energy-related occupant behaviour agent-based model.

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Abstract. Simulation of occupant behaviour (OB) is a topic considered to be crucial for further advancement in building performance simulation (BPS). Previous (statistical and stochastic) approaches in attempting to re-create in-building human activities were not sufficient to capture subtle activity changes with significant influence on building energy performance. Development of an occupant behaviour agent-based model seems to be a promising direction because such an approach allows deploying a time-dependent, reactive model. The main purpose of the agent will be its presence in the simulated thermal environment and its ability to react once the thermal conditions are outside its established thermal comfort zone. Herein, the agent model has to provide a personification of its thermal comfort condition. To introduce such features for OB simulations in BPS, a new model framework was introduced. It will enable probing of the simulated state of thermal conditions and the "sensing" of it. If conditions are inside the required limits of thermal comfort, the agent will not react. Otherwise, if the state of the agent's thermal comfort crosses its threshold values, it will try to adjust its thermal conditions using local adjustment possibilities, e.g. simulated adjustment of the set-point. The fundamental input data for this agent model can be obtained by use of the depth registration camera for direct observation of occupants. Continued monitoring of occupant reactions in various thermal conditions will be a foundation for the development of the occupants' thermal profiles. Storage and compilation of such information will contribute to the detection of the parameters that are mandatory for the development of the transient energy-related occupant behaviour agent-based model.

1 Introduction

According to the newest International Energy Agency annual report, thirty per cent of the globally produced energy is consumed in buildings [1]. A vast portion of this resource is explicitly consumed to match up with the expectation of its users. For the past forty years, researchers have investigated demand and the way the users exhaust energy. During that time, the topic has become mature enough to be considered a separate branch of scientific field related to the understanding of building energy performance. One of the milestones in the field of occupant behaviour studies was a work presented by Fanger [2]. His work on the presented ideas and application proposition initialised the process of describing human interactions with the indoor environment. Still, due to the multidisciplinary nature of energy-related occupant behaviour studies, it is difficult to develop a model that could apply to any and all conditions. Similar obstacles appear when it comes to a simulation of the different types of buildings. Lack of accuracy in existing models was noticed and pointed out in the work of Turner et al. [3]. In this, a comparison was made of the energy consumption results from building energy performance simulation and consumption during operation time (after it was built). Comparison have shown that only 30% of investigated buildings consume a similar amount of energy. It is possible to conclude that one of the reasons for such a mismatch is caused by underrating occupant influence on building energy consumption. It seems that the current resolution of monitoring occupant activity is not sufficient to capture energy-meaningful phenomena. The basic description of the occupant as a system user has to be more comprehensive, and it should allow the inclusion of a broader spectrum of occupant/building interaction. Such a conclusion can be made after reviewing Yan et al. [4]. As put forward by Hong et al., ontology is the classification of occupants regarding their energy-related behaviours [5-6]. The approach they present segregates a particular occupant's actions with regard to common behaviours that have influence on building energy performance. Among these are switching on/off the lighting or adjusting windows blinds. Such studies are a step towards transient agent-based modelling wherein a single agent represents the behaviour of one person. However. to gain access to the more comprehensive overview of occupant's actions, it is a necessity to understand their demands and needs. As Wagner et al. notes, this can be done by way of statistical analysis of the group or occupancy state coupled with multi-sensing techniques [7]. Additionally, occupant-related studies

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should be supported by survey and interviews that allow a description of the personal preference of the particular person. The previously conducted work of Dziedzic et al. shows promising results regarding developing precision in indoor occupant profiling via depth registration camera [8]. A good example of the broad spectrum of data collections was shown in Jamrozik et al. [9]. Herein, collected observations of the human reactions to the thermal environment were enriched by inclusion of occupant socio-psychological data. With such a multidisciplinary approach, it is possible to track occupant motivation for chosen action. A precise socio-psychological description allows compilers to gather, cluster and detect trends among occupant personality. Hence, capturing data holistically regarding energy-related drivers can be used as an additional asset in the development of an action-driven model of occupant behaviour.

Gaetani et al. provide a selection of models that are “fit-to-purpose” in order to show the current developmental level of occupant behaviour modelling [10]. Based on the provided [10], it is possible to notice that most of the developed occupant behaviour models are focused on one or only a few particular issues regarding occupant behaviour. What is also notable is the lack of communication among the model developers and that this has brought about overlaps and absence of cross-modal communication. The idea of “fit-to-purpose” propagates understanding that each application has its optimum workflow resolution, and in the present, there is no solution for scalable applications regarding occupant behaviour modelling. Similar conclusions were drawn in a work of Bing et al. [11]. The main challenge related to occupant behaviour modelling, in general, is operational resolution. Occupant activity that could be considered as significant regarding energy use can be triggered by an event lasting only a few seconds, for example, a draft caused by the sudden opening of a closed door. Yet, exposure to a particular “incident” may have long-term implications, like adjustment of the thermostat. Capturing such phenomena requires a high observational resolution of occupant behaviour. Previously developed models were not capable of portraying such events, because their initial resolution was beyond the ability to capture such an event.

The main disadvantage of any available OB simulators is that all of the spectra of actions are driven by probability or stochastic process. This means that particular occupant activity has no relation to the particular order of performance. Thus, there is a possibility to develop a “story-driven” or “action-reaction” understanding of simulated actions. This has come about by the input data for which previous models were compiled. The origins of limitations within previously developed models were engendered by the resolution of the data that they developed. Current models are capable of performing well on simulations that involve a group of occupants, such as shared lunch, or general occupancy of a room. Unfortunately, trying to identify a reason, meaning or driver of connected actions at the individual scale is impossible from such simulation results. Therefore, the actions triggers are also unknown. To fulfil all of this uncertainties, it is necessary to re-develop occupant behaviour models so that it is possible to explore the reasoning for a particular action. To reach all of the expectation regarding model features, the need is to develop an agent-based model. Here, the simulated agent represents an occupant and it is equipped with an embedded complex behavioural engine capable of simulating reactions to the various conditions of the indoor environment.

The main aim of this paper is to highlight the core milestones of the model development process. Due to the complex structure of the proposed, developed solution, it is necessary to highlight potential outcomes and to open dialogue with the broader scientific community. The proposed framework of the model does not aim at the promotion of particular software or application. This work aims only to introduce to the wider audience, the possible structure for simulation of indoor occupant behaviours.

2 Framework

With regard to heating and cooling, to reach the collective expected requirement that allows generating a contextual response to the simulated actions, the simulated agent has to experience similar thermal conditions. In bringing this about, it is necessary to probe data drawn from the constantly changing physical properties of the indoor environment. This means that the model has to operate on transient indoor environment proprieties. This data can be acquired from a computational fluid dynamics (CFD) simulation or through a multi-zonal model. Because both of the simulation methods consume a significant amount of computational time (at least for now), it is recommended to perform a series of parametrical studies beforehand. As the simulated occupant behaviour relays on reaction to the on-going environment condition, if environmental and physical properties are pre-simulated and the transition between states kept in order, such properties will not have influence upon the occupant behaviour simulator. This implies that while the environmental conditions will influence the occupant behaviour simulator, the simulated agent will not have influence upon the environment and the conducted actions by the agent will do so. Because this approach is based upon assumed model features, this approach is referred to as the ‘building occupant transient agenda-based model’ (BOT-ABM). The purpose of the model is to simulate more realistically the usage of the various energy resources. The agent (i.e. the simulated occupant) is brought into being by a collection of modules that re-create the routine activity of the building users. Herein, each individual module is responsible for the simulation of one specific behavioural feature. Moreover, all of the used modules operate in the same temporal resolution, and the general model architecture is designed in a parallel structure. As the solving of one particular time step will require the calculation of each activated module, this will increase the calculation time of each

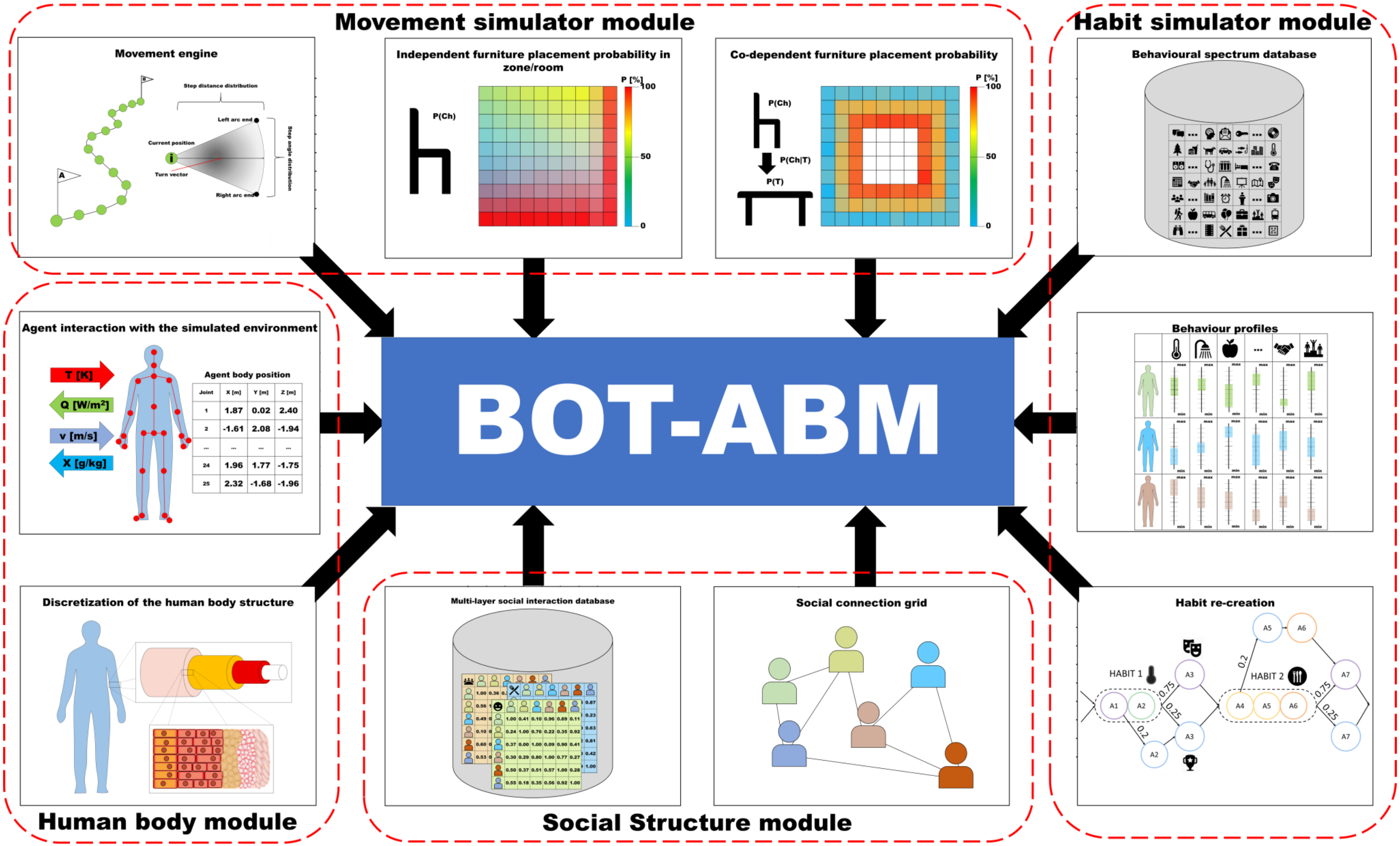

Fig. 1. Building occupant transient agent-based model

time step, but it will allow cross-communication between each of modules. Such a structure enables the development of co-depended scenarios where one particular phenomenon, such as spontaneous exposure to a cold draft, might generate a variety of BOT-ABM reactions. The general structure of this in the form of an information flow chart is presented in Figure 1. Individual module functionality will be briefly explained

3 Modules

3.1 Movement simulator module

One essential feature of occupant activity is the ability to move around. Nevertheless, this occupant behaviour feature is not explored enough with regard to applicability in building performance simulations. In doing so, however, the simulation of direct movement will require a radical incrementation of the time resolution, which, subsequently, will increase required computational power need.

In contrast, simulation of all the transitions allows a precisely described occupant exposure to the indoor environment. It green lights the gathering of data about the occupant position in time; therefore it allows implementing the module that simulates interaction with an indoor environment. The full probing of environmental data will be brought about through the collective response of individual models. This part of the model provides for discretised positioning and transition of the human body, in time.

The Movement engine module itself is solely responsible for simulating the natural transition between point A and B. It will operate through any defined polygon, but to re-create realistic usage of the building, it has to operate within a furnished layout. Once the floor layout is fully designed, the simulated agent actions will be relayed to general placement. Herein, the furniture setting will be used as a coordinate system for the agent movement. The agent will then perform the intended performance task, and will operate and interact with appliance in the same manner as would the building occupants. Data from such appliance usage could be collected via analyses of the plug load or through various Application Programming Interfaces (API). If the layout simulator is available, it will be possible to simulate the layout scenarios, to test various scenarios and to investigate which is producing the most energy efficient or most comfortable settings. Furthermore, it may allow testing how floor layout operational changes (like adding an extra, internal wall) may influence indoor air conditions.

Development of the layout generator has to be paired with the development of an extensive library of appliances and furniture designed for this purpose. This dataset has to hold information about appliance dimensions, heat map localisation (probability of the placement on a floor layout), potential activities that it may be used for and the zone wherein it is possible to interact within. All of these features are important for precise simulation of the building occupant activity. Appliance dimensions (Length, Height, Depth) and heat map localisation will be used for appliance placement in a simulated layout, and for development of the geometry for final operational air volume. If the study is aiming at a parametrical analysis, the heat map localisation feature will not be used. The list of potential occupant activities will be employed to enable a description of the appliance/furniture purpose, as well as to support the habit simulator and the physical environment sensing module. If the agent has to initialise an action, for example: prepare a meal, there are only a few appliance s that can support the execution of this task. The agent will be instructed to select one of the given options and fulfil the given “task/need”. Once the procedure of appliance selection is done, the agent will find a pathway from its current position to the aimed goal which is the space/area where is possible to for interact to occur.

3.2 Habit simulator module

The purpose of the habit simulator module is to trigger activity. This module will cover most of the essential description of agent personalities and their way of utilizing the space. Description of agent habits will cover a wide range of activities connected with maintaining a portrait of occupant routine and of related activities. Additionally, it will try to include a possible spectrum of irregular activities that are non-explainable or could be considerate as unreasonable. This module will be designed to operate within three separate layers: Behavioural Spectrum, Behaviour Profiles and Habit Re-creation.

The first layer (Behavioural spectrum database) will be used as general database source-set of potential activities. This database will deliver operational space for a selection of various behaviours. Thus, it serves as a pool of possible outcomes that can be triggered by any given condition at a particular moment. The spectrum and source of triggers may vary. These depend on the given situation – whether a sudden change of conditions or scheduled activity or simulated “loss of interest”. The more extensive that this library of activities is, the greater the potential exists to simulate more sophisticated activity. This can be analysed later on so as to improve performance. Every time a simulated action is triggered, it is recorded on a simulation timeline. This activity allows for developing an understanding of the context of each conducted activity. Therefore, it will be possible to analyse simulated occupant behaviour by way of a story-driven method. Such an approach will allow investigating building design that includes sensibility analysis of the potential group of building users, and, hence, an estimate of the potential energy demand that the group may require.

Second layer (Behaviour profiles) will focus on an individualization of the activity, by generating an individual behaviour profile description. Each particular activity has to be described by the following features: the conditions that triggers it, the spectrum object or tool that it has too interact with, the time that is consumed in conducting it, the mechanisms that must be operated, and the gain achieved. All activities have to be segregated into two sub-categories, cumulative sum-based or threshold-based. The functionality of the activities that are cumulative sum-based rely on the fulfilment of the task. Each utilized time unit of the selected task performance increases the cumulative sum. In contrast, threshold-based activities are triggered if the threshold of acceptance of the simulated conditions is crossed. Both of this actions trigger engines that control agent performance. Attributes can be defined by the selected trigger engine and described by its operation values. For example, the simulation may test appropriate occupant reaction on a spectrum of indoor air thermal conditions. If the simulated occupant is “sensing” that the indoor environment is beyond its thermal acceptance level, it will react. Its action will aim at a return to the "comfort" state. To do so, it will have a spectrum of potential actions that will provide a return to the acceptance level of a given condition. To avoid infinite feedback loop, each conducted activity will have a “death band” functionality. Therefore, the simulated agent will be described with a certain acceptance reaction latency.

The simulated behaviour of the agents will require behavioural specification. Each agent has to be described by the constraining values of their “personal” preference with regard to the global “character” description. This part of agent description will be held by the behavioural profile layer (second layer). Here, selection of the “basic” human needs and desires can be transferred from the field of anthropology, wherein the study of human behaviour modelling is a scientific pursuit. Through accessing this branch of natural science, it will be possible to define the fundamental features of occupant needs. The most applicable model that fits into the proposed model structure is that suggested by A.H. Maslow [12]. Pyramidal structure describing Hierarchy of Needs can be used as a template and be explored in terms of its applicability in building performance simulations. The selection of appropriate behavioural (anthropological) model and its modification, however, will not be elaborated upon in this paper. Whatever the anthropological model selected/modified for BOT-ABM performance purposes, all of the features included in the description of occupant profile must be transferred to the Behavioural Spectrum layer of the habit simulator. This procedure will allow for direct communication between all of the layers included in this module.

The third layer (Habit re-creation) of this module will be responsible for a re-creation of occupant habit and daily routine. By way of applying this part of the module, it is possible to simulate a task that can be considered as mandatory, such as going to work or school. Proper usage of this layer will allow to control agent health maintenance and the strategies that are triggered by occupant activities related to hygiene and healthcare. It must be noted that each individual has a routine – a daily rhythm and way of organizing daily activity. The order of the actions taken depends on various conditions like lifestyle, personality or employment. No matter what kind of routine each person follows, the day timeframe limits the amount of actions that person conducts per day. This means that pinpointing this on a timeline and limiting its duration can describe daily activity.

Additionally, as habits are desires expressed through a series of actions, each conducted activity can be considered as being a derivative of habit and routine. The module that is responsible for the re-creation of occupant habit, can be looked upon as a binder for a series of actions. Additionally, as the order in which particular activities are followed plays an important role, this part of the module will hold “recipe” information about each habit. However, BOT-ABM will be designed to follow habit protocols as long as its basic demands, described in the previous layer (Behaviour Profile), are balanced. This layer of the module will keep the agent following a daily routine without pointless wondering in uploaded space, zone or floor layout. It will also allow for tracking the overall understanding of the agent’s action purpose.

In attempting habit and routine simulation, there is a vast range of activities that cannot be considered routine or habit. Because their nature is unpredictable, as pointed out by Strengers, there are specific actions that cannot be directly explained [13]. Irregular occupant behaviour is defined as an act wherein the occupant consciously or unconsciously performs an action that does not fit in order or/and timeline of any routine. That is why the core description of conducted actions order cannot be completely fixed - it has to hold space for potential irregularity. To do so, all of the daily routines have to be described via a probability factor. This function is responsible for the scoring of the action inside one routine, regarding holding its order and timeline coherency. The higher the value of this probability factor, the larger the probability of habit re-creation inside the simulation.

3.3 Social Structure module

To re-create building occupant behaviour, it is necessary to include their interaction with other occupants. No matter what kind of building is being simulated, the existence of the social grid inside it cannot be by-passed. Indeed, its magnitude can be only forgotten if the designed space of investigation concerns one individual. In the other cases, the way occupants interact with each other has to be included in the simulation. This module will hold information about the social connection between agents, and it will be responsible for assessing the degree of potential collaboration between each in various tasks/routines. Here, selection of assignment has to rely on a hierarchy of relationship structures inside the simulated space. It also has to allow for agent collaboration, as well as following the grading system of simulation. Of note, the simulation of occupant social network also depends on building purpose. If the simulation targets a residential building, the social connection must consider family structure.

The data about the social network in the observation space can be captured by way of the use of mobile telephone data streams. As shown by Ren, Ye. et al., this makes it possible to obtain information that allows for re-creating the social communication structure of the monitored occupants [14]. However, a combination of various measurement methods may allow developing a better general understanding of social connections in different types of buildings. Once such a knowledge base is obtained, it may be used automatically to allocate specific social networks to the appropriate buildings. Until then, this has to be done via the use of pre-defended networks and application of hierarchy.

3.4 Human body module

This module is responsible for the positioning of the human body inside the simulation environment. Here, a general projection of the human body can be used to probe data from a selected body part or point of the body. This feature can be used to calculate the radiant temperature of investigated body limb/area or the general exposition to airflow streams. The limitations of the probing depend upon the used simulation environment and the embedded equations. The higher the resolution of the indoor environment simulation, the more detailed the study. To simulate human body reaction, it is also necessary to investigate the kind of processes that are happening inside the body. An excellent example of a model that could be used for this purposes is that proposed by D. Wölki, wherein the human body is divided into nineteen parts, each part being composed of a few layers of the human tissue structure [15]. This approach shows promising results, but it has to be improved in terms of simulation of the tissue composition. The current state-of-the art is that this model assumes uniform tissue distribution. To simplify modelling, uniform tissue distribution can be considered a good approximation, but for detailed study, such an assumption might be crucial. To provide a proper response to the habit simulator, the delivered input information has to be accurate in order to prevent agent misinterpretation. Hence, the more recent MORPHEUS model must be explored and assessed for simulation competence [15].
Besides sensing the environment, this module will be responsible for delivering information about agent activity level, clothing level and the related. Such information is crucial for the proper simulation of the energy-related occupant behaviour in buildings. Knowledge about activity level will support indoor environmental simulation by delivering data dynamics of energy relesed by the human body to the investigated space. Additionally, it will be a marker for a proper re-creation of the pendular movement of agent body parts. Simulation of the clothing will be embedded in the same way. It will provide an overview of skin exposure to the indoor environment, but it will also be charged by the response system from the habit simulator module.

3.5 Information exchange and modules hierarchy

Access to all of the features that are provided thru each separate module requires an understandable architecture of information flow. Without a specific order of hierarchy, a collaboration between modules might produce a chaotic representation of the actions without meaning. Centralised structure of the BOT-ABM allows for modular applicability of the whole model, but whole information exchange is via its centralised mainframe. It can be considered as a historical database of the particular agent.
In presented BOT-ABM structure, two modules (Movement simulator and Human body) are responsible for direct interaction with a physical environment. Therefore, these modules are not producing a "decision" impulse for conducting a task by the agent. Both of these modules operate on two-way communication with a BOT-ABM mainframe, but each of these modules has a low position in a decision hierarchy.
Other two modules are responsible for taking care of socio-psychological side of the occupant behaviour. The proposed model structure is aiming at a simulation of the individual occupant behaviour. Therefore, Habit simulator module will play a critical role in a decision hierarchy. This modules are not responsible for the probing of the data from the environment. They accumulates the collected information from the other modules, uses it as an input and process it with a defined personal trades. Generated output distributes information of an adequate response to the other modules.
Hierarchical position of the social structure module is hard to pinpoint directly. It might have a significant influence on a Habit and Movement simulator modules. It is also used as an information exchange port with other agents, which allows for a mutual collaboration of numerous agents while keeping their individual trades. Because the main aim of the BOT-ABM is to simulate individual occupant behaviours, Social Structure module has the lowest hierarchical position.

4 Discussion

The presented paper provides a brief overview of the occupant behaviour simulator that potentially can be used in ~~a~~BPS. The proposed solution operates upon four different modules - each responsible for one facet of human activity. The main aim of this model is to re-create inside building occupant behaviour. Due to the diverse operating resolutions of human beings and building structures, it is difficult to assume what kind of time resolution is optimal for simulation purposes. From the perspective of the building user, a one-minute resolution could be considered too shallow for portraying their behaviour correctly. On the other hand, same resolution can be considered as too detailed if the perspective is set as annual building operation. Therefore, it is difficult to decide what kind of time discretisation should be acceptable to portray events that could be considered as important from the perspective of the building user. Still, no matter what kind of operational resolution will be selected, the proposed structure allows exploring occupant behaviour phenomena through a multi-disciplinary approach.

Social structure can equally influence building user behaviour as does the sensation of thermal comfort. Therefore, the impact of this attribute cannot be ignored, but there are no available tools that allow for a numerical investigation of such. To by-pass, this issue, the proposed framework introduces a modular model structure that allows for non-invasive editing of the general model. This means that selected parts of the module can be modified, and the general compiler of the whole model will still be able to operate and communicate with the rest of the modules. Such model flexibility allows for a parametrical study of the many variables that must be included in any model. For example, it will allow for an investigation of the impact of the various social networks on energy usage inside a simulated zone/building. The same portion of study examples can be drawn via modification of the other modules.

5 Concussions

This paper is an introduction to the core design of the Building Occupant Transient Agent-Based Model (BOT-ABM). The prescribed format of the paper does not, however, allow for an in-depth introduction of each module functionality, but it is crucial for outlining the most critical features of the model within the overall framework. Therefore, development of such vast human behaviour model requires a multi-disciplinary team and proper feedback from future users. Development of a comprehensive model that capture advance functionalities of building users requires a lot of effort and long-term commitment. Therefore, it is necessary to rely on an existing framework. Presented framework is an effect of the extensive review of existing energy-related occupant behaviour modelling methods. Summarised modelling approaches delivered by Dong et al.[11] and Da et al.[4] allowed to highlight missing pieces in OB modelling and address them. Formulation of this framework can be considered as a result of this investigation which is presented in this paper.

Similar efforts in the formulation of building agent-based model could have been conducted in the past, but there are no records in the available literature. Reasons for such absence is unknown, but it might be suspected that it was caused by problem complexity and lack of proper data. No matter what was the reason, publication of framework proposal will open a new platform to scientific communication and discussion which eventually will lead to the new occupant behaviour model.

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Paper No.7	J. Dziedzic, M. Annaqeeb, D. Yan, V. Novakovic; Zone layout simulator for energy-related occupant behaviour modelling; Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019), 2020 Conference Paper

Zone layout simulator for energy-related occupant behaviour modelling

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Keywords: Occupant behaviour; Building performance simulator, Habit simulator

ABSTRACT

Today's world has placed emphasis on establishing or developing technologies aimed towards improving building energy efficiency. According to the recent International Energy Agency report [(15)], around 30% of all energy is used by the building sector. Hence, reducing energy use from this sector has significant ramifications. Besides investing in new solutions to enhance energy efficiency, focus must be placed upon fit-to-purpose design. Providing appropriate indoor conditions that ensure thermal satisfaction among building users can reduce building energy usage. This is best established in the early stage of building development and not as remediation. Currently, there are no available tools to examine the dynamic sensation of the indoor environment, and how potential building indoor layout might influence this parameter. Hence, we have begun the development of a tool that can support designers within this task.

INTRODUCTION

Introduction of the building information modelling (BIM) led to a simplified procedure of building design [(3),(4)]. Use of this software environment enabled a parallel collaboration of all of the parties involved in the design process. It provided an important asset for simulation of building energy performance. During this process, parameters like potential thermal loads, weather conditions, thermal comfort and other, are assumed to calculate building energy use. This method proves its usability, but has to be considered as a brief estimation. Studies conducted by Turner et al.[(5)] and Dong et al.[(2)], show that around 30% of all, investigated buildings match their simulated energy performance compared with measured value during commissioning. The reason for low accuracy is the oversimplified description of occupant behaviour [(7)].

Energy-related occupant behaviour has a major impact on energy use in buildings. Sonderegger [(12)] found that 71% of the energy demand variation in residential buildings is unexplained by conventional factors such as floor area, wall area, the number of bedrooms, the area of insulated glass, etc. According to Sonderegger, the most influential factor is occupant behaviour. Seryak and Sonderegger. In his study, occupant behaviour was found to affect energy consumption by as much as 100% [(8)].

Simulation of occupant behaviour during the building design phase is a challenging task, and current state-of art allows for only a partial re-creation of occupant energy-related actions. In practice, occupant activity is simulated with the use of the several numerical models. All of the models are connected under one building performance simulation (BPS) software platform[6][14]. Most of the used models describe occupant activities with a building-centric perspective. This has come about by applying a mere statistical generalisation of occupant activity. This approach is justified if the simulation goal is a brief overview of the building energy performance. However, the main disadvantage connected with such simplification is the average reliability of gained results [13].

Precise outcomes from BPS can be obtained if the models used during simulations are more occupant-centric. This can be achieved through applying an environment sensing agent-based model [16]. In this approach, the "occupant" is exposed to given indoor air conditions and eacts according to the applied rules. The main operating driver, responsible for agent behaviour is a description of the activities or habits of the potential occupant. When obeying standard protocols, this approach provides an additional thermal comfort layer inside the total simulation. This part of the model is, hence, responsible for describing thermal preferences of the simulated occupant. It will probe data from the surrounding environment and overwrite an actions protocol once the thermal comfort values are crossed beyond the acceptable level. The activity driver can be simulated via Dziedzic and Novakovic's proposed agent-based movement simulator [10], but this method requires the existence of a coordinate system that the agent might explore, thus it is more remedial. Data about occupant actions can also be collected via various, holistic measurement methods [1],[9]. It is even possible to detect this through order of particular electrical device usage (therefore, by way of cumulative electrical power records)[11]. Still, the issue of the positioning of features that the agent can interact is not addressed.

To reach that goal it is necessary to obtain information about the placement of furniture and household devices. This information will allow more precise simulation of occupant positions and interactions with surrounding infrastructure. A manual set up of these features is time-consuming and will extend the period of the design phase. Hence, we are developing a zone layout simulator that will be capable of delivering placement information. Such simulation can be achieved with the use of the procedural protocol of layout design. This approach allows for precise occupant behaviour simulations through access to metadata about the reasons of conducted action. The foundation of the zone layout simulator is thus built upon a batch date form and real measurements.

Due to the early stage of development, we focused on one zone that each residential building acquires. For the purpose of this study, we elected to simulate the kitchen layout. Herein, collection of the information about kitchen device and furniture placement requires access to an extensive database that includes precise description of these features. However, this paper will not focus on the development of such a database; rather, it will explore the possibility of simulating a residential house kitchen with a pre-assumed set of equipment.

METHODS

Survey

Each developed numerical model and/or simulator has to rely on data captured during measurement trials. Due to the novelty of this simulator, there are no data repositories holding information about device and furniture placement. Access to such information, however, can be obtained by conducting a series of anonymous surveys. Unfortunately, no currently commissioned survey engine that allowed online access, proved to be a convenient tool for allowing collection of the spatial data. Therefore, we designed a survey that was to be distributed via the classical, paper form. As the main goal of the survey was aimed at collecting spatial data, we had to develop a method allowing for efficient quantization of the collected input. The whole survey was thus divided into two main parts: to indentify appliance importance, and to draw the zone layout.

In the first step of the survey, the participants were introduced to a list of selected kitchen-based devices. They were then asked to select the appliances that they have installed in their kitchen. Subsequently, each selected device was labelled by importance. The only limitation in this part of the survey was that each device has to be described by one unique number. Defining devices in this manner allowed for the selection of the most crucial features of a particular zone, and to highlight the devices that can be considered as only peripheral in this zone. After the corresponding numbers described all of the selected devices, the same numbering was used in the second part of the survey.

During the second part of the survey, the participants were introduced to the drawing that would be used later for describing the zone layout (Fig.1). This consisted of three separate features: a blank rectangular area, a rectangular dashed area and a circle with a centred letter "N", next to the whole drawing. The first task that participants were asked to perform was to draw an arrow in the circle area, to show the kitchen façade's direction to north. This step was crucial for the unification of collected device localization input. Therefore, re-calculation of a building's positioning was necessary for the proper merging of the data. The next step required selection of zone shape (from a list) and the delivering of an approximated value of the zone size. If the shape of the zone was different then square, participants were asked to draw "x" signs inside the rectangle in order to deliver the proportional shape of the zone (Figure 1). If there were any other obstacles inside the zone such as columns or shafts, these were to be included.

After this procedure, each participant was asked to place the position of the windows and doors. Once all basic zone features were positioned, each participant was asked to place corresponding numbers of the devices (from the first part of the survey), inside blank rectangles. If the zone was relatively small, and the device large, such devices could occupy more than just one blank rectangle. Additionally, if two devices occupied the same spot (like an oven and a hob or a freezer/refrigerator), both could be labelled in the same blank rectangle. Once all of the devices selected in the first part of the survey were placed in the drawing, the survey was completed (Figure 1).

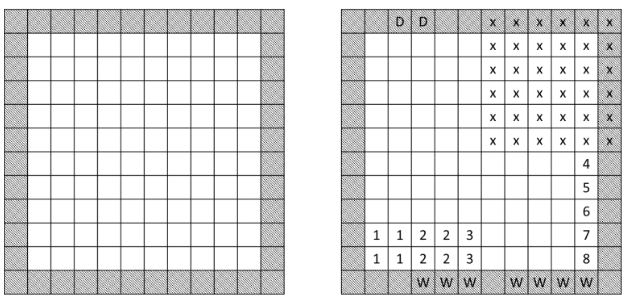

Figure 1. Empty layout matrix (left), Filled in example (right)

Processing of the survey results.
Data about device placement is harvested directly from the survey drawings. The fundamental drawing that was used for this survey purpose can be considered to be a form of matrix positioning wherein the entire package of collected data is stored in an 11-by-11 matrix. Although operating in the limited format of a two-dimensional matrix, each cell can be described via the use of (i,j) coordinates, where i is the number of the selected row, and j is the value it represents.

Development of a probabilistic map for each device requires careful processing to deliver accurate results. The first step is to digitalize all of the surveys. Digitalization of the north direction was discretised into a 45º resolution step. This means that whole survey can deliver up to eight different directions (0º, 45º, 90º, 135º, 180º, 225º, 270º, 315º) where 0 value represents north, and the subsequent turns are made in a clockwise direction. Each non-zero angel matrix has to be re-calculated in a flowing principle: the value of the cell has to be transferred accordingly to the mapped position with the rotated matrix. A simplified version of a cell mapping is displayed in Figure 2. Once all of the collected data was transformed geospatially with reference to True North, all of the collected survey results can be sorted and accumulated.

0˚			
11	12	13	14
21	22	23	24
31	32	33	34
41	42	43	44

45˚			
31	21	11	12
41	32	22	13
42	33	23	14
43	44	34	24

90˚			
41	31	21	11
42	32	22	12
43	33	23	13
44	34	24	14

135˚			
43	42	41	31
44	33	32	21
34	23	22	11
24	14	13	12

180˚			
44	43	42	41
34	33	32	31
24	23	22	21
14	13	12	11

215˚			
24	34	44	43
14	23	33	42
13	33	32	41
12	11	21	31

270˚			
14	24	34	44
13	23	33	43
12	22	32	42
11	21	31	41

315˚			
12	13	14	24
11	22	23	34
21	32	33	44
31	41	42	43

Figure 2. Mapped zone direction turn, 0˚ turns is used as a reference.

Due to the amount of collected survey data, a summarized placement of each included device was used to form the placement heat map. Development of the heat map begins with an assumed empty, rectangular zero matrix with the size the same as the data collection matrix. Every time a device is placed in a particular matrix cell, the heat map matrix of this device receives an added value within the same place. The combination of all collected inputs from the survey adds up into a device heat map. Still, the extraction of the data for the simulation purposes requires further sorting. Placement of the devices follows a particular schema. Therefore, individual devices are placed in similar positions. In a developed heat map, the greatest value number inside the cell highlights it and places it within a placement class. Each class is a label representing heat map value. The position of all cells that have value in it equal or greater than a class number are included in this class set. Segregation of the cells locations is essential for later steps in the simulation procedure.

The data collected during the first part of the survey was selected by the participants, and the devices included in their kitchens play an important role in the device placement solver. Aggregated in this manner, this experiment data allowed the formulation of an engine for the selection of the device order, but automatic placement of the devices has to be conducted with a specific order. If the device placement is conducted simultaneously, it might select the same place twice. The order of selected devices provided through the survey will be used to train the selection model. Results from this part of the survey are displayed in Table 1.

Table 1. Survey results; Importance number for each device

Device\ Importance number	1	2	3	4	5	6	7	8	9	10	11	12
Fridge	22	10	3	2	1	0	0	0	0	0	0	0
Freezer	5	2	4	5	1	3	2	0	2	1	0	0
Cooker	4	13	5	2	0	1	0	0	0	0	0	0
Built-in oven	1	5	5	2	3	0	2	1	1	0	0	0
Hob	7	6	1	1	0	1	0	0	0	0	0	0
Microwave	0	0	1	2	3	3	7	2	1	2	1	0
Espresso Machine	0	0	0	0	2	2	2	1	0	0	0	1
Kettle	2	0	0	1	4	6	5	6	3	1	0	0
Toaster	0	0	0	0	0	0	1	6	2	4	3	0
Blender	0	0	0	2	1	5	3	4	5	2	1	0
Exhaust	1	2	2	8	9	5	5	2	1	0	0	0
Sink	3	4	14	3	2	3	3	1	1	0	0	0
Dishwasher	0	1	3	8	8	3	1	6	0	0	0	0
Washing Machine	0	1	0	0	1	0	0	3	0	0	0	0
Tumble Dryer	0	0	0	1	1	0	0	0	0	0	0	0
TV	1	0	0	0	0	1	0	0	0	0	0	0
Radio	0	0	0	1	2	1	1	2	6	3	2	0
Other	0	0	0	0	0	0	1	0	1	2	0	0

Principals of simulation

The simulation is broken down into several stages: selection of the zone size, selection of the shape, placement of windows, door/s and additional external walls (if necessary), selection of the number of devices that will be positioned, placement of the devices and furniture. The first three stages are dependent on the time within the design stage wherein the simulator is used. If these parameters are available, then these have to be incorporated into the initial stage of the simulation. The number of devices to be located within the simulation is summarized throughout the survey, and this summary can then be used as a selector engine for the number of devices that have to be placed in one simulation run.

Once the number of devices included in a simulation is fixed, the simulation progresses to the next step. Here, utilizing the device importance matrix (Tab. 1), the simulator engine starts to select which device should be placed first, second, and so on. Device selection forms the first column, and selection progresses until the number of chosen items is not greater than the column index. Values in one column are summed up, and then each value is divided by the sum of the column vector to calculate its percentages. Each non-zero value is transferred to form a uniformly distributed piece-wise cumulative distribution. Ranges of each step correspond to the included distribution formulation percentages. Once the distribution is developed, a random number is generated, and it is used to assess which range of distribution holds generated value. This allows choosing the column row and, hence, selecting a particular device to be placed in a simulated zone. At the same time, the solver multiplies all of the rows in the entire matrix by zero in order to prevent picking up the same device once again.

Once a device is selected, the simulator accesses its segregated values from the placement heat map. To localize the proper cell, this part of the simulation is divided into two parts. Firstly, it randomly selects the class of the position that was formulated before. One the class is selected randomly; the selector engine then selects the row with cell coordinates. If the cell is already occupied by another feature/device or obstacle, it repeats the whole two-step procedure once again, until it positions the device. After the device is placed, it repeats the entire procedure, starting with the subsequent column in the importance matrix. Once the value of the column is greater than the selected amount of placed devices, the simulator finishes the placement procedure. The last step before the whole zone is created is a check of the value of the modelled zone turn. If this returns to True North, then the simulation stops immediately. If not, then the whole generated layout has to be transferred by way of the mapped turn matrix. The complete simulation process flow is displayed in Figure 3.

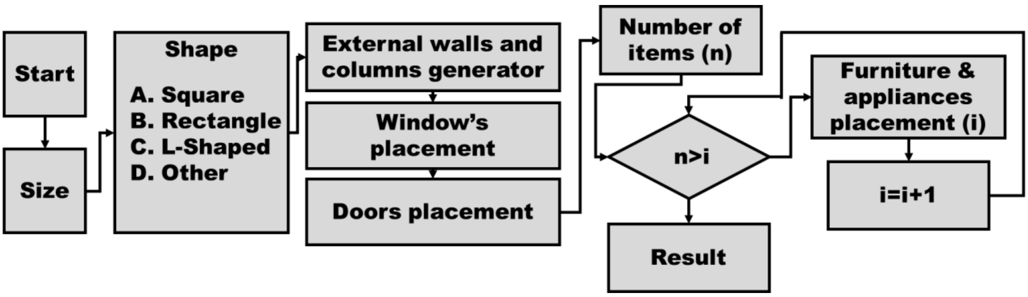

Figure 3 Flow chart of zone layout simulator

RESULTS

Due to the randomised nature of the simulator, it is possible to show only a potential solution. This then must be tested. Therefore, the publishing of a setup example has its value because it can be used for testing the grounds for a heating, ventilation and air conditioning (HVAC) solution. Additionally, if the given scenario does not provide an applicable solution; it can be used to generate a "blacklist" of scenarios that should be avoided. A simulation run is exemplified in Figure 4.

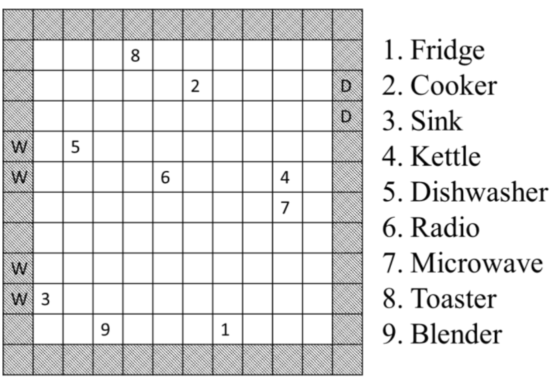

Figure 4. Example of the simulator results

As displaying all of the collected results of device heat maps would require much space to make it readable. It was decided to show the four most selected devices and their zone placement heat maps. (Figure 5)

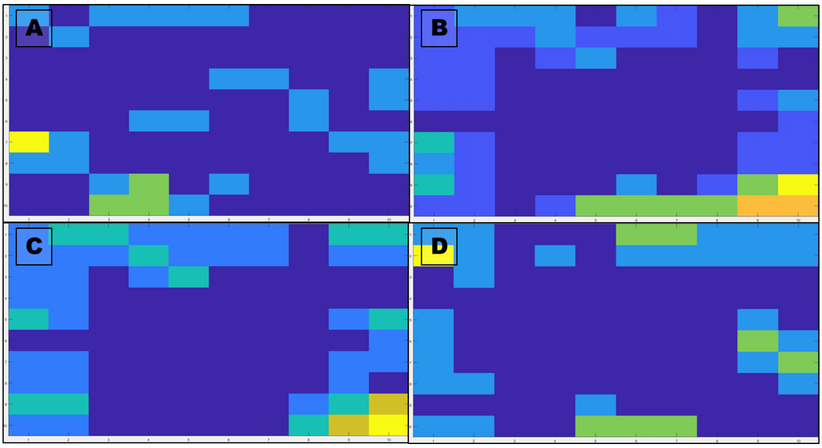

Figure 5Probabilistic heat map of placement of: hob (A) fridge (B), freezer(C), built-in oven (D)

DISCUSSION

The developed simulator is a first step towards building an occupant transient agent-based model [ref]. Such a model would allow for dynamic testing layout scenarios. With the use of the simulated agent, it is possible to monitor exposure to the indoor environment and investigate space for potential improvement. Moreover, when applied during the design phase, such a tool could potentially be used for accessing office layout scenarios if required initial data allows doing so. In conditions where building owners are sub-renting space, there is not much space for radical improvement of the HVAC system. Herein, the office rental agency defines its layout category (for example open-office), and then orders the interior design from a designing company. Prior to the development of this tool, simulations in terms of layout influence on users' thermal comfort were not available. Therefore, it was unknown how thermal sensation could potentially influence productivity. Investigation of this phenomenon could be the next step towards realisable, energy efficient building design.

In the future development of this tool, there are few issues that have to be investigated. This version of the simulator does not include interaction between device selections. Furthermore, the relationship between placements was not yet investigated. Therefore, to make such a tool more accurate for application in formulating layout scenarios, it is necessary to address this issue. Additionally, current access to the building features database is limited. To broaden this tool applicability, it is necessary to develop a more comprehensive library. What is more, it has to include features that can be used in describing the different types of rooms/spaces.

CONCLUSION

Simulation of the zone layout can be an important step towards including occupant behaviour during the design phase of the building. As this study shows, with a proper survey, it is possible

to build up a simulation tool that is capable of delivering results that can have a real application in building designing software. Therefore, to continue such study, it must be transferred into a more accessible form – for example, an online survey/platform. In such a medium, a database incorporating more extensive features can be generated due to its browsing accessibility.
Moreover, if the formulated database holds information about features geometry, it can be potentially exported to the geometry modelling software. Exporting these features to the CFD simulation environment will reduce significantly, time of simulation preparation for alternative layouts and for CFD parametrical studies.

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Paper No.8 J. Dziedzic, D. Yan, V. Novakovic; Evaluation of the occupants' exposition to the indoor environment; IAQVEC; IOP Conf. Series: Materials Science and Engineering 609 (2019) 042066 Conference Paper

Evaluation of the occupants' exposition to the indoor environment.

To cite this article: Jakub Wladyslaw Dziedzic *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **609** 042066

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042066 doi:10.1088/1757-899X/609/4/042066

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 mash 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

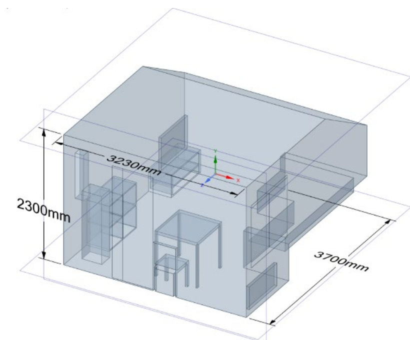

Figure 1. Visualisation of the room used for the numerical studies.

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-vison 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 threated as an inlet), door and ventilation outlet (that were later on threated 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 x 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.

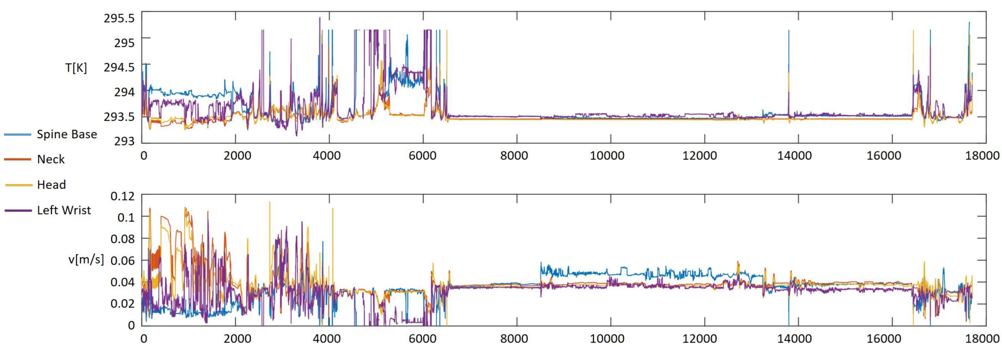

Figure 2. Plots with selected joints exposition to the indoor environment

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.

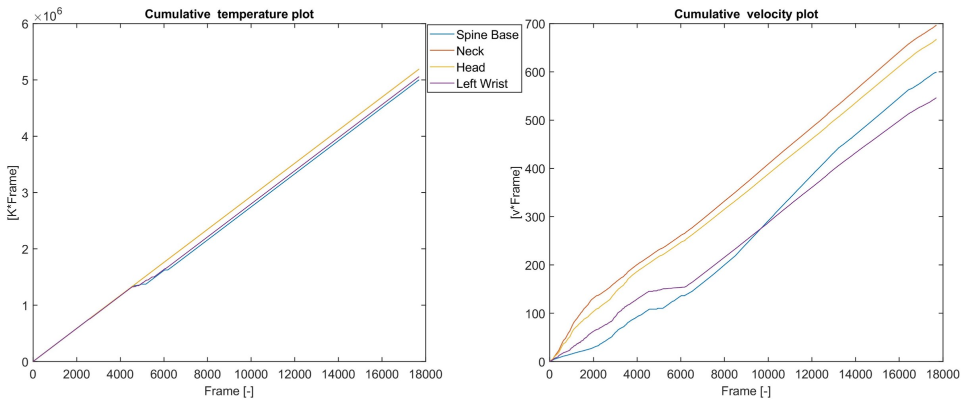

Figure 3. Plots of cumulative variables of selected joints

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.

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042066 doi:10.1088/1757-899X/609/4/042066

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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Paper No.9 J. Dziedzic, D. Yan, H. Sun, V. Novakovic; Building occupant transient agent-based model - Movement module; Applied Energy Journal; Journal Paper

Applied Energy 261 (2020) 114417

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Building occupant transient agent-based model – Movement module

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HIGHLIGHTS

- Unscheduled simulation of the occupant behaviour in buildings.
- Simulation of individual occupant behaviour by the agent-based modelling.
- Support for the personalising of the designed building space.
- Possibility to investigate individuals comfort during building design phase.

ARTICLE INFO

Keywords:
Occupant behaviour
Agent-based modelling
Building performance simulation
Human-building interaction
Personalised design
BOT-ABM

ABSTRACT

Simulation of occupant behaviour (OB) in buildings is a challenging task. Available software uses a broad spectrum of tools that try to reproduce the patterns of human activity. From building energy perspective, the main emphasis in research has been focused on discovering behaviour directly related to energy. In recent years, more attention has been given to simulating occupant actions that are indirectly influencing building energy use. In most of the cases, this is achieved with the use of agent-based modelling which allows describing occupant actions on a room level. According to the existing methodologies review, it is a proper step, but to include occupant behaviour in energy simulations, spatial and temporal resolution of the occupant behaviour model must be improved. Addressing this issue requires the development of a comprehensive model supported by numerous modules that would cover various significant occupant actions. This paper focuses on the development of the high-resolution, data-driven movement engine of occupants. It is one of the fundamental modules necessary to simulate occupant behaviour with high granularity. Once the model is developed within its essential functionalities, it will deliver a bottom-up model capable of testing various energy use strategies. It will allow for testing different heat, ventilation and air conditioning solutions and the responses provided by simulated occupants. The data used to develop this module was obtained thru in-situ measurements, with the use of depth registration. Information obtained from experiments is similar to previous research, but it also extends the investigation scope with an additional transition-based variable.

1. Introduction

1.1. Background

Building performance simulation is a common tool used in the design phase of a building. These tools make it possible to investigate several scenarios for the design conditions and select the one best suited to the given situation. The information provided is with the results of these simulations makes it possible to optimise the overall energy-use of the planned building. The energy performance of a building is influenced by several factors, such as construction faults, setup of the Building Management Systems (BMS) etc. To achieve an accurate design target with the simulation tools, it is necessary to take all the influencing factors into account. Even after accounting for all these factors, the energy performance eventually relies on the building occupants. A study conducted by Turner [1] shows that only 30% of the analysed buildings have similar operational and simulated energy use. Based on previously conducted research [1], such a mismatch between simulation and commissioning results might be caused by over-simplifying the factors like: occupant behaviour, construction quality, weather profiles etc.

The significance of the behaviour of building occupants on energy use has already been acknowledged. The description and foundation of current indoor environmental standards (ASHRAE 55 [2]) was made

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https://doi.org/10.1016/j.apenergy.2019.114417
Received 20 June 2019; Received in revised form 16 December 2019; Accepted 17 December 2019
Available online 06 January 2020
0306-2619/

half a century ago by Fanger [3]. Since this milestone, the work on this subject continues to this day. The recently finished IEA EBC Annex 66 delivered a significant contribution to this field by organising knowledge that already exists and provided organisation and instruction for the next steps of development [4,5]. The final report of Annex 66 [5] also pointed out that newly developed models should aim towards the occupant description on an individualistic level. Additionally, such models should be able to simulate various occupant indoor activities. Based on existing literature, occupant behaviour (OB) is usually represented as a stochastic process [6]. It means that each conducted action is assumed to have its reason and can be explained, although the accumulation of similar, registered activity can formulate particular distribution. The same action cannot be conducted under the same conditions: that is why its repetition might generate certain variations in performance or instruction in reaching a similar goal. The repetition might generate a sensation of the randomness of the observed action, but it is not the operational driver of the action. Direct OB cannot be considered stochastic due to the deterministic nature of the actions of the occupants. That is why the actions of building occupants should be analysed holistically to highlight the ways of reaching a similar target, which can later be extracted into the description (recipe) of achieving the goal. The only exception in forming the spectrum of possible behaviours is irregular behaviour [7].

1.2. Challenges in OB modelling

Indoor OB is a complex phenomenon. Therefore, development of a functional simulator is an iterative process, and it requires access to various data sources. Conducted study by Yan et al. [8] reviews, segregates and evaluates performance of OB models. In this study, many existing models are considered. Evaluation of the models took into the account three resolution criteria (temporal, spatial and occupational). Some of OB models that were considered were models already implemented in BPS software like Energy Plus [9,10], IDA-ICE [11,12] or De-ST [13,14]. C. Wang et al. [13] application was not taken into account in this review, but its contribution was already implemented in a DeST software while performing the review. One of the most accurate models has reached a temporal resolution of ten minutes and a spatial resolution that allows simulating the zone occupancy state [9]. Description of the zone occupancy state can be considered as a good enough, but as pointed out by Yan et al. [8], it does not allow for recreation of the behaviour of the individual occupant. Newly developed models need to aim towards higher resolutions of occupant description and better robustness.

Similar conclusions can be found in the work of Dong et al. [15]. As that study highlights, no solutions promote integrity or a broader framework for a spectrum of applications. Most of the models developed in this field are focused on presence of occupants, counting of occupancy, operation of windows, operation of blinds, operation of indoor lights, HVAC sizing and thermal comfort, crowd and security simulations, and design of building installations [15]. Usually, each model focused on one particular phenomenon related to OB. Proposed by Gaetani et al., the method of segregation of the models is one of the plausible steps towards the development of a communication platform [16]. Categorisation of the models in such a fashion proves that there are no universal models and the topic of energy-related OB in the building is complex phenomena.

1.3. Use of ABMs for OB

Based on provided evaluations, the new OB model requires changes in the observation of occupant actions in buildings. It is assumed that an extension of the observed spectrum of OB by new measurement techniques can improve the quality of the model. Following the conclusion delivered by Yan et al. [8] and Dong et al. [15], the newly developed model has to operate at the same time duration, as actions conducted by occupants might last. The same principle must follow the spatial localisation of their activity. The result of such measurement might produce additional noise to the data, but it will allow capturing reasoning for the actions that occupants conducted. Therefore, the occupants must be identified correctly in the BMS system and properly described, and the resolution of the data collection should allow for capturing the smallest significant event [16]. If such requirements are fulfilled, it is possible to process the data that have been gathered without losing any context from each registered activity and to gain in-depth knowledge of the observed subject. The main challenge related to this approach is its significant difference between operational temporal resolutions. Occupants conduct their actions in a temporal resolution of a second (or even less), where a noticeable reaction on a condition may last many minutes or more. The difficulty is simulation scaling. The cumulative sum of the actions of the occupant cannot be considered a significant approximation due to the dynamic nature of the behaviour of the occupant. Observed reactions to the given indoor conditions might be dependent on numerous factors such as thermal conditions, acoustic conditions, purpose of the occupation, and many more [17]. Therefore, activity sampling for the building occupant with the frequency of a second can be considered a sufficient operational resolution. Such resolution extension would address conclusion delivered by Yan et al. [8] and Dong et al. [15]. High-resolution sampling should allow capturing each important event, from the perspective of the building occupants. Discretisation at that level leaves relatively small room for any potential misinterpretation. However, such hardware application requires delivery of the probed data in the least invasive way. Meeting such specifications can be considered a challenging task. Fortunately, such challenges were addressed in past research. Currently, it is possible to fulfil this requirement with inexpensive gear such as ultrasonic sensor [18], stereovision camera [19], depth registration camera [20] or low-cost sensor for holistic monitoring of indoor environment quality [21].

Fulfilment of the requirements for the new OB model can be achieved with the use of agent-based modelling. It is a promising technique that is capable of re-creation of occupant behaviour that meets the three resolution criteria. This modelling technique allows design of an artificial being (agent) that can operate in any given environment. The agent reacts to the given conditions, based on given targets and specifications. Additionally, the agent can deliver feedback for any condition, even those that are not pre-scheduled. The agent follows instructions from the delivered set of rules. Rules could be considered to be a habit or “personal” preference [22]. This modelling technique allows for introduction of the modular OB model where each module is responsible for one particular OB-related phenomena. This approach allows for description of the OB through the perspective of the occupant. Currently, there are agent-based models focussing on human reactions that have origins in a building occupant [23–25], but its granularity does not catch up with future targets proposed by Yan [8] and Dong [15]. The applications that are closest related to human behaviour simulations are simulators that focus on fire escape [26–28], evacuation pathway testing [29,30], strategic and aid support [31], crowd management [32,33] or pedestrian movement [34]. None of mentioned models put extensive emphasis on the development of a sophisticated description of the distinct person. The most advanced agent-based models have functionalities such as agent age, sex, speed, maximum acceleration, body size, health and strength. Those functionalities are implemented in fire escape simulations [26]. With these parameters, it is possible to simulate complex fire escape scenarios with various placements of the fire origin. These methods are especially useful to test scenarios that aim to minimise causalities among exposed populations. This target can be obtained by different placement of sprinkler system, proper control of the smoke ventilation and crowd discharge columns. Similarly, other applications mentioned above were designed to investigate specific phenomena. It is noted that most ABM simulators of the OB are polarised into one of the two categories in terms of the temporal resolution. Most of the energy OB ABMs are aiming towards hourly simulations to capture the annual performance of the building. Another is more like an event-based simulation (like evacuation). Simulation timeframe does not last for a prolongated time, but its temporal resolution is close to capturing sudden occupant reactions.

2. Aim

Development of holistic OB models is already a well-established task in the research community, it was proposed to model occupant by their presence [35], simulate users' activity [36], implement OB models in larger spaces [37]. The maturity of subject have allowed to summarise its current progress [38], propose improvements of existing models [39] and implement OB-centric methodologies in the design process [40]. Nevertheless, a merge between precise (whole simulations that last for one particular event, with a high temporal and spatial resolution) and existing hourly models was not found in the literature. To connect those two approaches, it is necessary to divide the whole model into distinct modules due to the nature of its complexity. Each module has to communicate with other subparts and has to be reliable. Therefore, the development procedure has to be taken care of with extra caution and attention to details.

Based on existing literature it is necessary to develop a OB simulator tool that is capable of operating on high spatial and temporal resolution that can also perform annual simulations. Its application should allow for a fit-for-purpose approach of OB simulations. With the proper tool, it would be possible to investigate various occupancy scenarios and test whether there is space for potential optimisation of the building energy use. To address these issues, it is necessary to create a tool capable of conducting simulations that re-assemble the patterns of normal building usage. Such a tool must operate in an energy-cyber-physical system that might potentially be used during the design and operation phase of a building. The suggested tool should allow for a human-centric design of the building, where the existence of the occupants is not marginalised or oversimplified. The framework of such a model was described by Dziedzic et al. [41]. Progress towards such a goal must be initialised with a description of the basic functionality of the occupant. Each functionality will be referred to as a module.

The description of the actions conducted inside the room/zone by the occupants requires proper localisation. Information about the localisation state of the occupant might be used to describe the thermal preferences and actions that the person is engaged with. Thus, the initialisation point of the new occupant behaviour model should focus on the development of a solver capable of simulating movement indoors. This paper aims towards the development of the movement solver by analysing collected data through depth registration. The developed solver is a foundation for the new agent-based model. The primary purpose of this solver was a simulation of individual transitions inside a known building layout. It is assumed that the layout of the simulated zone is known, and the agent also recognizes starting and finishing points. The agent must generate pathways similar to the natural transition of the occupant. Therefore, the created pathway will not be optimal, nor the shortest. Such algorithms are already existing.

3. Methods

3.1. Collection and access to the data

Development of the movement simulator needs to rely on data obtained during the *in-situ* observation of the natural transitions inside the building. With the use of depth registration camera, it is possible to obtain this information. This technique allows observation of a surface in a space using an infrared projector and camera that allow monitoring a reflection of the projected beam. Collected information can be transferred into the raster map, where separate pixels hold information about the distance of the monitored surface. A static picture can be treated as a background. Any obstacle that crosses the monitored area will be distinguished from the background and treated as a dynamic object. Cover range and accuracy of this camera are directly related to the image amplifier that has been installed in camera. There are many available devices on the market capable of conducting such measurements. In terms of application readiness, one of the most popular cameras is the Microsoft Kinect v 2.0 for Windows [42]. Due to these reasons, this device was selected to be used in experiments. Access to the data and its applications was well described by Dziedzic et al. [20]. In short, the selected device transfers a humanoid-like shape into a built-in skeleton model (SM). The SM is a twenty-five-joint model, where each joint match up with a designated place on a humanoid body. For example, if the joint should be located at the base of the spine, the SM will try to estimate its position based on an observed shape. Each joint is described by four variables, three-dimensional information of the distance from the device centre point, and global clock information. Collection of the information from all joints can be used to formulate principles of the movement simulator.

Data collected through depth registration requires some amount of post-processing. With proper software tuning, it is possible to keep the data collection procedure in an infinite loop. Due to the hardware limitations, each procedure might collect a number of “frames” until the computer buffer memory runs out of space. To avoid this situation, each package of collected frames is transferred to the hard drive, which requires a temporary pause in the depth data acquisition. Consequently, if occupant was performing a transition while data was transferred to hard drive, few frames of this transition might be unregistered. To bypass this condition, double registration of the same scenario is required. Such a procedure minimizes the possibility of missing any potential activity. The number of collected frames is limited by the hardware calculation capabilities that are used. Data used during the development of the movement simulator module were accessed from the compilation of previously conducted research. Each participant in the experiments was adequately informed about the quality and quantity of collected information. All the participants gave their consent to collect and process data obtained with the use of the depth-registration camera. Therefore, the research that was conducted did not cross any ethical boundaries.

3.2. Data processing

Collected information about occupant activities must be post-processed in two steps: projection surface recalculation and pathway clustering. The device used in the experiment defines a local coordinate system. The position of the device and its angular position influence the data collection process directly. Fortunately, it is a repetitive error that can be eliminated by a transformation matrix that straightens the observation angle. Information about the transformation surface can be obtained via analysis of selected joint SMs. Use of joints that are not contributing significantly to the pendular movement of the human body is recommended, due to stability of the readings. For example, any of the joints that describe the spine. Analysis of this spot allows a description of the operational surface, where all measurements must be re-calculated to estimate the height-axis transformation vector. Points from the foot joints must be projected on an operational surface, and an average distance must be set. Once the data are calibrated to represent movement on a straight floor surface, it is possible to proceed with the next post-processing step.

A set of the whole number of points acquired during a measurement procedure can be connected in a formulation of the single pathway. To distinguish each pathway, it is necessary to apply a classification technique. Due to the significant amount of the recoded movement, it is necessary to use an unsupervised segregation technique. Additionally, the deployed processing methodology must be capable of connecting the missing pieces of movement records that occur during the temporary pause mentioned above. To fulfil all the given restrictions, a modified density-based scanning method (DBSCAN) was deployed. The principles of formulation of DBSCAN were introduced already in the 1970s [43], but back at that time, it did not attract too much attention. In recent years, this method has gained increasing applicability due to the ability to use it in the unsupervised cluster spatial data series. The method mentioned operates on two operators (alpha and epsilon) that must be set according to the data granularity. Operator alpha describes a range of the investigation spectrum of the point that is currently being considered. Operator epsilon controls how many points inside the alpha range must be included to consider such data set as a cluster. This method is efficient in detection of complex shapes and denoised data sets. According to this DBSCAN description, this method does not require definition of observed clusters. Therefore, there is no need to keep track of how many paths this clustering method must detect. To correctly detect classification of the given cluster with the use of this data type, it is necessary to introduce an additional dimension where temporal distance plays an important role. Otherwise, most of the collected data points will belong to the same cluster due to the spatial overlay. Introduction of the time parameter as an alpha variable block under classification enables data connection due to the temporal data acquisition.

3.3. Development of the movement solver

Segregated data sets were analysed to capture movement statistics. In this step, each detected path was processed separately. Each point in the recorded pathway was considered, except for the last step point. Statistical analysis included parameters such as movement speed distribution, and movement angularity distribution. Observation of the movement speed was done by direct calculation of the distance between the present step and following step divided by the amount of time between these two points. The second parameter was the movement angularity distribution. If each point can be considered a local Cartesian coordinate system, each next point formulates a corner with an x-axis, which has its angle value. The difference in the angle value between the present and previous step can be considered an angular movement fluctuation. These values aggregated in summary of the whole movement are considered a movement angularity distribution, which are processed later. The results of all investigated distributions are shown in Fig. 1.

As shown in Fig. 1A and C, both distributions show a particular pattern of movement of the occupants. Most of the observed transitions of most of the movements are conducted at a speed between 0,5 and 2 m per second. In terms of the angular distribution, there were no transitions that required a larger angular difference than 45° in one step. Analysis of the step progression did not show any significant proof that there is a pattern, where step speed accelerates in a particular phase of transition. Both variables were tested in terms of the correlation between each other. Surprisingly there is no correlation (correlation value of 0.015) between step velocity and angularity. It is a counter-intuitive statement, but there are no proofs to claim differently. Both speed and general angular distributions are formulated into cumulative distribution function where the order of sampling is dependent on the lowest to the highest value. Once both distributions are transferred into a cumulative distribution, both newly formulated curves are described by the function using polynomial regression. Obtained distribution function formulas are used as a basis for the simulator development. Using the random function as a solver, it is possible to obtain access to the variable values from both cumulative distribution functions (speed and angular distribution), allowing for a simulation of the transition steps. Additionally, the obtained cumulative distribution of movement speed matches with the previously generated distribution from conducted research that used GPS data [44]. As an additional novelty, it must be pointed out that with use of the depth registration camera it was possible to obtain a cumulative angularity distribution, that was impossible to generate with previously used measurement techniques due to is small spatial accuracy.

To simulate the movement of an agent, it is necessary to give it a selected target for a transition towards which it can aim. To do so, the room coordinate system is developed, and its development will be explored in the following text. Each time when a new step is updated, the agent moves following the vector generated in a previous step. Each time the agent is re-solving a selection of the step parameters, it updates its distance and angular difference from the turn of the previous vector. The side of the angle differential is selected by estimation of the future position from both sides of the previously followed vector. Both points are tested in terms of the distance from the aimed target. The shorter distance from both of the projections selects which is the following step position. Solving the dilemma at equal distances will be addressed in the following text. The sequence of pathway selection is illustrated in Fig. 2.

3.4. Floor layout and coordinate detection

The solver that has been developed can simulate any given step recreating the natural distribution of steps taken. To transform the designed solver to a form applicable for BPS, a definition of operational space is required. To do so, it is necessary to develop a grid of connection that represents a floor layout structure, that is used for this simulation. Obtaining the connection grid is generated automatically for any given investigated space. The source data for investigated space originates from a vector polygon drawing or a raster picture. If the layout is defined using the vector polygon, there is no need to prepare the layout for further processing. If the delivered information about the floor layout is available only in a raster picture, it requires further preprocessing. The raster picture of the floor layout is transferred to its binary representation, where the space representing floor layout has a value equal to one, and the rest of the features (such as walls) have a value of zero. The first step towards vectorization is the detection of the corners and outline of the given layout. Outline and corners are located from both the inner and outer sides of the layout, allowing for simplified further processing. If the emphasis on outline detection was put in one of the sides, it could potentially generate a formulation of pixel “stairs” that would complicate further calculations. Side outline points located on the inner side have surrounding five positive pixels. On the outer outline, side points have a sum of three surrounding pixel. Correspondingly, for the corners, the inner outline is four, and the outer outline is one. Detection of the whole set of the pixels on edges on the floor layout allows for a formulation of the layout pixel set, that are analysed by DBSCAN to classify all the selected pixels. If the clustering technique detects only one cluster, it means that there are no more non-connected outlines, which implies that this specific layout has no “holes” inside the layout. If there are more clusters detected, the vectorization process requires one additional following step. Access to the vector description is essential for the general reduction of the processing time of the movement simulator. Operation on a vector requires significantly less computational time than the constant recalculation of the high-resolution raster picture. Therefore, pre-processing of the raster type input is addressed properly.

Each outline cluster detected is described by the continuous sequence of points representing corners in a selected order (clockwise or counter clockwise). The last points are the same as the first, to close the entire loop. Because each corner was represented by two points during the detection process, from each pair of the mutual corner points, only one was used in the following process. Each corner point that has a value of one was used during the outline segregation procedure. The formulated outline sequence is directly transformed into the vector polygon. To check the quality of the vectorisation procedure each pixel that represents layout, is catalogued by its localisation value. If the sum value of all the points included inside the polygon, is equal the total amount of catalogued points, it means that the polygon was detected correctly. If it is smaller, it means that there are holes inside the

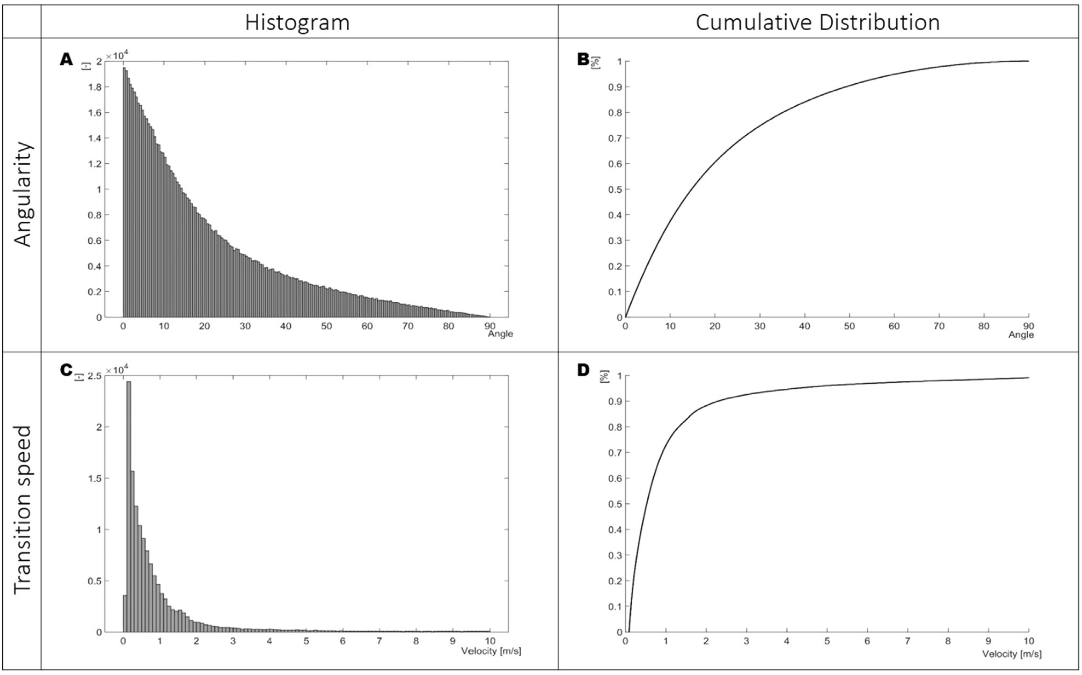

Fig. 1. Movement and Angular distribution of used data sets. Cumulative Angular Distribution (CAD) and Cumulative Velocity Distribution (CVA).

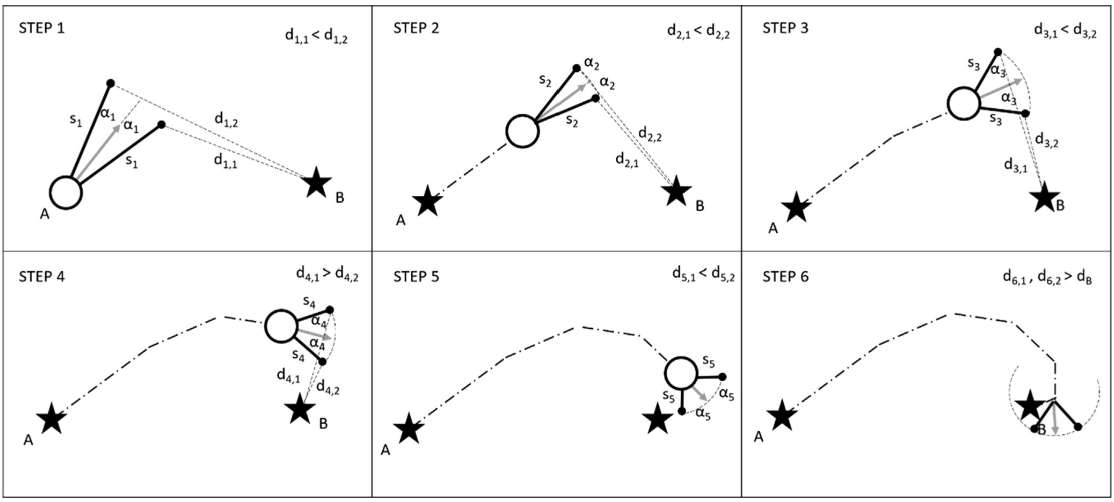

Fig. 2. Illustration of the step sequence of the movement. Star A - starting position; Star B - end Position; s_i - simulated following step distance; α_i - simulated following step angle; d_i - distance from the following positions to the end goal; grey arrow - starting/previous agent turn; black end-rounded line - simulated position in the next step; dash dot line - pathway; white circle with black borders - agent.

formulated polygon area, and its localisation has to be re-addressed. The same process of corner sequencing continues for each detected cluster. If the detected cluster, translated into polygon has a total amount of catalogued points equal zero, it is a definite "hole". Each detected "hole" is subtracted from the main polygon area by the Boolean operation. This process continues until the main polygon is formulated properly and passes the quality check test. This process assumes processing of one zone/room that does not allow for a formulation of the multiple "only positive" zones. If there are multiple starting clusters, the main starting cluster is selected by the largest initial area, before Boolean reduction of the space size.

Once the vector description is available, it is necessary to extract information about all the vector corners to initialize the process for automatic detection of the coordinate system. Each corner is being paired with others included in the set to position midpoints between connections that are capable of "seeing" each other without obstacles.

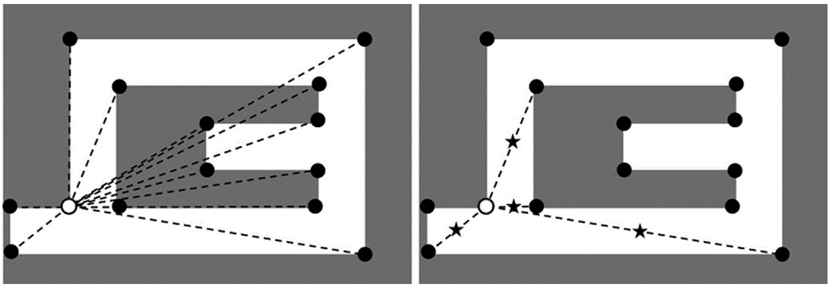

Fig. 3. Examples of coordinate point's detection. Grey area - walls, obstacles, non-transparent features; white area - floor area; white circle - investigated corner; black circle - all the other corners; dashed line - connection to the different corners; star - detected coordinate points.

The probing line is a set of artificially generated points on a line connecting two corner points, where the points are generated by the number of even divisions of the connection line. This probing line is responsible for detecting the obstacles. If there is any point from the probing line that is not included inside the polygon area, it means that this pair of corners is not visible by each other. Therefore, the midpoint is not formulated between these corners. This process of detection is illustrated in Fig. 3.

All the midpoints that are included on the edge of the polygon are not included in a further step. Each midpoint that is included in the main set obtains its individual fixed number.

The set of all midpoints has been tested according to the same principle as in the previous step. With the use of the probing line, midpoints are investigated in terms of the visibility to each other. Each visible midpoint highlights its visibility by marking it in a connection matrix (CM) for the other. This matrix is responsible for the formulation of the relationship between midpoints. It has a size of n*n, where n is the number of midpoints included in this analysis step. Each time there is a visible connection between two points, CM updates its status by giving value one to the cell that is represented by the row/column and column/row for both points. CM is symmetrical. Once the whole set of midpoints is tested in terms of their visibility to each other, CM is tested in terms of its potential for simplification. Each row that has a unique set of other connections is kept for the final version of the CM. If there is a row of connections that has the same set of connections but fewer connections than its comparison with other points, it is removed from the final version of CM. The result of this removal is that the amount of points is reduced to the necessary minimum. All the points included in the final CM will be used as main coordinates for the movement of the agent inside the selected layout.

3.5. Transition simulation

Simulation of the movement requires the definition of the start and the end points. For the purposes of the test, start (A) and end (B) points are being generated randomly inside the floor layout. Before the transition process can be initialized, the solver must select a set of CM to generate a pathway connection. The pathway between A and B must be established with the use of the coordinates from the final CM. The driving force for optimization of the pathway will currently be a distance. The root optimization will be done with the Dijkstra's shortest path routing algorithm [45]. This method delivers the shortest pathway based on a wage connection system. The generated matrix of connection will be re-calculated into the distance connection matrix, where each cell represents the distance between corresponding points from CM

Once the shortest pathway is selected, it is exported as a vector holding an instruction of coordinate points that an agent must follow to reach the final destination. During each step, the agent updates its aimed target of the corresponding point. If there is a visible corresponding point that is farther in the progression on a direction vector, the aimed target is updated, and the agent progressively continues generation of the next movement steps. If the simulated step will cause moving out of the layout polygon, then the step is re-calculated until the placement of the next step is not correct. The movement simulation continues until it is not in the last step distance to the selected target. If the agent can potentially reach the endpoint, then the movement simulations transition it to the final destination. Reaching the exact point of the pathway end would require a tremendous amount of iterations. It could potentially not reach a final point at all. That is why the direct step simulations stop in an iteration before the last step. In other words, there is an approximate destination point that the agent has to fit into to conclude the movement simulation process.

Simulation of more than one occupant can be done using the same solver. Each agent representing an occupant can have its own pathway. If they meet in the same corridor or path, both the agents must switch sides, as it happens in real life. This situation might happen if the one agent is blocking the view of another to the aimed corresponding point. Each agent has its physical dimensions (width and circumference) that are implemented in the simulations. To simulate passing of the agent, each has an additional set of supportive corresponding points that can be dynamically included in other transition pathways vectors. A set of two supportive points is placed in a position perpendicular to the current vector turn. Each additional point is in a distance from the body centre equal to its circumference. If the agent blocks the aimed target, the software will update the pathway vectors. Included in that scenario, agents will aim towards a supportive point of another agent that is closer to them. This situation will happen if agents are opposing each other. If the agents are following a similar pathway, one will follow another until the previous target of the following agent is not visible. Simplified version of the transition algorithm is shown in a Fig. 4.

3.6. Even distance dilemma

During simulations, there is a chance that the agent will be exposed to conditions where it must select one particular direction. If both the connections will be even in terms of the distance, or the simulated angular distribution will deliver an even distance from both sides to the aimed target. It could be possible to assume that the selection of the direction is random, but this solution has to be backed up by experiment. To investigate this phenomenon, a series of experiments were conducted, where, in an improvised maze, monitored humans had to select their transition. The whole experiment was divided into six series (cases), where each human had their unique maze layout (Fig. 5). Each maze was created using office desks, allowing participants to screen the whole space. It is possible to assume that each participant was aware of the direction that it was aiming to. Different maze setups were designed to investigate the influence of the entrance/exit placement on possible pathway selection. Data from this experiment were captured using the two depth registration cameras capable of covering the whole maze

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Input Arguments
Poly –polygon of simulation; Start_Poss – Start position; End_Poss – Goal position;
F_Ang_Cd - Angular cumulative distribution function;
F_Step_Cd - Movement speed cumulative distribution function;
Fq_Time – operating time resolution; I_T – Initial turn; i – Iteration step; Si - iteration step position;
Ti - iteration turns; Rand – random number (0-1); Eq_Pt – equial distance selector;
i=1
T1= I_T
S1 = Start_Poss
  WHILE sqrt((Si(x) – End_Poss(x))^2 + (Si(y) – End_Poss(y))^2) > F_Step_Cd(Rand)/Fq_Time;
  i=i+1;
  Step_Distance= F_Step_Cd(Rand)/Fq_Time;
  Step_Turn= F_Ang_Cd(Rand)
  Test_T1 = Ti-1-Step_Turn
  Test_T2 = Ti-1+Step_Turn
  Test_S1(x)= Si-1(x)+ Step_Distance +cos(Test_T1)
  Test_S1(y)= Si-1(y)+ Step_Distance +sin(Test_T1)
  Test_S2(x)= Si-1(x)+ Step_Distance +cos(Test_T2)
  Test_S2(y)= Si-1(y)+ Step_Distance +sin(Test_T2)
    IF TEST_S1 inside Poly
    Dist_Test1 = sqrt((Test_S1(x) – Si-1(x))^2 + (Test_Si(y) – Si-1(y))^2)
    ELSE
    Dist_Test1 =Inf;
    END
    IF Test_S2 inside Poly
    Dist_Test2 = sqrt((Test_S1(x) – Si-1(x))^2 + (Test_Si(y) – Si-1(y))^2)
    ELSE
    Dist_Test2 =Inf;
    END
    IF Dist_Test1= Dist_Test2 & Dist_Test1 = Inf
    Redo_step= Redo_step+1;
    i=i-Redo_step;
    ELSEIF DIST_Test1= DIST_Test2
    Redo_step=0;
    Select_S= Dist_Test(Ee_Pt(rand));
    Si=Test_S(Select_S)
    Ti= Test_T(Select_S)
    ELSE
    Redo_step=0;
    Select_S= min(DIST_Test);
    Si=Test_S(Select_S)
    Ti= Test_T(Select_S)
    END
  END
i=i+1;
Si = End_Poss
```

Fig. 4. Simplified movement simulator algorithm.

setup area. In the experiments, ten participants were involved (seven male and three female). During the experiments, each setup had to be executed ten times at a normal transition speed. Repetition of each maze was performed to check if there is any influence of task repetition, where participants could lower their focus and perform actions that rely on their automatic response.

Collected data were analysed in terms of the path section selection. Each maze had its entrance, middle corridors, and exit. Detection of the distribution of a particular selection of the pathway was done by analysing the entrance/exit of the maze with a detection where the side of the maze was used to move towards another side of the maze. Therefore, one setup generated twenty decisions per person. The results of the collected data distribution are summarized in Fig. 5.

As expected, there is no particular correlation between the selections of the pathway, while all of them have a similar direction. If there is a pathway that is obviously longer than a more straightforward

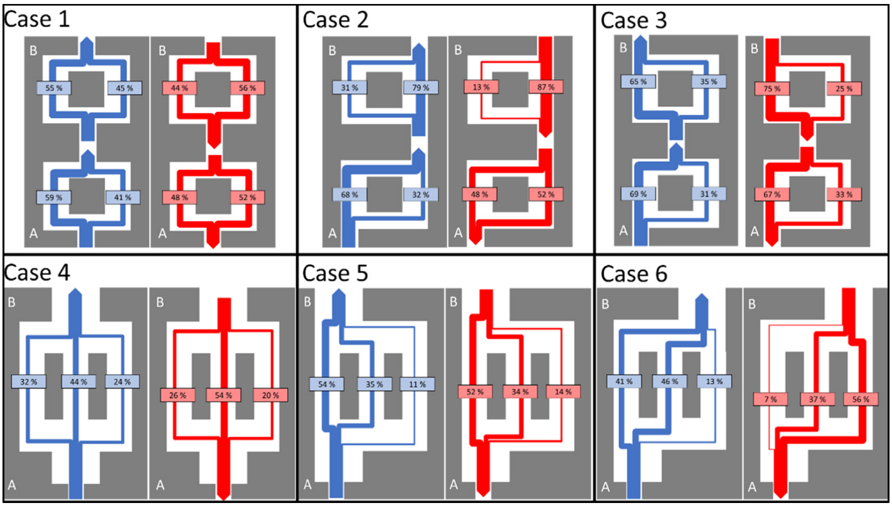


Fig. 5. Movement transition experiment setup and transition vectors. Each case was analysed separately regarding aimed direction Each transition for A to B was coloured as a blue graph, and from B to A as a red graph.

pathway, in most of the cases, such pathway will not be selected. Nevertheless, it is not justified to discredit selection of the longer pathway. Therefore, obtained distributions regarding path selections were implemented into the movement simulator module.

4. Validation

The developed model was validated by following commonly practised validation methods included in the existing literature [46]. To do so, it is necessary to identify the baseline of the phenomena and compare its performance with the following scores variables: "Reaching the target", "Too many steps", and "Outside layout". The whole simulator operates on a fixed time resolution. Therefore, the time variable can be neglected. If the agent reaches a goal, it scores on a "Reaching the Target" variable.

If the agent fails to transit into the target within ten times of steps (iterations) that in average are necessary (shortest distance divided by the average speed) the agent fails the transition. In such a case the transition scores on a "Too many steps" variable and ends simulation in that spot.

The developed module operates on the following five functionalities: cumulative velocity distribution (CVD), cumulative angular distribution (CAD), Shorter distance selector (SDS), floor layout detection (FLD), Even distance dilemma (EDD). Each functionality was described and defined in a subsection of the Methodology section of this manuscript. Each included functionality pays a significant role in re-creation of natural occupant movement. Lack of one or more functionality might generate a successful transition, but it might emerge due to the probabilistic chance. To check the significance of all the functionalities, it was proposed to test all the potential permutations of all functionalities scenarios where each of them could have status as ON or OFF. This will include all functionalities except EED. It does not influence the success of the pathway generation, but it might slightly increase the number of steps (iteration) if the dilemma is met. Therefore, it is a supplementary functionality that does not influence the success of the movement simulations. Each included functionality in the validation process can be implemented to the code as with status on or off. If FLD functionary is turn off, the agent has no information about the layout. It only has access to the initial and endpoint. Therefore, it will directly aim towards the endpoint of transition without concern of the surrounding geometry the obstacles. The rest of the functionalities (CVD, CAD, SDS) are considered as a status OFF when instead of using its discovered properties, its parameter is selected by random.

Consequently, CVD and CAD use the range of its distributions but do not use it for step selection. Instead, the variable is selected randomly. If SDS functionality is OFF, the agent chooses randomly one of potential steps.

In this validation procedure, there are sixteen different functionality scenarios. Previous studies have shown that typical daily transitions in a residential building are lasting for around 6000 s per day [47]. Each transition typically lasts for approximately 5–10 s. It is approximated that occupants are committing about 1000 transitions daily. To check how the developed model is capable of simulating one whole day, validation simulations were tested 1000 times. Each test was evaluated through the selected score variables. The baseline functionality scenario is the one where each functionality was set on a status OFF. Used layout for the validation and its results are shown in Fig. 6.

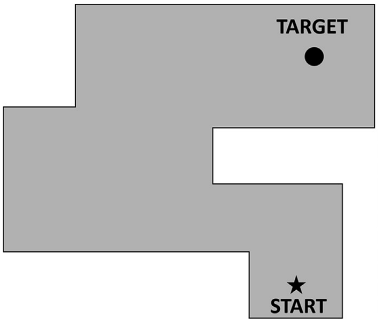
5. Simulator sample results

To investigate abilities of the developed movement simulator, two type of tests were conducted, focusing respectively on general transition and pathway repetition.

To simulate general transition, two zones were selected; a general transition inside an apartment and inside an office. Each simulation for this segment included the random positioning of the start and the end point. Each variation was simulated fifty times. Transitions inside these layouts are displayed in Fig. 7 by the movement transition points and heat maps. Each heat map represents a cumulative value of an Agent's presence in a particular space, operating on a fixed resolution. Higher number of generated pathways could make zone layout blur and it would be difficult to recognize single pathway. Each heat map was generated in a resolution of one hundred times one hundred, and dimensions of the whole layout are the boundaries of the heat map.

To display the variability of the pathway repetitions, three simple layout scenarios were shown in Fig. 8. A simple straight pathway transition, an elbow connection, and a straight pathway separated by the wall parallel to the corridor length are shown. The result of these simulations is displayed similarly as previous simulation.

Each simulated pathway is represented by a gathering of the points



	Status of Functionalities				Validation Variables		
Case	CVD	CAD	SDS	FLD	Reaching the target	Too many steps	Leaving the layout
1	ON	ON	ON	ON	949	0	51
2	ON	ON	ON	OFF	0	573	427
3	ON	ON	OFF	ON	0	0	1000
4	ON	OFF	ON	ON	844	0	156
5	OFF	ON	ON	ON	928	0	72
6	ON	ON	OFF	OFF	0	0	1000
7	ON	OFF	ON	OFF	0	1000	0
8	OFF	ON	ON	OFF	0	1000	0
9	OFF	ON	OFF	ON	0	0	1000
10	OFF	OFF	ON	ON	773	0	227
11	ON	OFF	OFF	ON	0	0	1000
12	ON	OFF	OFF	OFF	0	0	1000
13	OFF	ON	OFF	OFF	0	0	1000
14	OFF	OFF	ON	OFF	0	1000	0
15	OFF	OFF	OFF	ON	0	0	1000
16	OFF	OFF	OFF	OFF	0	0	1000

Fig. 6. Validation geometry with model functionalities validation results.

displayed on a layout heatmap. Each path is described by the vector that holds spatial information of each taken step. For the result purpose, the initial localisation of the movement was selected randomly in space. As shown in Figs. 7 and 8, no matter where the agent initialises its transition, it is capable of finishing its movement goal.

If this application were implemented in BPS software, then there would be an initial and end movement point in a similar location, of building/zone exit. The whole transitions are aimed to be simulated continuously until the agent leaves the investigated area. Information about the agent location can be used to draw an occupancy schedule, but it can also be implemented to investigate occupant thermal comfort with high granularity. Ability to position the human body allows the calculation of a local radiant temperature. Additionally, the same step points can be used to probe data about local air thermal properties, if the used solver supported a multizonal simulation.

6. Discussion

The test of the developed movement simulator shows that it is capable of generating pathways that are not prescheduled. It operates on a simple coordinate system that does not require an extensive calculation power to operate. The general movement simulation process does not include a necessary preparation phase. This phase requires access to a polygon drawing that represents the floor layout. The process of vectorization operates on a raster picture. This makes the completion of preparation a time-consuming process. The vectorization

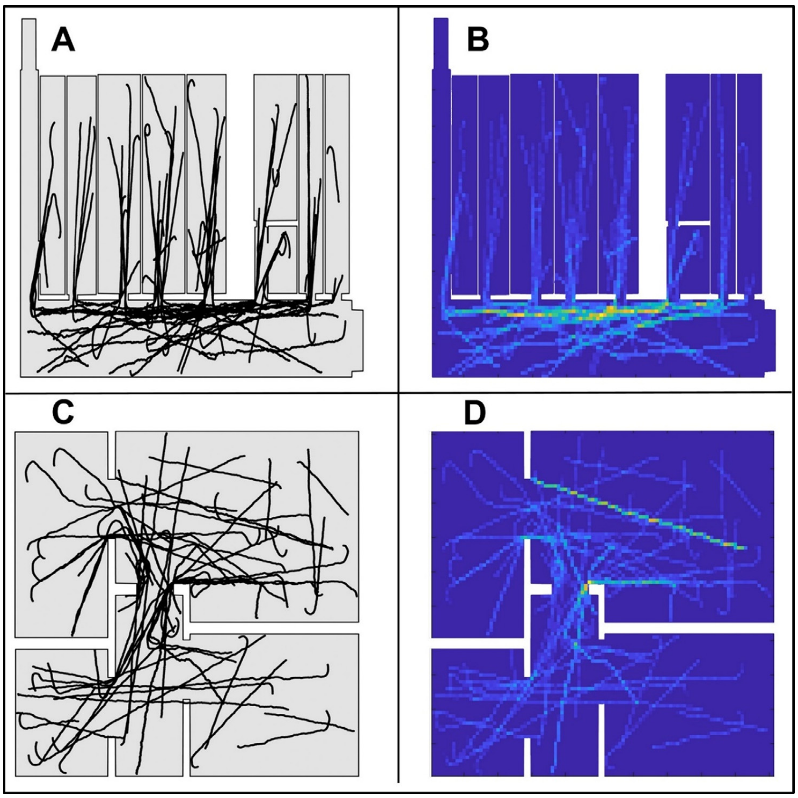


Fig. 7. Simulation results for an office layout (A) and its heat map (B). Simulation results of a typical flat layout (C), and its heat map (D).

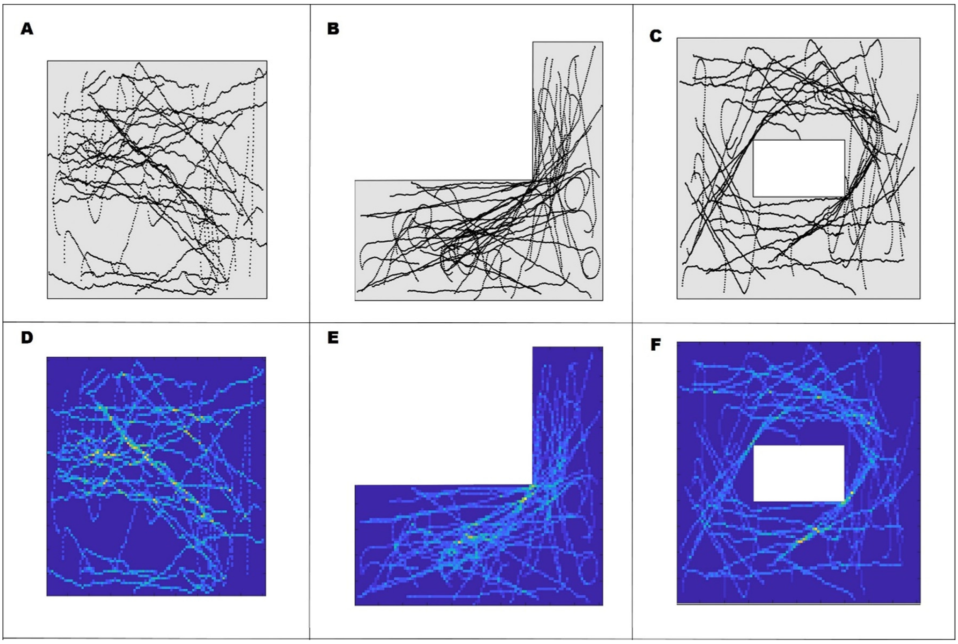


Fig. 8. Simulation results for different layouts. Simple corridor (A), and its movement heat map (D). L-shaped corridor (B), and its movement heat map (E). Corridor separated by an obstacle (C), and its movement heat map (F).

is a one-time process not induced in the general computational performance test. The necessary computation time for the vectorization relies on the complexity of the given area if it covers a large space, or it has numerous amounts of holes area inside. The same situation concerns the description of the coordinate system. Once it is calculated, it can be explored until there is no significant change inside the building layout. Additionally, numerous possible corridors influence the calculation time process. General simulation of the transitions of each case took approximately five minutes, without plotting transition pathways. It must be pointed out that each case was exposed to one thousand simulations, where each simulation had a mean value of three hundred steps, and each step was simulated in approximately 0.01 s. Such fast processing allows to assume that it is possible to simulate transitions of more than one occupant in a relatively short time. If such performance is maintained during the whole simulation procedure, simulation of the whole year of transitions can be done in twenty-four hours, with the assumption that each year an occupant spends 10% of its total time on a transition movement. Used computer hardware specification was described in the acknowledgement.

Tested layout scenarios were drawn as an orthogonal shape. A vectorization method would be able to handle the process of more diagonal shapes but not more opaque shapes. Any kind of rounding could be considered as a corner, formulating an advanced structure of a polygon at the same time. This problem could potentially be solved by simplifying the shape by fine resolution grain, or by the introduction of a round shape detection function that will immediately detect the existence of a rounded shape, and it will describe the shape with an arc-shaped vector.

Zone layout outlines are necessary to detect the corresponding points and to hold agents inside the layout. Their primary function is limited, but it can be extended. The whole zone can be multiplied and separated as a layer. Each layer can be responsible for different floor features such as the placement of the furniture, doors or electrical appliances. It can be done in the same way as it is organised in BIM software (e.g. Revit or Sketch Up). It can share similar modular architecture. Each included device must be described by the extensive metadata that hold information about device dimensions, localisation of coordinate points, and the list of activities it can be engaged in. An example of the simple scenario scene is displayed in Fig. 9. Each activity had different corresponding pathway colours. All the included actions were kept in a pre-scheduled sequence. In this simulation, the agent was instructed to start from the home office zone and to sit in front of the desk. After that it was instructed, to enter the kitchen (red path), pick up a meal from the refrigerator (blue path), cook the meal on the stove (magenta path) and finally eat the meal while using the table in the living room (cyan path). Once the meal was finished, the agent had to wash the dishes at the sink (black path) and go out of the flat (yellow path).

Movement of the agent is represented by a singular point, but it can be extended to full body representation. Data collected via the depth registration technique allows for a formulation of the whole-body numerical representation. It can be transferred to the movement simulator as well. Projection of the body can be re-calculated by the defined number of points. Therefore, it is possible to generate numerous three-dimensional strings that represent points of the human body transiting inside the indoor space, which can be used to monitor how the agent is exploring and perceiving the given space. Information of the body turning and placement of the limbs can be used to sense the environment by using other numerical software such as IDA-ICE [11] or ANSYS Fluent [48]. Data obtained from these external sources can be used to generate a feedback loop for an agent to react on given environmental conditions if such rules are applied.

7. Conclusions

The current state of the building occupant transient agent-based model development can be considered to be a foundation of an artificial intelligent occupant behaviour model, but further progress requires more research. The current state of the model allows formulating a series of next tasks for the development of a comprehensive agent-based

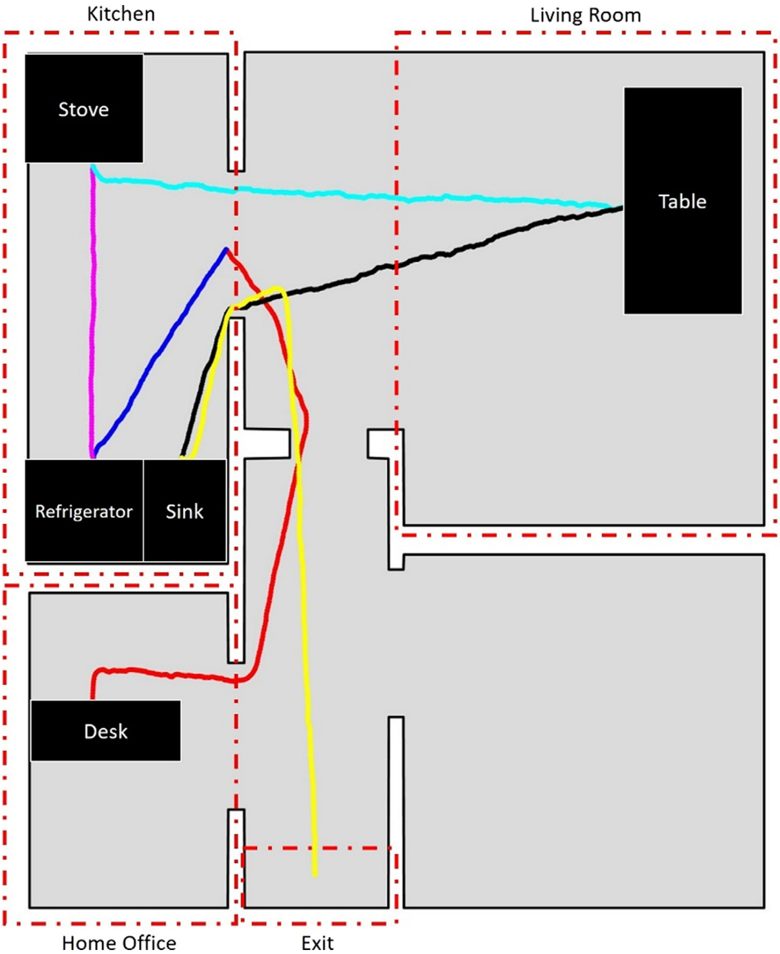


Fig. 9. Simulation results of the sequenced movement inside the selected layout. Each taken pathway is coloured by the corresponding action.

model enabling human-centric building design.

The movement simulator that has been developed delivers a new dimension for building energy performance simulations. Use of this application allows simulating all occupant transitions inside the buildings. It includes actions related to adjustment of the comfort, opening the windows or adjustment of the setpoints on the thermostat. All these actions require movement of the occupants to be conducted. As shown in the Results section, the tool can deliver the functionality of formulating a procedural generation of pathways taken by building occupants. It does not require an advanced artificial setup of the pathways, which can be considered a time-consuming activity. It allows to put the focus on the scheduling of the activity or programming the potential reactions of human behaviour. Therefore, that task can be introduced to a broader audience, not only to building design practitioners or scientist related to the field, but also to social scientists, behaviourists and psychologists. Use of this technique allows for an extraction of data about the position of the individual body. This information can also contribute to occupant behaviour thermal comfort models. Ability to probe data about indoor air states from numerical simulation allows for the introduction of the new numerical solver that reacts on a particular "sensed" condition. In consequence, it will influence simulated building energy performance by adjusting the indoor environment to its preferences.

The main functionality is simulated by the simple solver, which leaves significant space for the addition of potential modulators. The source of those triggers can be obtained from other future implemented modules of the building occupant transient agent-based model. Execution of the signal modulation inside the solver can be done by providing a set of additional variables in the decisions of the agent making the step. For example, while selecting the pathway, the main driver is pathways distances between the start and the end point. However, it is possible to influence the pathway selection by other parameters that could originate from other modules, e.g. possibility to fulfil other tasks on the fly, or preferable thermal conditions of a different pathway.

As shown in Fig. 9, the agent can simulate pre-scheduled activities being "aware" of the placement of the features. This assumes that agent is familiar with the used space. Hence, it does not require permanent space recognition systems, such as Simultaneous localisation and mapping [49,50]. Therefore, simulated occupants, i.e. agents behave, such as typical occupants of that building do. Implementation of the "first-time use occupants" module can be conducted in a similar simulation environment, but it requires a different computational approach.

Floor layouts used in the displayed simulations (Fig. 7, Fig. 9) were quite large, with a relatively advanced connection grid. In the future, the indoor layout connection grid should be decentralised. Use of one large connection grid should be avoided. Otherwise, it will generate an unnecessarily complex connection matrix to simulate. Each room can be separated by the doors, which can be considered a separator and coordinate point. Implantation of this feature will decentralise the connection graph, which will significantly reduce the complexity of the connection matrix. Simplification of the connection matrix will automatically accelerate the computation time. Additionally, if during a simulation, more than one agent was included, it would be necessary to constantly update the connection matrix by moving the position of supportive corner points from the agent. Operation in a one-connection matrix that would require such constant refreshment would generate unnecessary use of computational power.

The introduced foundation of the agent-based model can follow a given instruction of the activities/actions. No matter how complicated scenario is generated, the agent will be able to follow its instruction. Development of the tool that allows the formulation of the action instruction is not yet available. This feature will be addressed in the future research. Additionally, it is recommended to describe actions in a way that allows for a certain degree of freedom of a behavioural pattern's digital representation. Each task should be described by the time that it should last, parameters that it might influence, and input arguments that might modulate its action. With such a comprehensive description, the agent would interact with the given environment more autonomously. Introduction of this parameters should be followed by a description of personal profiles of the occupants. Ability to describe and generate various profiles of occupants would allow testing their reactions to the given environment during the design. Occupant profiling should include parameters that hold a certain level of individualism, such as thermal comfort or hunger.

Access to all the mentioned functionalities can increase the accuracy of general building performance simulation. The implication of the presented simulation methodology can contribute to a better understanding of building occupants. A better understanding of occupant needs might contribute to development of the new, human-centric rules for building design and control. It can be used to identify limitation of already existing buildings and propose a solution that might optimise building energy use and increase the general well-being of occupants. The present movement simulation method would add a missing piece that links the dynamic behaviour of occupants with building design and simulation software.

Further extension of the present movement simulation tool will eventually grant the ability to develop a "digital twin" of the building. Where each object included inside real-building, has its digital representation in a software. As already recognised, humans play a significant role in building energy use. Therefore, their presence and activity must be included in every simulation of building performance.

Ability to generate high-resolution sampling of the movement patterns can benefit numerous applications. It can allow simulated occupants to probe information about the micro-environment surrounding them. In the same time it can introduce a threshold-based feedback control of the building control system. Not only does it allow to investigate the implications of the proposed heat, ventilation and air conditioning system, but it can also be used to benchmark building sustainability and resilient. Such a solution enables testing the security of the building and system design regarding the handling of various weather conditions. Oncoming global warming correlates with frequency appearance of hazardous weathers conditions such as heatwave. With the proposed application, it is possible to simulate dangerous weather conditions and check what is expected thermal stress that the human body will be exposed. Access to such information might influence future designed routines, where potential misconduct might directly affect occupant's health security.

The idea of this model is to simulate natural occupants' indoor transitions. The current stage of the model allows simulating transition of the occupant represented as one point in the plane, which is the current limitation of the model. Even if the position of the skeleton model will be described by a three-dimensional humanoid, it is not possible to re-create all of the natural limp pendular movements while transiting. Additionally, each interaction with an appliance or furniture in a room has no representation in motion-captured limb transitions. Skeleton model stands stiff in front of its target. The current model assumes a particular amount of time that occupant is interacting with its destination place. If both of this issue were addressed, it would open a possibility to simulate an occupant activity rate, by introducing a physical property to each occupant limb. Future research should focus on resolving this issue and delivering a promising tool for building performance simulation.

CRediT authorship contribution statement

Jakub Wladyslaw Dziedzic: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Visualization, Validation, Writing - review & editing. **Da Yan:** Methodology, Formal analysis, Writing - review & editing. **Hongsan Sun:** Methodology, Formal analysis, Validation. **Vojislav Novakovic:** Formal analysis, Writing - original draft, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

Acknowledgements

The data collection and storage method applied do not allow identifying the participants of the study. Therefore, this study does not require certification by an ethics board. The authors declare that they have no conflict of interest. For this type of study, formal consent was verbally delivered by the participants of the study. The authors do not endorse any specific brand or device developer. The study has not been sponsored or influenced in any other manner by private companies.

The computer setting for the measurement procedure was as follows: Intel® Core™ i7- 4785T with a CPU of 2.20 GHz: 16 GB DDR3 RAM; Intel HD Graphics 4600. Using a different setting of hardware for the measurement purpose may influence the sampling time. This publication does not seek to promote any specific product or brand.

The authors of this paper received funding from the EU-China "IRES-8" Mobility Project under EU Contract Number No ICI+/2014/347-910. The contents reflect only the author's view, and the European Union is not liable for any use that may be made of the information contained herein.

This position paper has benefited from broader discussion of occupant behaviour in the International Energy Agency Energy in Buildings and Communities Program (IEA EBC) Annex 79: Occupant-Centric Building Design and Operation.

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Paper No.10 J. Dziedzic, D. Yan, V. Novakovic; Exploring possibilities to quantify the qualitative description of occupant behaviour, BuildSim Nordic 2020, Conference Paper, Under Review

The final published version is available in
BuildSIM-Nordic 2020. SINTEF Proceedings no 5 s. 333-342

Exploring possibilities to quantify the qualitative description of occupant behaviour

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Abstract

Human behaviour is a multidisciplinary subject that is being investigated by numerous scientists around the world. The ability to understand and forecast reactions can be beneficial for all scientific branches that are related to this subject. With the increase in the accessibility of personal monitoring systems, a new era of human behaviour research has begun. Currently, in the market, there are many inexpensive and reliable solutions that can grant extra insights into the everyday lives of human beings. Regardless of whether the monitoring solutions are stationary or wearable, they can provide very detailed information with high operational and temporal resolution. Access to these data has advanced our understanding of human routines and habits, but it does not provide insights into the "soft" data that define human beings.

Once the quantitative data has started to enrich scientific databases, the community has started to question whether such information is suitable to detect or record qualitative ("soft") output. Typed text is not included, but it is possible to extract existing data and to obtain "soft" data. This manuscript will try to address this issue. It proposes a straightforward solution that can have great potential for implementation purposes. It investigates the existing literature and tries to evaluate its applicability for numerical implementation. One of the highlights of the manuscript is the proposal of a novel modelling solution that can cooperate with other occupant behaviour-related simulation models. Finally, the manuscript tries to outline future steps to enable the possibility of translating or modelling quantitative input into qualitative output.

Introduction

The possibility of fully re-creating human behaviour can be considered an enormous task if certain boundaries are not stated. The main question depends not only on whether it is even possible but also on the potential simulation goal and the operational resolution. Beyond typically measurable "hard" parameters such as temperature, CO2 or humidity, which can be adopted in any investigation scenario, there is a "soft" side of data, which is considered qualitative information [1]. Such data deliver a subjective opinion about the subject in question. For example, if a person is asked about whether he or she is comfortable, the obtained answer can be hard to quantify. In most cases, the delivered responses might be similar to answers such as "I am fine" or "I feel slightly uncomfortable". The main issue regarding such qualitative output is its measurable repetitiveness [2]. Does such an input operate on a linear scale? If yes, what is the threshold for a specific answer? How similar or overlapping are specific states? If such output cannot be explained based on a linear model, what kind of model should be implemented? These are very important questions, but presently, even with the existence of social media such as Facebook, Twitter and other applications, it is hard to provide a definite answer regarding such "simple" questions [3]. This can be considered a major limitation if the desire is to translate qualitative data into quantitative output. To overcome this issue, the problem could be potentially reversed engineered in a specific way.

It is nearly impossible to ask building users about their satisfaction level during each activity that they are involved in. Even if such measures were possible, the reliability of the results would be questionable. Constantly questioning test subjects about their status would be more like a burden than a support system. After a very short period, participants would become tired or fed up of being involved in such an extensive study, which consequently would corrupt the collected data [4]. Being involved in an experiment would play a major role in their daily routine, and their answers would reflect this phenomenon. To make such interventions more reliable, their frequency cannot go against participants' comfort. Therefore, the sample rate will be rather small, especially if such information is compared with information that can be gathered about the environment. However, this issue does not automatically discredit the applicability of such data. If test subjects agree to be extensively monitored using in situ methods, such quantitative data can be used to formulate an ontology for labelling various activities [5]. Each discrete action observed can be formulated in sequence or parallel scenarios. If the observed phenomena are repetitive, these activities can be labelled as a routine or a habit. During each intervention, an interviewer might present a list of all observed habits and ask about the purpose, feelings and desires that were associated with such activities. In this way, each recorded activity can be labelled, and with the use of sophisticated deep-learning methods, such data can be used to pre-train and to develop a labelling tool. This tool can help to observe and examine quantitative output.

Labelled data would allow to describe the origin of a specific qualitative output. Proposed solution would act as a supportive machine to define whether the specific qualitative output is embedded in psychology, physiology or a mixture of these parameters. If the repetitive pattern of activities constantly provides similar output and for unknown reasons the response is different, then it will be an indication that the origin is embedded somewhere beyond quantitative observation. Therefore, it will enrich the model structure by providing a new branch of connection to the outcomes of actions. Additionally, conducting such a study will highlight the spectrum of activities that could influence human well-being. Such analytics can be conducted at the individual, group or population level, which might highlight the personality differences among test subjects. Studies that try to reach such a sophisticated level of occupant behaviour description have not been found. There might be many reasons for such a situation, but one of the identified constraints might be a low level of interest in the direct monitoring of occupant actions. This situation is changing with each passing year, but the methodology for fully tracking occupant indoor activities has not yet been established. There are studies that focus on this subject such as [6], [7], but studies that track all indoor activities (to a reasonable extent) have not been found in the existing literature.

Since it is currently not possible to translate qualitative data into quantitative information, it might be possible to develop a methodology (application) for receiving a qualitative output from a simulated occupant. For application purposes, it is necessary to establish a framework and to define all potential functionalities that enable the simulation of a "virtual being". The aim of this manuscript is to define, develop and discuss the possibility of connecting qualitative and quantitative studies about occupant behaviour in residential buildings. The focus is on the possibility of simulating each occupant as a separate "virtual being" and the possibility of obtaining qualitative feedback from them. In this way, the interaction between occupants can be included in the simulation environment. This work is based on a collection of reviewed papers and numerical explorations of modelling practices for re-assembling the typical family. This manuscript has to be considered a hypothetical exploration of the ability to portray the qualitative desires of indoor occupants in a simulated reality. The ability to simulate each particular individual output will open a new dimension with regard to the interaction of virtual occupants. Additionally, this will allow us to formulate a social structure of interactions in which each virtual occupant is an active or passive participant. The motivation among occupants might vary, but it can be considered a main driving force of being involved. For the purpose of explaining each day of the occupants, this is considered a "game". The fulfilment of a specific motivation is considered a "win". Each included virtual being will participate in a "game". For this reason, such a "game" requires a description of its "mechanics". Studies that focus on simulations of human behaviour can be divided into two main categories: indoor and outdoor simulations.

The occupant is recognized as a crucial part of the building's "metabolic system". This is a relatively fresh concept. Therefore, the current time spent on development has allowed the validation of general theories. The use of the metrics proposed by Fanger is considered a good approximation [8]. The proposed approach bounds all building users and defines the principles for the human-centric design of a building's heating, ventilation and air conditioning (HVAC) system. The solution proposed by Fanger was considered as a state of the art in previous years. It was one of the first attempts to include the "human" factor inside the building. Fanger's studies could be considered a first milestone that establishes a building's users as an important factor during the building design phase. Fanger's discoveries have opened a new methodological branch of building science that focuses on occupant behaviour [9], [10], [11]. Once the subject of interest was introduced, it started to gather a larger audience. It became a foundation for investigating human indoor comfort, and it was extended even further. It has allowed to formulate many highly impactful discoveries about the human indoor environment [12], [13], [14]. Extending the research subject with regard to the impact that an occupant has on a building's energy systems has allowed us to formulate important theories about energy-related occupant behaviour [15], [16]. Currently, research is part of a larger subject that focuses on building energy performance. The combined efforts of scientists who have contributed to the development of this scientific branch have allowed us to formulate a "know-how" [17] guidebook that tries to describe occupant behaviour investigations in a holistic way. Additionally, it summarizes current knowledge about the subject and highlights new challenges [18].

One of the offshoots of occupant behaviour studies has made it possible to formulate and implement numerous numerical models that are now commonly used in commercial building simulation software, such as IDA-ICE, Energy Plus, DeST or Rhinoceros' Grasshopper with LadyBug [19]–[22]. Due to the currently available computational processing power, it is possible to introduce more detailed models that focus on individual building users. Currently, there are no guidelines that limit the complexity of the proposed models. As a rule of thumb, the calculation time should allow forecasts of the near future (for model predictive control applications) or annual simulation. Both applications require a different level of temporal and spatial resolution, but in both approaches, the validation process still requires a huge improvement to check its clarity, applicability and robustness. Typically, such applications have a description of the physical properties of the used materials and a simplified energy equation (selection of the numerical methods depends on the software used and application purposes). Additionally, the entire simulation can be enriched with a series of probabilistic models focusing on specific occupant-related aspects such as presence, window and blind operations or plug load use. There are a few more sophisticated methods that try to re-create occupant indoor activities, such as those proposed by T. Hong, in which the occupant behaviour model operates as a functional mock-up obFMU [5].

The simulation of occupants outdoors focuses on the behaviour of the crowd. These simulations are mainly applied to model a specific phenomenon in which the crowd is involved, such as setting up proper sidewalls [23], checking the labelling of streets/large areas [24], setting up a time opening for pedestrian lights or designing escape routes from large spaces/buildings [25]. The description of each particular occupant is dependent on the purpose of the simulation. The description of functionalities is simplified, and a specific simulated feature operating on specific distribution to generate a crowd profile. For example, to simulate a pedestrian crossing light, each simulated occupant must obey the lights to a certain extent. However, the factor of following the rules might be time-dependent. Therefore, if a specific waiting time is prolonged, the threshold for breaking the rules decreases. Combined with an extra occupant following functionality, it is possible to produce a significant model for testing the safety of a street. Both functions can be considered occupant attributes, and levels that trigger specific reaction can be individualized and distributed among pedestrians by certain distribution functions.

Previous studies that have tried to portray occupant behaviour have used a representative occupant [26]–[28]. This means that all groups included indoors or outdoors were represented as artificial occupants that hold the sum of all actions. In those cases, there is no individual simulation of behaviour, and all actions are captured in a group-size resolution. The model data obtained in such a manner can be used as a support for future development attempts, but precise information on individual actions plateaus. The data used for these observations were collected mainly from interactions with various controllers (such as a thermostat [16]) and indoor monitoring devices (such as plug load metres or the PIR sensor [16]). Even without high spatial and temporal resolution, it is possible to distinguish a few types of representative energy user archetypes [29], where their behaviour operates on two dimensions related to energy awareness and general wealth. Despite the lack of individualization, such studies can be used to develop a database of all potential activities. It has to be pointed out that such an approach guarantees the stability and direct reproducibility of the study due to the operation on a purely statistical basis. This flattens the specific context (knowledge of users) but delivers a model that is reliable. This model representation of users offers a probabilistic approach, which is sufficient to a certain extent. If an investigation target focuses on personalized control, it is necessary to implement solutions that involve a more deterministic approach. It is very common to justify and explain occupant behaviour with the use of stochastic methods. Although they are a convenient method for describing repetitive actions, where the initializations might vary due to numerous implications, stochastic methods are a simplification of deeper phenomena [30], [31]. The use of this methodology implies that occupant behaviour is a stochastic process, which contradicts its deterministic nature. Put simply, the actions of occupants depend on proper circumstances and motivations, not a randomized action. Therefore, to create an individualized simulation for a specific building user, it is necessary to operate on a similar structure. The closest method that operates on similar principles is a pre-trained artificial intelligence model.

The urge to define occupants as individual "virtual beings" in a simulated environment is also suggested by other scientific branches, such as medicine [32], and sociology [33], [34]. However, these branches can also be connected by topics focusing on energy usage by various social groups. Most of these studies aim to recognize the current understanding of energy uses inside residential houses from the perspective of their own scientific context [38]–[42]. One investigation subject that can be explored is the impact of ICT on the structure of the family or how occupants understand the concept of energy savings. This study allows for a multidimensional analysis that can be related to sociology, psychology and energy studies. Unfortunately, such studies are carried out in a relatively small group of participants, but they still provide valid and representative output. The utilization of the insights gained allows the construction of a model that relies on a typology of activities, similar to Pavlovian conditioning [40]. Such an application can be a separate model, or if its structure has a modular application, it can be considered a module of a larger occupant behaviour simulator [41].

Aim

From the qualitative research perspective, there are a few models that can be implemented in functional applications, such as the theory of planned behaviour or Maslow's hierarchy of needs [42], [43]. The main issue regarding these modelling approaches is their Eulerian nature. This means that the proposed models have a clear and understandable structure, but their implementation is difficult. For this reason, it is necessary to try to approach this issue with a more Lagrangian approach, where the structure of the model might be more complex and convoluted, but implementation will be more straightforward. The main aim of this manuscript is to define and describe the process of developing an occupant behaviour model/module that delivers qualitative data as an output. Due to the lack of data that can completely support this process, the whole development will rely on existing studies, discussions and conclusions provided by the literature. Additionally, the whole model/structure is designed from the implementation perspective.

Studies in the literature have shown that there are a few examples of attempts to approach the qualitative output issue. Unfortunately, deeper analysis does unravel the problem is relatively ignored [15]. In this study, the attributes of particular occupants are defined as a trigger to carry out an action, which is counted as the fulfilment of a need/desire. This could be considered a "shallow" ontological approach in which specific needs can be met by a selected driver, which, to a certain extent, is correct, but its structure limits the existence of other options. In other words, models are blocked by this framework.

To address all these issues this manuscript will try to develop a semi-open structure for a framework in which each sub-part of the model is described. To not overextend the subject, the proposed simulated model will be tested to simulate two specific scenarios that were investigated in previous studies.

Methods

First, with regard to the description of model development, it is necessary to define all the vocabulary used and the basic mechanics of the "game". This manuscript is operating on the edge of engineering and sociological studies, and each of these fields has similar terms, but their meaning might vary. Therefore, it is necessary to define an operational library. Each simulated person is considered to be an occupant. Each occupant is simulated individually. The qualitative model output is considered a defined spectrum of answers from simulated occupants that informs the status of goal fulfilment. There is no predefined pathway that will promote fulfilling a goal. The goals are defined as a target of actions or a state that one specific occupant has to obtain to fulfil his or her personal needs. Personal needs are the pre-defined boundaries of each person that cover a spectrum of basic human needs, such as hunger, stamina, and social interaction. Each target has its selected description that defines the conditions for reaching it, what is an acceptable buffer and what is a qualitative outcome. For the purpose of theoretical analysis, this study will limit itself to five specific needs (Entertainment, Hunger, Hygiene, Social interaction, Stamina), which are usually mentioned in research related to the description of personality [44]–[46]. The "game" is a simulated activity with a selected time horizon. A whole "game" has four main layers, and the first layer defines the rules for reaching the target. The second layer focuses on relationships and the relations of the simulated occupants. The third layer focuses on describing the elements of the activities and actions that the occupants have to take to be involved. This layer can be considered a building block for formulating the action. The fourth and final layer describes the occupants individually. The result of each game is ultimately connected to two outcomes, winning or losing. A "win" is an outcome in which the target desire is fulfilled while staying within the boundaries of personal needs. Losing is considered a state where one or none of the winning elements is not fulfilled. The outcome of the "game" influences the qualitative state of the simulated occupant. Winning boosts the level of well-being, and losing decreases it. Well-being is a one-dimensional variable that operates on a mathematical plane of real numbers. If the value is positive, the occupant reports a positive state, and vice versa for a negative value of well-being. It is a time-dependent variable that aims to obtain a neutral zero value. This process will be called "mood neutralization". The dynamics of this parameter can vary between occupants, but for this approximation, the parameter will be held constant at a selected value. Therefore, each occupant has one linear curve of mood neutralization. To make the description more transparent, each layer of this model will be described in descending order in a separate subsection.

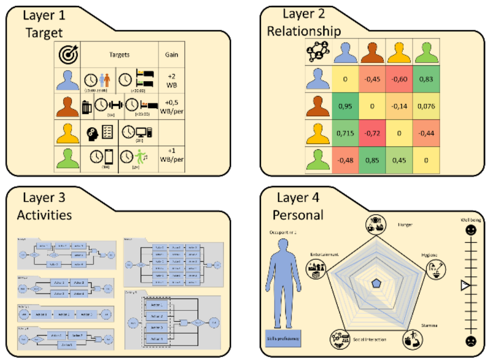

Figure 1. Layer structure of the whole model

The structure of each target is the same in terms of the framework, but the selected conditions have to be defined on an individual level. Such an implementation allows us to formulate means of personalities and allows space for the potential simulation of the personal evolution of the needs of occupants. The qualitative outcome of a simulated activity strictly depends on a buffer of acceptance, which makes acceptance a dynamic variable. If a simulated occupant "wins" the "game" even without being fully in aligned with his or her personal needs but is still inside the buffer zone, the occupant's personal needs will be impacted. If such an event occurs more frequently, the description of personal needs will evolve. It is possible to forecast that if such a numerical simulation is left alone (continuous simulations of daily activity), it will tend to generate "pathological" scenarios where one participant will be overused. This will consequently lead to a reinforced shift in personal needs. Such a situation might happen in real-life scenarios, but in most cases, it will not happen in a short period of time. To counter the development of an excessively accelerated change in personal needs, it is necessary to implement a negative reinforcement. This will gradually reduce the previously gained modifications of the personal need parameters. In terms of the core structure, in whole "games", there are three times more losing than winning outcomes. Therefore, observing the "personal" evolution during the simulation process must be connected to a constant positive "game" outcome. To implement this functionality, each occupant has to hold a memory of the baseline of each personal need and the changes that occur due to modifications. To make the description more transparent, the whole model structure is presented in Figure 1.

Reaching the target requires performing all the actions in a series of activities. All of the actions are operating on a global time step. Each activity that can be performed in the real life is considered as a series of actions that are defined by the specific activity. The completion of one action depends on the time and effort spent on performing it. It is a cumulative threshold value that triggers a confirmation that the action has been completed. There is no qualitative evaluation of the action performed. If there is an action that does not require constant involvement, in its description, there is an additional "NaN" parameter. This means that the action has at least three threshold cumulative values, where the first defines the amount of time that has to be spent to reach the "NaN" status. The second threshold defines the amount of the cumulative time value until the action will stay inside the "NaN" status. During this time, occupants cannot accelerate the process by using their skills. The third threshold defines the amount of the cumulative value that is necessary to finalize the activity. One activity can have more than one "NaN" status, and its appearance depends on the types of actions that are defined. It is assumed that occupants are aware of the structure of whole actions. During the "NaN" status, occupants gain an additional timeline that can be used to perform any other action. For example, to boil water with the use of an electric kettle, it is not necessary to wait for the entire boiling process. This time can be used to become involved in other actions, which are defined by the activity. Each time step that contributes to the completion of actions reduces the amount of stamina of occupants. From the operational perspective, actions are defined by two variables: time-dependency and score-ability. If an action is time-dependent, this means that its appearance exists during the specific moment in the timeline. If the targeted occupant will not engage in performing the action within a defined time window, this action is concluded and cannot be performed. Scoreable actions are events in which the performance of such actions has a direct influence on the whole activity. Therefore, the outcome has an influence on the entire activity that the occupant was involved in. To summarize, activities can be divided into four groups separated by two variables, (time-depended scoreable; non time-depended scoreable; time-depended non-scoreable; non time-depended and non-scoreable). The visualization of the action block that can be used to model the whole activity process is presented in Figure 2.

Place	Action n		Gain
{Location}	• Time requested	n=T[s]	
	• Proficiency mod.	X*n	
	• Penalty		
	➢ Entertainment	$-x_1$	$+y_1$
	➢ Hunger	$-x_2$	$+y_2$
	➢ Hygiene	$-x_3$	$+y_3$
	➢ Social interaction	$-x_4$	$+y_4$
	➢ Stamina	$-x_5$	$+y_5$

Figure 2. Action module structure with all necessary inputs and outputs

The completion of a specific activity depends on two functions, proficiency and focus. Proficiency is a fixed function that describes the experience of the occupant in performing a selected action. The more similar the category of actions performed, the more skilled the occupant becomes. The proficiency level accelerates the process of performing an activity. It can be considered a multiplier for its completion since actions are performed based on an accumulation of time steps that occupants use to participate in these actions. The action proficiency level will multiply the value of each time step that was used for these actions. The focus parameter is a survival model that defines the amount of time that a specific occupant will stay focused on an action. The survival model is a probabilistic time function that describes the amount of time that specific phenomena will last. It makes it possible to describe one-dimensional phenomena in which the chances of occurrence increase over time. For example, with this approach, it is possible to simulate the time until a window will be shut once it is opened. Initially, the chances that the window will be closed are small, but once time starts to pass, there are higher chances that it will be closed. This approach is usually supported by a prolonged period of observations. Observed phenomena are investigated based on the time they last, and aggregated data allow us to formulate a distribution. The formulated distribution becomes the foundation of the survival model. This model will be implemented to simulate the focus of the occupant and to provide the solver that will be responsible for simulating the attention time spent. The shape of the curve is dependent on numerous variables, and due to its simplicity, it is possible to introduce its modulators. Some impactful parameters might be age, the time of day, weather conditions, the amount of stamina or open timelines due to the parallel involvement in a few actions.

The simulation of the whole activity requires a precise definition of its sub-elements (actions). The whole sequence of actions has to be defined, with its characteristics, the cumulative time required to complete it, the necessary previous actions and the amount of necessary resources to finish it. The global order within one activity does not have to be fully specified. Some actions have to be followed by other actions, but some can be carried out in parallel. Additionally, an activity has to define the maximum number of occupants who can conduct the activity. The use of this structure allows the formulation of various scenarios. This requires defining each activity separately, but this allows us to formulate various, more realistic scenarios. The logic of the actions is not directly defined. Therefore, it is possible in such a structure to define unreasonable activities and to observe their impact. The larger the database of defined activities is, the more sophisticated simulations can be conducted. If an activity is completed, it grants specific rewards that are defined by the activity description. An activity can be built from at least one or more actions. With such a structure, it is possible to introduce the utilization of resources. This could be an additional trigger for a new spectrum of activities that rely on the control of resources levels. For the current form of the model, such a feature will be avoided because it would demand a significant effort to define the operational library. For the current state of the model, it is assumed that occupants have access to all the resources necessary to perform each activity.

The relationship layer defines the hierarchical structure of the group. It has a significant impact on the whole model. The time spent on each action can be modified by the number of people who can be involved and the number of people who will be impacted. For example, the time necessary to prepare a meal for one person will be different from that preparation of a meal for a whole family. Additionally, the potential involvement in collaborative efforts can affect the process of completing activities. If there is a difference in the proficiency level among the occupants who are involved in an activity, the occupant with the highest proficiency level will become the supervisor of the task. The supervisor will have a reduced amount of focus on the task because he or she will be controlling the others, but the proficiency level of the supervised occupants will grow faster. The proficiency level can grow to the level of supervisor. These are the rules of the task-based hierarchy that allow us to define the main person responsible for an activity that is being performed. It is assumed that the proficiency parameters are known to each occupant, as well as all other personal need parameters. Each time a task is performed by more than one occupant, the social interaction need parameter of each occupant increases. If an occupant's action involves only one person, the same parameter is reduced. Beyond the local hierarchical system, it is necessary to establish the global hierarchical system among the occupants included in a simulation. This feature will influence the involvement in actions, where a spectrum of activities must be distributed among occupants. If this parameter is left unsupervised, it can produce an uncontrollable artefact. The global hierarchical system is established in the relationship matrix, and it is assumed that the main decision makers are the parents. Therefore, if the list of activities must be distributed among the occupants, occupants representing parents will define who is involved in a specific task. In this structure, it is possible to implement a sub-layer that represents a negotiation phase, where a child can try to disobey parent and where the combination of basic-need parameters might play a significant role. For the development of the current model, this functionality will not be introduced.

Reaching the target of the "game" requires completing specific subtasks that are dictated by the ongoing daily routines. Each occupant has his or her own targets that he or she is motivated to achieve. Reaching a target requires completing a series of activities. If a target is reached with a successful score, it boosts the well-being variable. The status of well-being can change during the occurrences of various events. The current structure of the "game" assumes that each occupant aims to "win" his or her "game". The main idea of the "game" is to constantly involve the occupants in "play". Their statuses over time will be modified by the actions in which they will be involved, which can be used to evaluate their qualitative response in any selected time step. The initial conditions will play a significant role, especially if there are implications connected with having a low status of well-being variable. The current status of the whole model must be considered an initial approach for building a sophisticated occupant behaviour simulator. The methodology section describes many interactions between the different layers of this model. The interactions vaguely define the components and mechanics behind the model. Access to data that would define more concrete, quantitative connections is currently not available. For this reason, it is necessary to fine tune all the parameters to make a model functional; this will be the focus of the analysis (results) section.

Simulation setup and results

To set up simulations, it is necessary to define a set of specific actions and activities and the target of each occupant. This manuscript will test the scenario of evening routines. The whole set of activities and the necessary actions are displayed in the process graph, in Figure 3. The idea of the simulation scenario is adopted from a study on the influence of ICT on a one daily routine (Activity), family dinner. [36], [47], [48]. In the simulated test case, a family consisting of four members, two parents and two children, was generated.

		Inital Penalty				
Activity	Time[s]	Entertainment	Hunger	Hygiene	Social interaction	Stamina
Tea	120	0,1	0	0,1	0,01	0,01
Sandwich	600	0,2	0,1	0,2	0,01	0,01
Tap water	30	0,1	0,1	0,1	0,01	0,01
Table preparation	1000	0,1	0,1	0,1	0,01	0,2
Cutleries	200	0,01	0	0	0,2	0,2
Eat	2000	0,01	0	0	0,3	0,1
Phone	60	0	0,1	0,01	0,1	0,01

		Process Penalty[per/s]				
Activity	Time[s]	Entertainment	Hunger	Hygiene	Social interaction	Stamina
Tea	120	0,01	0	0,01	0	0,05
Sandwich	600	0,01	0,01	0,01	0,01	0,01
Tap water	30	0,01	0,01	0,01	0,01	0,01
Table preparation	1000	0,01	0,01	0,01	0,01	0,1
Cutleries	200	0,01	0,01	0,01	0,02	0,1
Eat	2000	0,01	0	0,01	0,01	0
Phone	60	0	0,01	0,01	0,02	0,01

		Action Gain						
Activity	Time[s]	Entertainment	Hunger	Hygiene	Social interaction	Stamina	Relations	Well Being
Tea	120	0	0,5	0,1	0	0	0	0
Sandwich	600	0	1	0	0	0	0,05	0
Tap water	30	0	0,2	0	0	0	0,02	0
Table preparation	1000	0	0,2	0	0	0	0,5	0
Cutleries	200	0	0,1	0	0,1	0	0,3	0
Eat	2000	0,5	2	0	0	1	0,5	0,5
Phone	60	0,3	0,2	0	0	0	0,5	0,1

Figure 3. Sample action table with variables necessary for simulation

Setting up this simulation requires performing a series of sensibility analyses to establish the accuracy rates and parameter modifications to reach a balanced output. The analysis of the parameter weights is shown in Figure 4. Setting up the first simulation requires a certain stabilization of the parameters to control the tuning procedure. For this reason, it is assumed that everyone is involved in activities and that occupants have the same initial personal parameters.

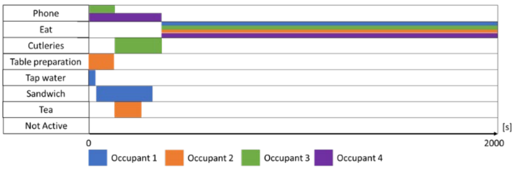

Figure 4. Simulated action sequence results

Each occupant performs his or her action and is a part of the activity process. Their actions do not operate on any dimensions other than time, at least for this approximation of the model. The lack of a physical connection makes it possible to operate on an abstract plane of the whole process, where involvement in a specific action can be visualized. Each occupant has his or her own "game", which can be considered a process. Each occupant has its own needs that are evolving thru the actions that are involved. The results of this simulation of occupants' needs are displayed in Figure 5.

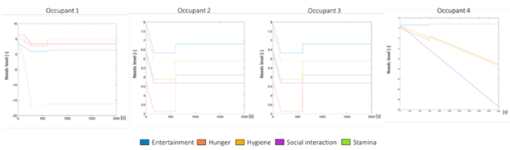

Figure 5. Occupants' needs simulation results.

Discussion

The ability to simulate occupants' qualitative output is a novelty in the research field. Performing validations of this concept would require conducting multiple tests, where trained personnel would collect data for this purpose. It is a challenging task, but with the selection of a specific mechanics, it is possible to narrow down the number observations necessary to complete such a task. Put simply, once the framework is established, it is easier to define the goals of observation.

The proposed model is developed with an application goal. It is recognized that occupant well-being has a significant impact on the performance of occupants, and this parameter must be included. The main issue with "soft" parameters that describe occupants is the lack of knowledge about how to include them in a simulation. The issue is exacerbated if it is assumed that feeling and sensation are a subjective, personal experience. If such a status is accepted, the development of this model has to be defined by each separate person. This would require a detailed "bottom-up" approach, but certainly, it is possible to implement this methodology in small test cases.

The proposed model is built from the engineering perspective, where actions are followed by the reactions of the overall model. Studies that followed a similar procedure or that investigated human behaviour in similar matter were not found. There are many good models proposed in a past, that define human drivers and that describe human dynamics, but none of these descriptions allow us to atomize the content of the investigation. This means that tremendous efforts that were made to develop a structural model do not allow to extract the contents of actions and reactions. Existing studies can be considered inspirational, but the qualitative data that they collected are far from being considered for implementation in numerical simulation. Additionally, current control of status parameters requires more tuning, but this should be fixed once the proper measurements are conducted.

The main disadvantage of the proposed model is its reliance on action, activity and human profile libraries. This requires access to a huge variety of activities to function correctly. Development of vast library is beyond one research group or project. To develop such a database, it is necessary to involve volunteers. With the formulation of a proper survey, participants can be asked to describe their daily routines. Each routine can build from action/activity blocks. These blocks will represent each action that occupants can be involved in. While describing an activity, participants can be asked about the benefits and requirements that are related to routine, activity or action. In this way, it would be possible to develop a crowd-sourced database that defines daily activities. Each similar routine could have multiple, different actions included, or its order may vary. Once the data base is saturated with a significant number of activities, it can be implemented in the proposed model.

The complexity and variety of scenarios can be extended nearly to infinite. Especially if each included in simulation occupant has an extensive list of factors that might influence the motivation and need. Even if the amount of the influential parameters would be limited to a small number, the core design of the proposed numerical solution promotes lack of direct reproducibility, but the reasoning of the actions is capped. Each action can be stopped or initialized based on specific, defined distribution. Each distribution function can be modified or transformed by numerous conditions like weather, health, type of event, date, relationship to other occupants or others. Combination of all of these factors influences occupants engagement in action. If all of these parameters are also time depended, the level of complexity rises exponentially. This is a significant limitation because it does not allow to validate the proposed model on an operational level. The proposed solution can be tested with the use of the stochastic methods, which will blur the main context of the model. It will not draw one single cue of actions, rather a set of cues that are emerging into a similar status. If the rules of the proposed "game" for increasing well-being status are considered as a correct, the direct link between the motivation of actions and reaching the goal can be measured by means of entropy. It changes the mathematical apparatus and do not discards the story that leads to effect. It instead evaluates each action, or piece of a timeline how it declines from the goal.

Additionally, it is important to discuss the pros and cons between simulation and rule-based modelling. Both approaches are fundamental, but each of them has its flaws. Numerical simulation operates on a non-natural random number generator. If such setup is left running without any supervision (rule), it will not produce any consistent results. Each simulation has to have its limitations that are stated by the set of rules, for example, the level of convergence or boundary conditions. On the other hand, fully rule-based methods will not promote any diversity; the rules are followed until the fulfilment conditions are met. Incorporating occupants simulation by the use of these methods as a seldom solver is inapplicable. It is possible to assume that each person has its plan (cue) of action set in a logical order. However, such a plan could be considered as rational only for them, due to their limitations or personal triads. Therefore, the fully rule-based methodology cannot be applied. Promotion of any diversity among the simulated individuals, requires introduction a certain amount of variety, that can be found in simulation methods. To somehow overcome issue connected with both of these methods, it is necessary to combine positive sides of each approach and overcome existing disadvantages. Such a task is an important limitation because it requires a definition of how rule-based or chaotic is a specific person and their personality.

The development of this model aims to be implemented in a building performance simulator. There are existing building numerical models that could potentially operate on outputs provided by this model [41]. For this purpose, access to an activity scheduler would be a significant asset and would allow to simulate the realistic utilization of energy resources. Currently, the available functional models do not allow us to track the reasoning of individuals. The links of cause and effect are broken by implementing fixed schedule or time-series models [49]–[51]. In proposed model, it would be possible to trigger interaction with a simulated building infrastructure. Therefore, each action would have its own marker. Similar to the block-chain technique, each component of the simulation would hold a permanent record of who was using it and when. Incorporating the well-being status would introduce a new dimension that could influence the energy usage of the building. In particular, the link between occupant thermal comfort and well-being could be established.

Conclusion

The idea presented in this manuscript tries to capture and implement in simulation software artificial qualitative responses of human beings. The main aim is to implement a systematic solution that can be further developed. Due to the limited resources applied, this methodology cannot be extended, but its current state can be used as a reference framework. It is difficult to judge whether such a methodology is fully correct from the social science perspective because the work presented is a mock-up. Its main advantage is the possibility of simulating the human-interaction process, where each included person plays his or her role in reaching his or her goals. The proposed solution has a relatively simple core structure, but the interconnection between parameters starts to increase the level of complexity significantly. The design of the model and its key parameters was selected to be fully used during simulations. This indicates that such similar parameters should be considered when performing a model validation data collection procedure.

Based on existing studies, it is possible to extract pieces of information about how the model delivers qualitative output. The closest approximation can be found not in the scientific literature but in interactive entertainment systems. Pieces of software that focus on a procedural world building environment develop similar simplified tools, but their applicability is questionable. Applications such as Dwarf Fortress or RimWorld focus on a computer simulation of societies where each new application user delivers a unique social network and history of events and relations is shared between non-player characters (NPCs) [52], [53]. It is obvious that it is impossible to program all of the connections between NPCs; therefore, an algorithm that is dedicated to such a task must exist. Additionally, substantial access to the computer's rapid access memory must be held to operate with all of the connections that are delivered during the simulation process. It is expected that the only applicable solution for handling social interaction and simulating qualitative responses can be achieved with the use of procedural techniques. Procedural generated interaction is relatively simple in a core design, but it allows to build advanced scenarios without the extensive influence in software code.

The initial challenge that was presented in this manuscript concerned questioning the possibility of translating qualitative human input into accurate quantitative response output. Such a task can be considered unachievable due to the overcomplexity of human nature. However, the combination of extensive in situ monitoring techniques and the further development of the proposed model can be a solution to this task. It requires appropriate detection ontology, recognition of an observed person, and detection activity that the observed person is performing. Those parameters can be an initial input to pre-training the model that is presented in manuscript. Once the significant training is completed, the monitored occupant can be evaluated in terms of his/hers potential qualitative output. Such a combined system can be considered a model predictive control for human qualitative response (MPC-HQR). The use of such a technique is blocked not by the current limits of technology but by the critical mass of activity descriptions and number of studies that share similar methodology and framework. Once this status will be changed, collected data can be process with a support of advanced statistical methodologies. The contemporary advancement of machine learning and deep learning techniques makes it possible to precisely classify data without a significant amount of computational time. Usage of this technique with collected information would allow to train a labelling tool for proper qualitative recognition. With this knowledge, it is possible to conclude that once a proper targeted study that aims to collect different activity scenarios is conducted, it will be possible to reach application of MPC-HQR in a relatively short period of time.

Acknowledgement

The authors gratefully acknowledge the support from the Research Council of Norway and several partners through the Research Centre on Zero Emission Neighbourhoods in Smart Cities (FME ZEN).

This position paper has benefited from broader discussion of occupant behaviour in the International Energy Agency Energy in Buildings and Communities Program (IEA EBC) Annex 79: Occupant-Centric Building Design and Operation

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Paper No.11 A. Das, J. Dziedzic, M. Annaqeeb, V. Novakovic, M. B. Kjærgaard; Human Activity Recognition Using Data Fusion and Deep Learning Methods, Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, Journal Paper, Under Review

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