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Agent-based Modeling in Building Simulation: Where do we stand?

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KURZFASSUNG

Diese Diplomarbeit beschäftigt sich mit der Darstellung von NutzerInnen in Gebäudesimulations-Anwendungen, insbesonders in jenen, die Energieeffizienz und Innenraumklima von Gebäuden untersuchen. In den letzten Jahren wurde der Bedarf an umfangreicher und detaillierter Information von nutzerbezogenen Einflussparametern auf die Gebäudeperformance immer wieder zum Ausdruck gebracht. In diesem Kontext sind eine Vielzahl an stochastischen Modellen entwickelt worden, die als Alternativen zu konventionellen, regel- und zeitplanbasierten Formaten vorgeschlagen wurden. Insbesondere wird die agentenbasierte Modellierungstechnik als flexibles und leistungsstarkes Format vorgeschlagen, welche die Komplexität individueller Verhaltensmuster von GebäudenutzerInnen erfasst.

Basierend auf diesem Hintergrund umfasst die Diplomarbeit folgende Beiträge: *i)* ein Überblick des aktuellen Standes der Technik in Hinblick auf personenbezogene Modelle in der Gebäudesimulation; *ii)* eine allgemeine Darstellung von agentenbasierter Modellierungstechnik; *iii)* ein umfangreicher Review von agentenbasierten Modellierungsanwendungen im Bereich der Gebäudeperformance-Simulation. Abschließend legt die Arbeit den Fokus auf die Einschätzung von zukünftigen Entwicklungsperspektiven sowie Forschungsschwerpunkten von agentenbasierten Simulationsanwendungen im Bereich der Gebäudeperformance.

Keywords

Agentenbasierte Modellierung, Benutzerverhalten, Gebäudeperformance-Simulation

ABSTRACT

This thesis concerns the representation of occupants in building simulation tools that deal with buildings' energy and indoor-environmental performance. In recent years, arguments have been made suggesting the need for more sophisticated user-related building simulation input data. Thereby, stochastic models have been promoted as an alternative to conventional schedules and rule-based formats. More specifically, agent-based formalisms have been suggested to provide a powerful and flexible tool to capture the complexity of building users' presence and behavior in buildings.

In this context, the present thesis offers the following contributions: *i)* a brief overview of the state-of-the-art in user-related models in building simulation; *ii)* a general discussion of agent-based modeling techniques; *iii)* a concise review of application instances of agent-based modeling in building (energy and indoor-environmental) simulation. The thesis concludes with a general assessment of future development prospects in this domain.

Keywords

Agent-based modeling, user behavior, building performance simulation

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CONTENTS

1 INTRODUCTION

1.1 Motivation

Representation of building users has been mentioned as a major source of uncertainty in building performance simulation (Bishop and Frey 1985, Hoes et al. 2009, Hong et al. 2016a, Li et al. 2014). Thus, occupants are considered as a crucial aspect in simulation efforts that focus on buildings' energy and indoor-environmental performance. In recent years, arguments have been made suggesting the need for more sophisticated user-related building simulation input data. In this context, the use of stochastic occupancy models is proposed to be preferable than using conventional static schedules and simple rule-based assumptions. Stochastic behavioral formalisms better capture "the random nature of occupant presence and movement behavior" (Luo et al. 2017).

As a result, there have been efforts to develop more detailed models of occupant-related processes in buildings (Wagner et al. 2018). Specifically, agent-based modeling (ABM) has been suggested to offer a flexible and powerful tool for capturing occupants' behavior and presence patterns in buildings. Despite a number of previous review efforts (see, for instance Gaetani et al. 2016, Parys et al. 2014) that identify and discuss strengths and weaknesses of several occupant modeling approaches, there is still a need for a specific review of concepts and approaches that integrate agent-based modeling in building simulation.

Given this context, the present study provides a concise overview of recent research work in the utilization of agent-based modeling (ABM) methods in building performance assessment.

Toward this end, a brief description of ABM (section 3) is given. Subsequently, the focus lies on ABM as applied to the main area of interest, namely buildings' energy and indoor-environmental performance (section 4). The study concludes with general thoughts regarding the current state and future perspectives of ABM.

1.2 Background

In recent years, a number of scientific contributions focused on the integration of different occupancy models in building simulation. Several research publications (i.e., Feng et al. 2015, Li and Dong 2018) and projects (such as Annex 66 (2020) and 79 (2020)) pertaining to this domain discuss concepts and approaches of modeling and simulating occupant behavior in buildings.

Recent and ongoing international efforts within the framework of IEA EBC Annex 66 (2018) and 79 (2020) focus on behavioral models of building occupants as well as occupant-centric building design and operation. The IEA EBC Annex 66 (2018) addresses the development and incorporation of occupant behavior models in building performance simulation. The follow-up IEA EBC Annex 79 (2020) focuses on occupant-centric building design and operation. One of the main objectives within this Annex is to acquire a better understanding of the interactions between occupants and building systems.

In this context, agent-based modeling is suggested as a powerful simulation modeling technique to capture agents' (occupants') behavior including actions and interactions with other agents. Figure 1 shows a schematic illustration of agent-based modeling.

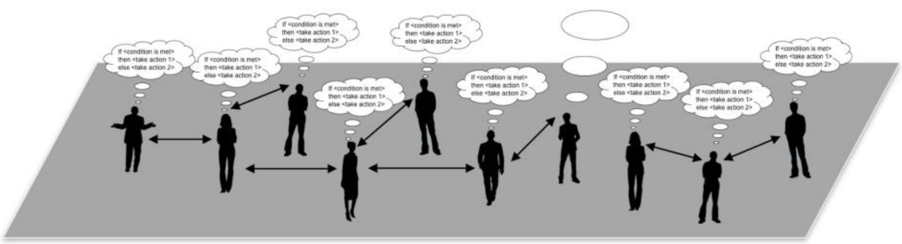

Figure 1. Schematic illustration of agent-based modeling (Heppenstall and Crooks 2016).

Roots of ABM can be found in the fields of robotics, artificial intelligence as well as social and organizational behavior (Macal and North 2008). Moreover, the ABM technique can capture complex dynamics in the social, natural, and engineering field.

ABM has links and applications in other domains, such as complexity science, computer and social science as well as system or management dynamics (Macal and North 2008).

A number of efforts use the widely used abbreviation "ABM" (agent-based modeling), whereas other contributions refer to "ABMS" (agent-based modeling and simulation), "ABS" (agent-based systems/simulation) or "IBM" (individual-based modeling) (Macal and North 2008). Within this work, the abbreviation "ABM" is used to refer to "agent-based modeling".

A detailed description of the agent-based modeling technique, application areas, and examples of software environment and tools are given in section 3.

1.3 Overview

This thesis is not based on specific hypothesis testing. Rather, it aims at documenting the state of knowledge in the relevant domain. It thus follows the common structure of a review effort and intends to provide a thorough state-of-the-art and potential assessment of user-related models in building simulation.

As such, the proposed thesis entails the following steps:

i) a brief review of the state-of-the-art in user-related models in building simulation;

ii) a general discussion of agent-based modeling techniques;

iii) a concise review of agent-based modeling as applied to buildings' energy and indoor-environmental performance.

The thesis is expected to result in a structured representation of the state of knowledge in agent-based modeling applications in the building performance assessment domain. Specifically, the results from and experiences with previous efforts (projects, publications) in this area are collected and commented upon. The results are expected to aid future research and development activities in this area. Specifically, the relationship between core captured behavioral traits in agents and the derivative system behavior manifestations will be presented and interpreted.

2 STATE-OF-THE-ART IN USER-RELATED MODELS IN BUILDING SIMULATION

People's presence and behavior in buildings have an impact on buildings' performance. Occupants' influence on the energy use of buildings has been presented in empirical studies as well as simulation-supported case studies (e.g., Azar and Menassa 2012a). Whereas occupants can have passive effects on the buildings' performance by their mere presence, building users can also actively interact with the building environment. Hence, both active and passive effects of occupants need to be considered in the context of building performance simulation.

Gaetani (2019) describes the modeling of occupant behavior in building performance simulation in terms of three types, namely occupants' presence, adaptive behavior, and non-adaptive behavior.

- The first category refers to passive effects of occupants on the building performance. Building users release heat (latent and sensible), carbon dioxide, water vapor, odors, and other substances depending on their activity level (Mahdavi and Tahmasebi 2019). Passive effects of occupants' presence are included in building simulation models in terms of metabolic rates or activity level values. Usually, these values are derived from guidelines and standards, such as ASHRAE Standard 90.1 (2020), or empirical studies.

- In many buildings, inhabitants can actively interact with the built environment. Occupants can operate windows, doors, blinds, radiators, fans, and lights, or adjust heating and cooling settings. Adaptive behavior is mainly triggered by environmental conditions and associated with comfort preferences (e.g., thermal, visual, acoustic, air quality).

- Moreover, non-adaptive behavior of building users is incorporated in occupant behavior models. Thereby, the behavior is not triggered by comfort preferences, but rather refers to an activity that influences buildings' performance. For instance, the use of electric appliances or domestic hot water use are not triggered by environmental conditions, but reflect an activity that influences buildings' energy use.

A number of different occupant behavior modeling approaches aim toward representation of occupants' behavior and presence in building simulation. In the following, widely used modeling methods are presented, including schedules, probabilistic models, non-probabilistic models, and agent-based models.

Schedules

In many cases, conventional schedules are used to represent occupants' behavior and actions in buildings. Schedules describe time-related ratios or probabilities of building users' behavior and presence. Typically, schedule profiles are distinguished for weekdays, Saturdays, Sundays, and holidays (Mahdavi and Tahmasebi 2019). Schedules often rely on information provided in standards (i.e., ASHRAE Standard 90.1 (2020)) or empirical data (derived from surveys, monitored data). As schedules represent occupants' behavior in a simplified and static way, recently efforts have been made toward capturing users' behavior in terms of probabilistic models.

Probabilistic models

Probabilistic models estimate the probability of occupants' presence and interactions with the building. Different mathematical formalisms (e.g., hidden Markov model, logistic regression, linear regression, survival analysis model, Bernoulli process) are deployed in probabilistic models (Gaetani 2019).

Non-probabilistic models

Non-probabilistic (rule-based) models consider one or multiple threshold values for certain variables to estimate occupants' actions in buildings. For instance, threshold values (set-point values) for a certain variable (illuminance level) are specified to model occupants' operation of lights.

Agent-based models

As alluded to before, agent-based models have been suggested to capture the representation of occupants' behavior patterns in a flexible way. A detailed description of the agent-based modeling technique is provided in chapter 3.

It has to be noted that none of the above mentioned occupant behavior models represent an approach that is appropriate for all types of use cases. The application of a certain behavior model is dependent on the level of resolution. Different kinds of simulation-aided building performance queries need different types of occupant behavior models (Mahdavi and Tahmasebi 2019).

Some research efforts focus on the comparison of different occupant behavior models. For instance, Mahdavi and Tahmasebi (2015) studied occupancy models toward prediction of occupants' future presence. Thereby, two existing probabilistic models and a newly developed non-probabilistic model are evaluated. The two probabilistic models refer to the model developed by Page et al. (2008) and the "Lightswitch-2002" model by Reinhart (2004). The proposed models are trained with monitored data from an office environment in a university building in Vienna. The predictive accuracy levels of all three models were rather low and the proposed non-probabilistic model was observed to perform better with regard to short-term predictions of occupants' presence patterns.

3 AGENT-BASED MODELING

3.1 Overview

Agent-based modeling (ABM) involves decision-making entities called agents (for instance, occupants of a building), who individually assess their situation and make decisions based on a set of rules (Bonabeau 2002). Railsback and Grimm (2019) describe agents as "unique and autonomous entities" that can represent humans, but also organisms, businesses, institutions, etc. Representing a unique agent implicates that they differ in their characteristics (such as size, location, or history) (Railsback and Grimm 2019). Representing an autonomous agent implicates that they aim to achieve different goals (Railsback and Grimm 2019).

Given the complexity of the interactions between agents and their environment (Wilensky and Rand 2015), ABM provides means of modeling individual behavior, including aspects of adaptive learning. Including adaptive learning allows changes over time and adjustments to the agents and their environment. This aspect allows the possibility to model variations of agents and environmental aspects over space and time (Railsback and Grimm 2019) compared to other simplified occupant modeling techniques.

Bonabeau (2002) mentions flexibility, provision of natural system description, and capacity of capturing emergent phenomena as main advantages of ABM compared to other - more traditional - modeling techniques. Thereby, ABM's flexibility pertains to the capability of adjusting the level of description or complexity of the individual entities (Bonaubeau 2002). Moreover, ABM can capture complex, individual, nonlinear behavior patterns, but also learning processes and socially-relevant interactions (Bonabeau 2002).

3.2 Agent-based modeling technique

Agent-based modeling involves decision-making entities (referred to as agents). For instance, building users can be represented as agents. Computational agents have the possibility to individually assess the surrounding context and act according to a set of defined rules (Bonabeau 2002). Moreover, ABM can capture agents' interactions with the built environment and with other agents.

Figure 2 shows a schematic illustration of interactions and processes including agents and their contextual setting.

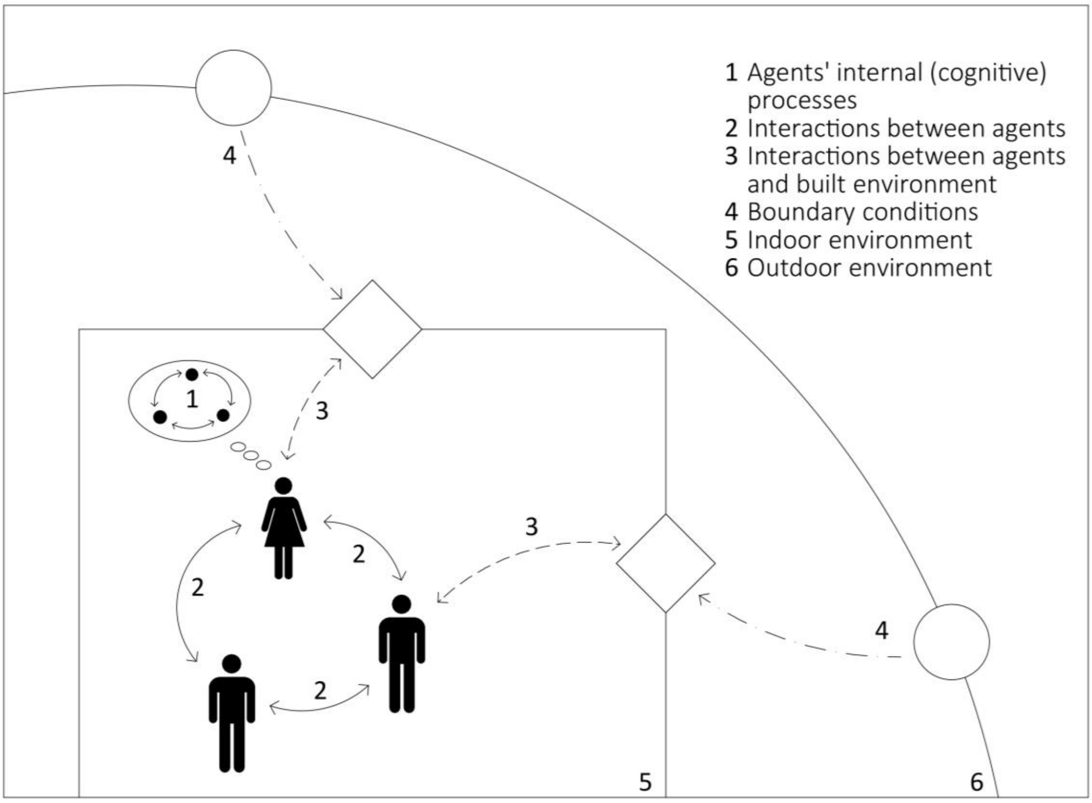

Figure 2. Schema of interactions and processes captured within an agent-based modeling framework (Berger and Mahdavi 2020a).

As illustrated in Figure 2, the representation of agents involves a number of processes and interactions. Thereby, an occupant-centered building performance simulation scenario in the built environment includes six different layers:

- the agents' internal (cognitive) processes,
- the interactions between agents,
- the interactions between agents and the built environment,
- boundary conditions,
- the indoor environment, and
- the outdoor environment.

First, a solid basis of knowledge from relevant disciplines (i.e., physiology, psychology, and sociology) is highly relevant in order to represent people's behavior. Agents' internal, cognitive processes can be captured (in terms of rules, decision-making processes, etc.) by using agent-based formalisms. In practice, many research efforts conduct surveys, interviews, and questionnaires to obtain information about occupants' behavior. Other approaches measure occupancy data about their interaction with the built environment.

Second, interactions between agents and interactions between agents and the built environment (via building interfaces and control systems in the indoor environment) can be defined in agent-based models. Occupants often have control to adapt their surrounding by operating windows, blinds, doors, lights, equipment, fans, radiators etc.

Moreover, ABM methods could presumably be applied to model environmental conditions in both the indoor and outdoor environment. The environmental representation is per se not agent-based, but uses typical numeric modeling techniques, such as energy or visual performance simulation models.

Thermal, visual, and acoustic simulations often deploy standards, guidelines, and codes to represent the environmental processes.

Whereas the processes and interactions of computational agents are usually captured in ABM, the environmental conditions are typically modeled via numeric simulation tools. Thus, coupling formalisms need to mediate between the behavioral (agent-based) representation and the numeric representation of the built environment.

3.3 Application areas

ABM is deployed in various disciplines and thematic fields. Bonabeau (2002) points out four main application areas*:*

i) flows, *ii)* organizations, *iii)* markets, and *iv)* diffusion.

Thereby, "flows" refer for instance to customer flow patterns in museums or shopping malls, and traffic simulations. Other ABM applications include operational risks and adoption dynamics (Bonabeau 2002). Moreover, the author describes stock markets as a further application of ABM.

ABM application domains include a variety of different disciplines. A number of application fields and related publications are listed below:

- Archeology (Wurzer et al. 2015)
- Economics (Arthur et al. 1997, Fang et al. 2002, Tesfatsion 2002)
- Ecosystem management, agricultural economics, land use science (Berger 2001, Bousquet and Le Page 2004, Rindfuss et al. 2008)
- Medicine (Folcik and Orosz 2006, Silverman et al. 2014)
- Population dynamics (Pablo-Marti and Santos 2013, Singh et al. 2016)
- Social sciences (Epstein and Axtell 1996, Gilbert and Troitzsch 1999, Macy and Willer 2002)

Furthermore, ABM is applied to capture behavior and processes in the built environment. Several efforts focus on the following thematic areas:

- Evacuation scenarios (Almeida et al. 2013, Ha 2012, Hu et al. 2012, Liu et al. 2016, Kasereka et al. 2018, Yi and Shi 2009)
- Pedestrian's movement (Rindsfüser and Klügl 2012, Ronald et al. 2007, Zheng et al. 2019, Zhou 2008)
- Transportation and traffic scenarios (Hager et al. 2015, Haman et al. 2017, Huynh et al. 2013, Ziemke et al. 2017)
- Urban phenomena (Crooks 2013, Heppenstall and Crooks 2016, Perez et al. 2017)

3.4 Examples of software environments and tools

A number of different software tools and simulation approaches have been used toward implementation of ABM applications. Macal and North (2008) point out two ways of simulation approaches. On the one hand, general programming languages and software (i.e., spreadsheets, programming languages such as Python (2020) or Java (2020)) can be used for ABM. On the other hand, specific ABM software environments and tools (i.e., AnyLogic (2020), MASON (2020), NetLogo (Wilensky 1999), Repast (2020), Swarm (2020)), provide a way to conduct simulations.

In the following, some selected ABM software environments are described in more detail.

3.4.1 NetLogo

This open-source tool is a multi-agent java-based programming language and modeling environment (Wilensky 1999). The tool can be used to simulate natural and social phenomena including many (up to hundreds/thousands) agents (Wilensky 1999). NetLogo provides the user a rather simple way to develop a medium to large-scale ABM model (Abar et al. 2017). Hence, it is a suitable tool for teaching and research purposes in multiple disciplines.

3.4.2 AnyLogic

Other studies use the simulation software AnyLogic (2020). This tool is a java-based modeling environment and captures three different modeling methods, namely discrete events, system dynamics and agent based (Grigoryev 2018). Abar et al. (2017) rate the model development effort as moderate and the scalability level of the simulation model as high/large-scale. AnyLogic is a closed source, but a free personal learning edition is available.

3.4.3 Repast Simphony

Repast Simphony is an open-source, java-based ABM tool (Repast 2020). The tool includes an ABM library to model complex adaptive systems (North et al. 2013). This application can be used among others for 2D/3D simulations in social sciences, supply chains or complex adaptive systems (Abar et al. 2017). Efforts, such as Abar et al. (2017), evaluate the model development effort as rather complex and the scalability level of the simulation model as high/large-scale.

4 APPLICATION OF AGENT-BASED MODELING IN THE CONTEXT OF BUILDINGS' ENERGY AND INDOOR-ENVIRONMENTAL PERFORMANCE

4.1 Overview

4.1.1 Selection process

As alluded to before, a large number of research efforts use agent-based modeling to capture individuals' behavior in various disciplines. Many of them refer to the built environment to model transportation, evacuation scenarios or urban phenomena. However, this review approach specifically focuses on ABM as applied to buildings' energy and indoor-environmental performance.

Thereby, multiple search engines and databases, together with a combination of a number of pertinent keywords were used (see Table 1).

Table 1. Search engines/databases and keywords used in the selection process of relevant research publications.

Search engines/ databases	*Google Scholar, Science Direct, Scopus, Research Gate*
Keywords	*agent-based modeling, agent-based simulation, agent-based, occupant behavior, occupancy, behavior simulation, building simulation, human factors, human behavior, simulation, energy use, energy estimation, energy/building simulation, thermal comfort, building energy performance, human-building interaction*

As most of the studies in this domain were published fairly recently, the focus is laid on research efforts that are published within the last 10 years (roughly between 2010 and 2018), and are written in English language.

Figure 3 schematically illustrates the selection process to identify relevant publications. In a first iteration, a structured search through search engines (see Table 1) and already known papers resulted in a list of 40 papers. A further iteration is used to check cross-referencing within the publications and exclude papers that do not fit due to several criteria (i.e., date of publication is not between 2010 and 2018, the paper is written in a different language than English, the topical focus does not fit in the intended review scope). After an initial review of the resulting 31 publications, a list of 23 publications is identified that closely fit the agenda of the present review effort.

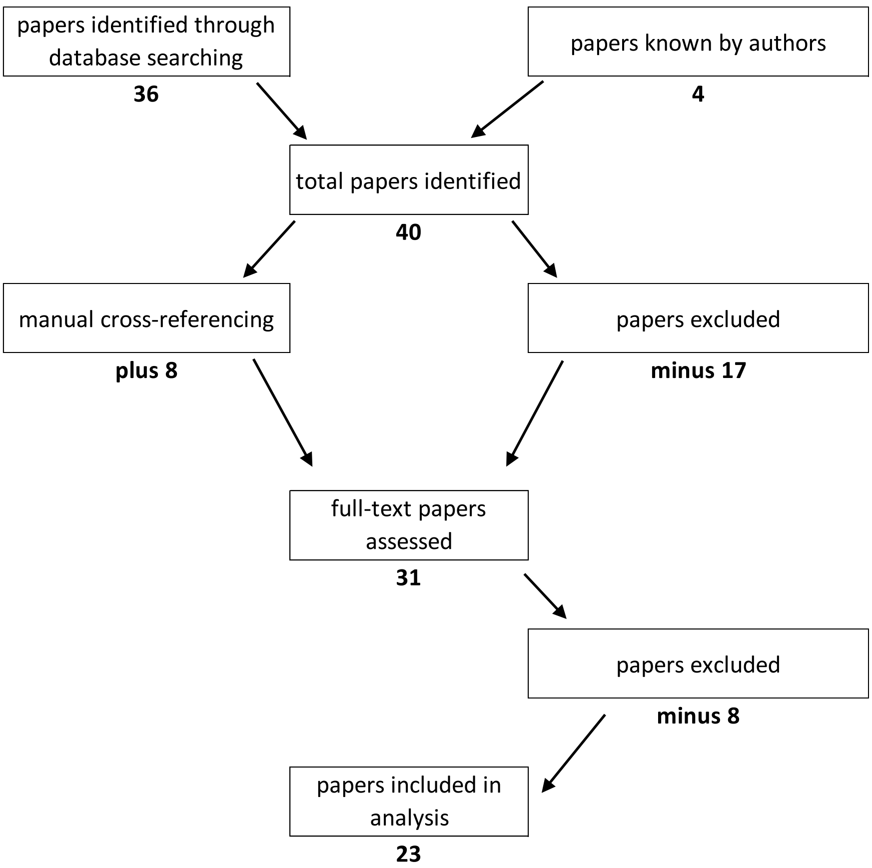

Figure 3. Schematic illustration of the selection process.

It has to be noted that the list of selected publications is not suggested to be exhaustive as new research studies are continuously developing. However, the review effort intends to present a state-of-the-art and first orientation in this research domain. Moreover, a systematic search procedure is attempted to identify studies that deal with the ABM of occupants in the context of buildings' energy and indoor-environmental performance simulation.

4.1.2 Review process

In a next step, the selected publications are reviewed and relevant information is extracted and analyzed. Thereby, general publication information (i.e., publication year, type of publication etc.), thematical focus as well as specific information about the presented framework (i.e., definition of the ABM, sources of domain knowledge, implementation tools etc.) are discussed in detail.

In the course of the review process, different types of articles are considered (see Table 2). Most of the reviewed articles are journal papers or conference proceedings. The reviewed publications are published between 2010 and 2018 (see Table 3). The most frequent mentioned keywords are listed in Table 4. Some of the reviewed studies contain case study simulations in different climatic regions. The majority of the case studies are conducted in the US (Table 5).

Table 2. Frequency of article type.

Article type	Frequency
Journal Paper	11
Conference or Symposium Proceeding	10
Research Article	1
Dissertation	1

Table 3. Year of publication.

Year of publication	Frequency
2010	2
2011	1
2012	1
2013	2
2014	3
2015	1
2016	5
2017	5
2018	3

Table 4. Frequent mentioned keywords.

Keywords	Frequency
agent-based modeling/ agent-based model	14
occupant behavior	9
building (energy) simulation	4
agent-based simulation	1

Table 5. Case study locations.

Region	Frequency
US	15
UK	2
UAE	1
Netherlands	1

The selected publications that closely fit in the review scope are analyzed and reviewed with regard to different aspects. The modeling purposes are discussed in section 4.2. In addition, representational methods of both behavioral representation and context representation are analyzed (see section 4.3). Furthermore, different implementation approaches of occupants and their environment as well as computational coupling of agents with their context are reviewed in section 4.4.

An overview of the selected publications is shown in Table 6. Thereby, information with regard to the thematic focus, representational methods (for both occupants and their built environment), and implementation approaches is entailed. As alluded to before, the list of selected publications is by no means exhaustive or definitive, but is considered to present an overall view and preliminary direction in this field of research.

Table 6. Listing of selected publications including thematical focus, representational methods, and implementation approaches.

Authors	**Thematical Focus**	**People**		**Context**	
		Domain knowledge	**Implementation tools**	**Case study**	**Implementation tools**
Alfakara and Croxford (2014)	the proposed approach deals with the impact of occupants' behavior (including users' interaction with the building) on energy consumption of residential buildings (in the context of summer overheating)	occupants' interactions with the building include window and cooling system operation; "concept of seniority" is incorporated; two different behavioral scenarios (including a base-case scenario and an improved-case scenario) are compared in terms of the impact of energy-conscious behavior	Repast Symphony	a case study is performed in a flat (including four rooms) in a high-rise building	TAS
Andrews et al. (2011)	the study focuses on occupants' visual comfort, energy performance and energy costs of buildings	the occupant behavior model is based upon the Theory of Planned Behavior (TPB) and the Belief-Desire-Intention (BDI) framework; a survey is conducted to collect occupants' behavior information	NetLogo	a simplified five-zone office building is used to simulate daily occupant light use patterns	Radiance
Azar and Menassa (2010)	the papers study the influence of different types of occupants and interactions among occupants on the buildings' energy consumption	three different types of occupants: High Energy Consumer, Medium Energy Consumer, and Low Energy Consumer with different energy usage profiles are considered; occupants can operate blinds, lighting, equipment, and hot water; the influence on energy use habits among occupants ("word of mouth effect") is included	AnyLogic	a case study in an office setting including ten occupants in Madison-Wisconsin is performed	eQuest
Azar and Menassa (2012)	the papers study the influence of different types of occupants and interactions among occupants on the buildings' energy consumption		AnyLogic	a case study in an office setting including ten occupants in Madison-Wisconsin is performed	eQuest
Barakat and Khoury (2016)	the paper studies occupants' influence of thermal, visual, and acoustic comfort levels on the buildings' energy consumption	three groups of building users, namely green, neutral, and non-green users, with different thermal, visual, and acoustic comfort preferences are considered	AnyLogic	NA	NA
Chen et al. (2016)	the paper presents an web-based agent-based modeling application	the occupant behavior patterns are based on the OB XML Schema that is built upon the OB DNAS framework; occupants' movement and presence in built spaces is captured	Occupancy Simulator	a case study office building in US is selected	NA
Luo et al. (2017)	the study mainly focuses on the performance evaluation of the Occupancy Simulator (a web-based agent-based modeling application)	the occupant behavior patterns are based on the OB XML Schema that is built upon the OB DNAS framework; occupants' movement and presence in built spaces is captured	Occupancy Simulator	a case study office building including 13 occupants is simulated	EnergyPlus
Chen et al. (2018)	the proposed approach focuses on occupants' behavior (movement and presence) in buildings	occupancy patterns are based on the OB XML schema that builts upon the OB DNAS theoretical framework	Occupancy Simulator	a case study in an office building in the US is performed	EnergyPlus
Jia et al. (2017)	the proposed ABM simulation framework is used to study the impact of occupants' behavior on energy consumption in commercial buildings	occupants can adapt the state of windows, doors, blinds, and heaters; thermal, visual, and air quality comfort levels are considered	PMFserv	a case study in a single-occupied office area in Gainesville, Florida (US) is performed	EnergyPlus
Jia et al. (2018)	the proposed ABM simulation framework is used to study the impact of occupants' behavior on energy consumption in commercial buildings	a GSP (Goals, Standards, and Preferences) tree is used to describe occupants' behavior	PMFserv	a case study in a single-occupied office area in Gainesville, Florida (US) is performed	EnergyPlus
Jia and Bharathy (2018)	the study focuses on validating the proposed ABM framework by Jia et al. 2017, 2018	occupants can adapt the state of windows, doors, and blinds	PMFserv	five single-occupied office spaces in a university building are selected	EnergyPlus
Langevin et al. (2014)	the study presents an approach to simulate occupants' adaptive thermal behavior with regard to energy and comfort effects of occupant behavior in an office setting	occupants react according to the Perceptual Control Theory (PCT); different adaptive behaviors with regard to thermal comfort are considered	MATLAB	a case study office building is simulated in five different climate regions in the US	EnergyPlus
Langevin et al. (2015)	the paper focuses on the description and validation of the proposed ABM	occupants react according to the Perceptual Control Theory (PCT); different adaptive behaviors with regard to thermal comfort are considered; a one-year field study is conducted to collect information about occupants' behavior	MATLAB	a case study office building is simulated for validation purposes	EnergyPlus
Lee (2013)	occupants' influence on the energy use in office buildings is studied	occupants' behavior is adopted from the Reasoned Action Model (including behavioral, control, and normative beliefs); occupant actions include the interactions with windows, doors, blinds, fans, and heaters	MATLAB	a case study office building is simulated in different climate regions in the US	EnergyPlus
Lee and Malkawi (2014)	occupants' influence on the energy use in office buildings is studied		MATLAB	a case study office building is simulated in different climate regions in the US	EnergyPlus
Linkola et al. (2013)	the proposed approach focuses on the impact of occupants' behavior on water consumption in residential settings	agents' decision making process is based on the TPB (Theory of Planned Behavior) and the BDI (Belief-Desire-Intention) framework	NetLogo	two case study buildings in the US and the Netherlands are selected including three different household scenarios (single, couple, and family)	NA
Papadopoulos and Azar (2016)	the impact of occupants' behavior and building systems interactions on buildings' energy consumption of office buildings is studied	different occupancy characteristics (including lighting and equipment use patterns as well as cooling and heating thermostat set points) are considered	AnyLogic	a case study office building is selected including occupants and facility manager	EnergyPlus
Azar and Papadopoulos (2017)	the paper focuses on the uncertainty of occupants' behavior and the influence on the buildings' energy performance	occupants' actions include the use of lights, equipment, and control of cooling and heating set points	MATLAB	a simulation in an office building including occupants and facility managers is performed	EnergyPlus
Putra et al. (2017)	the models' main purpose is to analyse the impact of thermal and visual comfort levels and adaptive behavior on the energy consumption of buildings	a questionnaire about occupants' preferences and behavior is conducted; the occupant behavior model is built upon the BDI framework	NetLogo	the proposed simulation framework is applied to case study office buildings equipped with different building controls	EnergyPlus
Schaumann et al. (2017)	the proposed approach addresses occupant behavior (including occupants' movements and activities) in a hospital setting	information about occupants' behavior is obtained via interviews and field observations	Unity 3D	a case study in an simplified hospital layout including different types of spaces (i.e., patient rooms, offices, nurse areas, medecine spaces) is performed	Autodesk AutoCAD
Thomas et al. (2016)	the paper focuses on the effect of adaptive thermal behavior on the overall buildings' energy consumption	the occupant behavior model includes three different types of occupants with different thermal comfort preferences and is based upon the model by Azar and Menassa (2013, 2015)	AnyLogic	the proposed simulation framework is applied to a case study office building	EnergyPlus
Wang et al. (2016)	the paper deals with the impact of occupant behavior on the lighting energy usage in office buildings	a self-conducted questionnaire gives information about occupants' light switching behavior; the occupant behavior model considers same rights to access lights within the offices among all occupants and the light use behavior adapts as soon as occupants are interacting with each other (occupants are not allowed to turn the lights off in case other occupants are still in the office working)	NA	the study includes a simulation of occupants' light usage in an open-plan office setting	NA
Zhang et al. (2010)	the ABM research effort focuses on occupants' impact on energy consumption in an office setting	empirical surveys and observations of occupants' behavior are conducted to collect information about building users' behavior; three different types of agents are considered: the energy user agent (represents an occupant), the computer agent (passive agent), and the light agent (passive agent)	AnyLogic	a case study building at the University of Nottingham, UK focusing on the electricity consumption is simulated	NA

4.2 Modeling purpose

Several publications address the application of ABM for simulating user-related factors that influence buildings' energy performance (Azar and Menassa 2010, 2012b, Azar and Papadopoulos 2017, Chen et al. 2016). A number of other publications concern the behavioral adaptions of building occupants to achieve thermal comfort (Alfakara and Croxford 2014, Langevin et al. 2014, Lee 2013, Lee and Malkawi 2014, Thomas et al. 2016).

Few ABM studies focus on comfort requirements of occupants with regard to visual comfort (Andrews et al. 2011), acoustic comfort (Barakat and Khoury 2016), and air quality (Jia and Bharathy 2018, Jia et al. 2017, 2018). However, the reviewed ABM approaches are not only focusing on indoor-environmental comfort.

One ABM study addresses the simulation of building occupants' behavioral patterns regarding water consumption (Linkola et al. 2013). Another ABM effort is used for optimizing HVAC system design and operation (Putra et al. 2017).

4.3 Representational methods

In the reviewed publications, a number of different approaches are considered to represent occupants' behavior and their environment. Figure 4 shows a schematic illustration of the represented entities. People's behavior is dependent on knowledge from different disciplines, including psychology, physiology, and sociology. The representation of the built environment is per se not agent-based, but uses typical numeric modeling techniques (e.g., energy, lighting, or environmental simulation models). Representations of occupants and environments are computationally coupled to model the interaction between people and buildings.

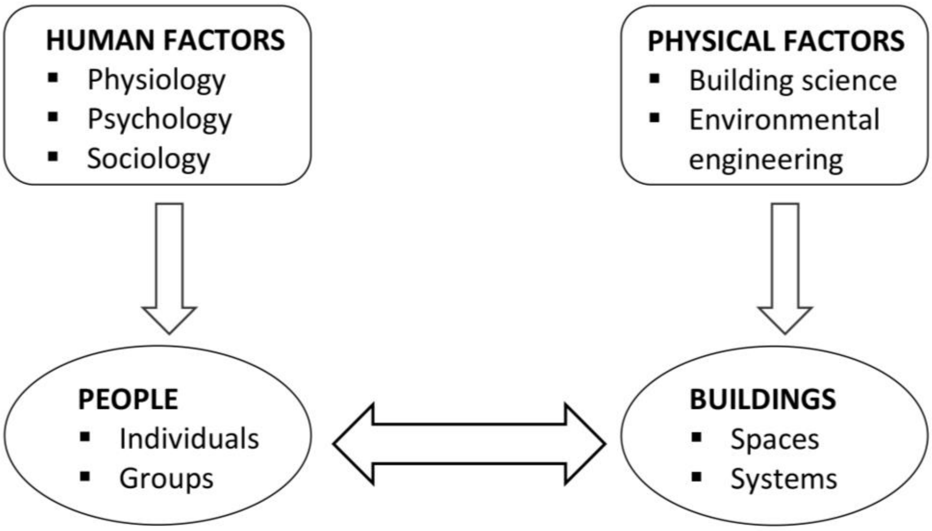

Figure 4. Conceptual illustration of the represented entities, including interactions between people and the built environment and sources of domain knowledge.

4.3.1 Behavioral representation

Agents' behavioral patterns need to be based on solid domain knowledge, sound behavioral theories, and relevant occupancy information. A number of studies conduct interviews and surveys in order to define occupancy patterns (Jia and Bharathy 2018, Jia et al. 2017, 2018, Langevin et al. 2014, Luo et al. 2017, Putra et al. 2017, Schaumann et al. 2017, Wang et al. 2016a, Zhang et al. 2010).

More commonly, existing information in scientific publications, and professional standards and guidelines is used (Lee 2013, Lee and Malkawi 2014).

Moreover, various behavioral theories – of different levels of coverage and specificity – are meant to capture occupants' patterns of perception and behavior. These include, for example, the Reasoned Action Model (Fishbein and Ajzen 2010), the Perceptual Control Theory (Powers 1973), and the Theory of Planned Behavior (Ajzen 1991).

Table 7 gives an overview of the different behavioral representation approaches. In the following, the behavioral representation of people in the reviewed research efforts are discussed in detail.

Table 7. Overview of reviewed behavioral representation approaches.

Authors	**People**	
	Domain knowledge	**Implementation tools**
Alfakara and Croxford (2014)	occupants' interactions with the building include window and cooling system operation; "concept of seniority" is incorporated; two different behavioral scenarios (including a base-case scenario and an improved-case scenario) are compared in terms of the impact of energy-conscious behavior	Repast Symphony
Andrews et al. (2011)	the occupant behavior model is based upon the Theory of Planned Behavior (TPB) and the Belief-Desire-Intention (BDI) framework; a survey is conducted to collect occupants' behavior information	NetLogo
Azar and Menassa (2010)	three different types of occupants: High Energy Consumer, Medium Energy Consumer, and Low Energy Consumer with different energy usage profiles are considered; occupants can operate blinds, lighting, equipment, and hot water; the influence on energy use habits among occupants ("word of mouth effect") is included	AnyLogic
Azar and Menassa (2012)		
Barakat and Khoury (2016)	three groups of building users, namely green, neutral, and non-green users, with different thermal, visual, and acoustic comfort preferences are considered	AnyLogic
Chen et al. (2016)	the occupant behavior patterns are based on the OB XML Schema that is built upon the OB DNAS framework; occupants' movement and presence in built spaces is captured	Occupancy Simulator
Luo et al. (2017)	the occupant behavior patterns are based on the OB XML Schema that is built upon the OB DNAS framework; occupants' movement and presence in built spaces is captured	Occupancy Simulator
Chen et al. (2018)	occupancy patterns are based on the OB XML schema that builts upon the OB DNAS theoretical framework	Occupancy Simulator
Jia et al. (2017)	occupants can adapt the state of windows, doors, blinds, and heaters; thermal, visual, and air quality comfort levels are considered	PMFserv
Jia et al. (2018)	a GSP (Goals, Standards, and Preferences) tree is used to describe occupants' behavior	
Jia and Bharathy (2018)	occupants can adapt the state of windows, doors, and blinds	PMFserv
Langevin et al. (2014)	occupants react according to the Perceptual Control Theory (PCT); different adaptive behaviors with regard to thermal comfort are considered; a one-year field study is conducted to collect information about occupants' behavior	MATLAB
Langevin et al. (2015)		
Lee (2013)	occupants' behavior is adopted from the Reasoned Action Model (including behavioral, control, and normative beliefs); occupant actions include the interactions with windows, doors, blinds, fans, and heaters	MATLAB
Lee and Malkawi (2014)		
Linkola et al. (2013)	agents' decision making process is based on the TPB (Theory of Planned Behavior) and the BDI (Belief-Desire-Intention) framework	NetLogo
Papadopoulos and Azar (2016)	different occupancy characteristics (including lighting and equipment use patterns as well as cooling and heating thermostat set points) are considered	AnyLogic
Azar and Papadopoulos (2017)	occupants' actions include the use of lights, equipment, and control of cooling and heating set points	MATLAB
Putra et al. (2017)	a questionnaire about occupants' preferences and behavior is conducted; the occupant behavior model is built upon the BDI framework	NetLogo
Schaumann et al. (2017)	information about occupants' behavior is obtained via interviews and field observations	Unity 3D
Thomas et al. (2016)	the occupant behavior model includes three different types of occupants with different thermal comfort preferences and is based upon the model by Azar and Menassa (2013, 2015)	AnyLogic
Wang et al. (2016)	a self-conducted questionnaire gives information about occupants' light switching behavior; the occupant behavior model considers same rights to access lights within the offices among all occupants and the light use behavior adapts as soon as occupants are interacting with each other (occupants are not allowed to turn the lights off in case other occupants are still in the office working)	NA
Zhang et al. (2010)	empirical surveys and observations of occupants' behavior are conducted to collect information about building users' behavior; three different types of agents are considered: the energy user agent (represents an occupant), the computer agent (passive agent), and the light agent (passive agent)	AnyLogic

Alfakara and Croxford (2014) adapt a hierarchical decision-making model that takes occupants' level of seniority into account. Within the "concept of seniority" the most senior agent has the privilege to make behavioral decisions in the built environment. Occupants' interaction in the residential setting include the operation of windows (open/close) and the mechanical cooling system (on/off). Moreover, two different behavioral scenarios (a base-case scenario and an improved-case scenario) are compared with regard to energy-conscious behavior.

Andrews et al. (2011) and Linkola et al. (2013) adopt the Theory of Planned Behavior (TPB) (Ajzen 1991) and the Belief-Desire-Intention (BDI) (Rao and Georgeff 1998) framework to model decision-making processes. Linkola et al. (2013) consider agents' responses to external and internal incentives and inputs, be those conscious or not. Different water usage practices of occupants (i.e., cooking, drinking, dish washing, personal hygiene) and three types of household configurations (including singles, couples or families) are considered. In this model, occupants' behavior is led by behavioral, normative, and control beliefs as defined in the Theory of Planned Behavior (Ajzen 1991). Andrews et al. (2011) conducted a survey in an office building concerning occupants' values, beliefs, preferences, and actions.

Azar and Menassa (2010, 2012b) work with an occupant categorization concerning energy use habits (High, Medium, and Low). Thereby, three types of occupants with different energy usage profiles are considered. Moreover, their ABM approach attempts to consider changes in one agent's energy use behavior due to other agents' influence. The "word of mouth effect" (Allsop et al. 2007) is incorporated to represent the probability of influence among occupants with regard to their energy use habits. Occupants' hot water consumption and operation of blinds, lights, and equipment is considered in the proposed approach.

Barakat and Khoury (2016) consider internal (occupants' states and preferences) and external (operation of buildings' control systems) factors. Specifically, internal factors refer to thermal, visual, and acoustic preferences of three different groups of occupants ("green", "neutral", and "non-green" building users). Occupants are assumed to seek improvement in their perceived state via selection of preferred options within the space of possible actions. Thereby, occupants can operate windows (open/close), shades (open/close), lights (on/off), as well as the HVAC system (high/medium/low/off). It is suggested that occupants have equal right to adjust and control their built environment.

Jia et al. (2018) rely on a “Goals, Standards, and Preferences” (GSP) tree to capture the mindset and value systems of agents. Building users perform actions (i.e., operating windows, doors or blinds) to react to uncomfortable thermal, visual, and air quality comfort conditions. Occupants can interact with the built environment by operating windows, doors, blinds, and heaters. Agents decide on actions (i.e., operation of environmental control systems as per GSP) and settings (perceived indoor-environmental conditions).

Jia and Bharathy (2018) aim at validating the proposed ABM framework by Jia et al. (2018). Thereby, indoor-environmental data (including temperature, humidity, illumination, and CO2 concentration) was measured and information about occupants' interaction with the building is obtained through a survey. The survey had to be filled in a 15 minutes' interval by the participants over a period of several weeks.

The Perceptual Control Theory (PCT) (Powers 1973) informs Langevin et al. (2014) in their ABM approach. As soon as thermal conditions are out of the preferred range, occupants act adaptively and take behavioral adaptive actions. Specifically, five adaptive behaviors seeking thermal comfort (clothing adjustment, use of heater, fan, or thermostat, operation of windows) are considered.

The approach is tested using data from a one-year field study in an office building (Langevin et al. 2015). The field study included 45 participants occupying different office types and are equipped with different control possibilities. They are asked to fill a daily online questionnaire (three times per day) and a final retrospective questionnaire at the end of the study. Thereby, the individuals are asked about thermal preferences, acceptability ranges, and behavioral actions. Moreover, indoor-environmental data, such as temperature, humidity, and air velocity, as well as occupant interaction with the building (i.e., operation of windows, heaters, and fans) are measured.

Lee and Malkawi (2014) concentrate on agents' behavior (e.g., operation of shades, windows, fans, heaters) regarding thermal comfort. Occupants' beliefs (behavioral, control-specific, and normative) are adopted from the Reasoned Action Model (Fishbein and Ajzen 2010). The proposed human behavior model comprises three main processes, namely to define behavior, to identify behavior triggers, and to measure/quantify behavior. The behavior actions are triggered by the occupants' thermal comfort preferences (adopted from the PMV model by Fanger (1970)). Moreover, the study includes a cost function to support agents in performing an adequate decision. The agents are trained and learn to select the appropriate decision to achieve comfort and simultaneously minimize the energy consumption.

In case of Papadopoulos and Azar (2016), energy use attributes (preferences for cooling and heating thermostat set points, lighting energy use patters, and plug loads) are assigned to occupants and facility managers. Acceptable comfort ranges are derived from the building code ASHRAE (2020). The LHS (Latin Hypercube Sampling) process is used to randomly sample the occupancy-related variables. LHS is a statistics method to generate distributions of selected variables.

Putra et al. (2017) consider perceptual and thus behavioral differences concerning preferred thermal and lighting conditions. A multi-attribute utility function (involving environmental impact, effort, cost, and discomfort) is used to identify an adaptive action based on perceived indoor-environmental conditions. This utility function is based on the BDI (Belief-Desire-Intention) framework (Rao and Georgeff 1998). A questionnaire is conducted to obtain information about occupants' behavior and comfort preferences. Moreover, the study considers three types of buildings users including building managers, tenant representatives, and occupants.

Schaumann et al. (2017) use interviews and observations in an orthopedics department together with information obtained from relevant literature on hospital environments in their ABM development process. The study focuses on occupant behavior in a hospital layout that is assumed to be a mainly process-driven environment. Thus, occupants' behavior is suggested to be led by a set of procedures. The proposed multi-agent model includes narratives that are suggested to represent occupants' behavior.

Thomas et al. (2016) adopt the human behavior model developed by Azar and Menassa (2013, 2015) by replacing occupants' attributes (energy intensity levels) with thermal comfort levels. Three types of occupants with different thermal comfort preferences are included. Moreover, interactions between occupants are modeled in a way that occupants can influence each other in their energy use patterns.

Wang et al. (2016a) start from a questionnaire before the definition of occupants' light switching behavior. The ABM is guided in this case by a number of rule-like assumptions about occupants' lighting-related behavior. The proposed human behavior model considers equal rights among building users to operate lights in an office setting. Interactions among occupants are considered so that for instance it is not possible to switch lights off in case other occupants are still in the office.

Likewise, Zhang et al. (2010) rely on questionnaires and observations as the source of information on occupants' behavior, who as active agents, interact with two passive agent types, namely the computer agent and the light agent. Moreover, actual data of buildings' energy consumption was collected.

4.3.2 Context representation

A number of different approaches are considered to represent the occupants' context. In the following, a number of environmental settings (such as office, residential, and public settings) included in the reviewed efforts are discussed in detail. Table 8 provides an overview of the representational approaches with regard to agents' environment.

Table 8. Overview of reviewed context representation approaches.

Authors	**Context**	
	Case study	**Implementation tools**
Alfakara and Croxford (2014)	a case study is performed in a flat (including four rooms) in a high-rise building	TAS
Andrews et al. (2011)	a simplified five-zone office building is used to simulate daily occupant light use patterns	Radiance
Azar and Menassa (2010)	a case study in an office setting including ten occupants in Madison-Wisconsin is performed	eQuest
Azar and Menassa (2012)	a case study in an office setting including ten occupants in Madison-Wisconsin is performed	eQuest
Barakat and Khoury (2016)	NA	NA
Chen et al. (2016)	a case study office building in US is selected	NA
Luo et al. (2017)	a case study office building including 13 occupants is simulated	EnergyPlus
Chen et al. (2018)	a case study in an office building in the US is performed	EnergyPlus
Jia et al. (2017)	a case study in a single-occupied office area in Gainesville, Florida (US) is performed	EnergyPlus
Jia et al. (2018)	a case study in a single-occupied office area in Gainesville, Florida (US) is performed	EnergyPlus
Jia and Bharathy (2018)	five single-occupied office spaces in a university building are selected	EnergyPlus
Langevin et al. (2014)	a case study office building is simulated in five different climate regions in the US	EnergyPlus
Langevin et al. (2015)	a case study office building is simulated for validation purposes	EnergyPlus
Lee (2013)	a case study office building is simulated in different climate regions in the US	EnergyPlus
Lee and Malkawi (2014)	a case study office building is simulated in different climate regions in the US	EnergyPlus
Linkola et al. (2013)	two case study buildings in the US and the Netherlands are selected including three different household scenarios (single, couple, and family)	NA
Papadopoulos and Azar (2016)	a case study office building is selected including occupants and facility manager	EnergyPlus
Azar and Papadopoulos (2017)	a simulation in an office building including occupants and facility managers is performed	EnergyPlus
Putra et al. (2017)	the proposed simulation framework is applied to case study office buildings equipped with different building controls	EnergyPlus
Schaumann et al. (2017)	a case study in an simplified hospital layout including different types of spaces (i.e., patient rooms, offices, nurse areas, medecine spaces) is performed	Autodesk AutoCAD
Thomas et al. (2016)	the proposed simulation framework is applied to a case study office building	EnergyPlus
Wang et al. (2016)	the study includes a simulation of occupants' light usage in an open-plan office setting	NA
Zhang et al. (2010)	a case study building at the University of Nottingham, UK focusing on the electricity consumption is simulated	NA

Office setting

In case of Andrews et al. (2011), a commercial case study building is selected to evaluate different variations of lighting designs and systems. Thereby, the daily occupant lighting use is simulated including up to ten building users in a simplified five-zone office area.

An office space in a university building is used in the study by Azar and Menassa (2010). A case study including ten students is performed over a period of 60 months in the office environment.

Jia and Bharathy (2018) and Langevin et al. (2014, 2015) use an office setting in their studies and collected indoor-environmental information by measuring temperature, humidity, air velocity, and illumination. In case of Jia et al. (2017, 2018), a case study is performed in a single-occupied office area in Gainesville, Florida (US). An office space in a case study building in Chicago (US) is used in the study by Thomas et al. (2016). The ABM study by Langevin et al. (2014, 2015) includes multiple building occupants and several climatic zones in the US for the simulation of a case study office building.

In case of Lee and Malkawi (2014), a case study is performed in an office building in Philadelphia, US, including a single occupant. Thereby, several climate regions are considered. A prototype building model that is provided by the DOE (2020) is used in the studies by Papadopoulos and Azar (2016) and Azar and Papadopoulos (2017). Thereby, both building users and facility managers are included in the case study building.

Putra et al. (2017) conduct a case study including two office buildings that deploy load shedding (for lights and HVAC systems). Another study (Wang et al. 2016a) conduct simulations in an open office environment focusing on occupants' operation of lights.

Residential setting

Alfakara and Croxford (2014) conduct a case study in a flat housing two building occupants. The residents are allowed to open and close windows and modify the state of the mechanical cooling system. It is assumed that the doors are closed by default. The flat is located in a high-rise building and comprises four rooms.

Likewise, in the study by Linkola et al. (2013), a residential setting in two different locations (Netherlands and UK) is selected. The study focuses on the interaction between occupants and water use interfaces and appliances. Thereby, three different household scenarios including singles (full-time working adult), couples (two retirees), and families (two working adults and two students) are considered.

Public setting

In case of Schaumann et al. (2017), a hospital setting is selected to perform a case study simulation. Thereby, a case study is performed in a simplified hospital layout including different types of spaces (patient rooms, offices, nurse areas, medicine spaces).

In the study by Zhang et al. (2010), a building at the University of Nottingham (UK) is selected as a case study model to simulate electricity consumption.

4.4 Implementation approaches

In the following, computational approaches (software environments and tools) are discussed that are considered within the reviewed publications to implement representations of occupants (section 4.4.1), their context (section 4.4.2), and computational coupling of agents with their context (section 4.4.3).

4.4.1 Occupants

In order to represent occupants' behavior, different tools and software environments are used. Several studies (Andrews et al. 2011, Linkola et al. 2013, Putra et al. 2017) use the tool NetLogo (Wilensky 1999). This open-source tool is a multi-agent java-based programming language and modeling environment (Wilensky 1999).

Other studies use AnyLogic (2020), which is a java-based modeling environment (Azar and Menassa 2010, 2012b, Barakat and Khoury 2016, Papadopoulos and Azar 2016, Zhang et al. 2010).

A web-based ABM application, called Occupancy Simulator, is used by Chen et al. (2016, 2018) and Luo et al. (2017). This application is open-source and limited to commercial settings (Occupancy Simulator 2020).

Another study (Alfakara and Croxford 2014) uses the open-source ABM library Repast Symphony (Repast 2020). In case of Lee and Malkawi (2014), Lee (2013), Langevin et al. (2014, 2015), and Azar and Papdopoulos (2017), the tool used to represent occupants' behavioral attributes is MATLAB (2020).

In case of Jia et al. (2018) and Jia and Bharathy (2018), the platform PMFserv (Silverman 2006a) that was developed at the University of Pennsylvania, is used to represent occupants' behavior. The study by Schaumann et al. (2017) uses the open-source video game engine Unity 3D (2020). Thereby, a pre-defined library is included to coordinate occupants' behavior.

4.4.2 Context

Usually, ABM is not used to model the context of agents except of few examples, such as Zhang et al. (2010). As alluded to before, Zhang et al. (2010) includes not only occupants as computational agents, but also other (passive) agents (namely computer agents and light agents) in the ABM.

Some tools are deployed to model the thermal and visual behavior of buildings. A well-known, frequently used tool is EnergyPlus (2020). This open-source tool reads input and output files as text files, but can benefit from a number of graphical interfaces (e.g., OpenStudio (2020), DesignBuilder (2020)). Most of the reviewed studies include EnergyPlus (2020) for simulating the energy performance of buildings (Azar and Papadopoulos 2017, Jia and Bharathy 2018, Jia et al. 2017, 2018, Langevin et al. 2014, 2015, Lee 2013, Lee and Malkawi 2014, Papadopoulos and Azar 2016, Putra et al. 2017, Thomas et al. 2016).

The energy modeling application eQuest (2020) is used in several other studies (Azar and Menassa 2010, 2012b).

Alfakara and Croxford (2014) incorporate the tool TAS (thermal analysis software) (2020) for simulation of heating and cooling loads. For simulating lighting systems and designs, the tool Radiance (2020) is used (Andrews et al. 2011). This visual simulation tool uses ray tracing techniques (Radiance 2020).

4.4.3 Computational coupling of agents with their context

A number of reviewed studies (Azar and Papadopoulos 2017, Langevin et al. 2014, 2015, Lee 2013, Lee and Malkawi 2014, Papadopoulos and Azar 2016, Thomas et al. 2016) computationally couple agents with their built environment (building energy model). Some other approaches manually couple the interaction between agents and their context (Jia et al. 2017, 2018, Jia and Bharathy 2018).

An approach to couple the ABM and the building energy model (BEM) is described in Azar and Papadopoulos (2017). Thereby, the authors couple the ABM (defined in MATLAB (2020)) and the BEM (simulated in EnergyPlus (2020)). MATLAB (2020) is applied in a twofold manner: the tool is used as a coupling engine and as a surrogate model for training and validation purposes. The approach by Papadopoulos and Azar (2016) also uses MATLAB (2020) and MLE+ (2020) to couple the ABM with the BEM.

Another study (Langevin et al. 2014) uses BCVTB (Building Controls Virtual Test Bed) (2020) to couple the ABM (developed in MATLAB (2020)) and the BEM (using in EnergyPlus (2020)).

Lee and Malkawi (2014) use MLE Legacy (2020) and BCVTB (2020) to couple agents and their environment.

Thomas et al. (2016) manage to couple the BEM and the ABM by the use of LCM-based communication (Lightweight Communications and Marshalling) (LCM 2020).

In case of Jia et al. (2017, 2018) and Jia and Bharathy (2018), users manually couple the energy simulation and the occupant behavior models.

4.5 Discussion

4.5.1 Reflections on the state-of-the-art of ABM applications in the built environment

This review effort provides an overview of a number of publications that apply ABM to represent people's behavior in buildings. The modeling purpose is to capture the interactions between agents (building occupants) and the interactions between agents and their context (built environment).

Generally speaking, ABM comes with a number of beneficial features. Occupants (traits, behavioral habits, etc.) can be presented both as individuals and as groups in a systematic manner. Once agents are computationally established, their behavior and interactions evolve without the need for explicit procedural programming efforts. These features come handy, when one aims at modeling, for instance, the impact of consciousness-raising measures on occupants' energy consumption behavior. Consequently, ABM-based incorporation of occupant behavior in simulation applications concerning buildings' energy and environmental performance can increase the versatility and effectiveness of such applications. Some of these benefits were demonstrated in the approaches and results of a number of papers reviewed in this work.

Nonetheless, the state-of-the-art in this area, as represented by the reviewed publications, display various shortcomings. It is not so much the technical implementation issues that represent the main challenges in ABM deployment. The tools and platforms of course can be further enhanced technically and in terms of user interfaces. But the main obstacles toward pervasive ABM application is a different one. The main problem is arguably the lack of comprehensive and reliable (empirically-validated) knowledge concerning processes that are related to building users' perception, behavior, and evaluation. Most of the reviewed research projects rely on fairly limited sources of foundational information in the course of their ABM efforts. Figure 5 shows the fraction of the main sources of domain knowledge in the reviewed publications.

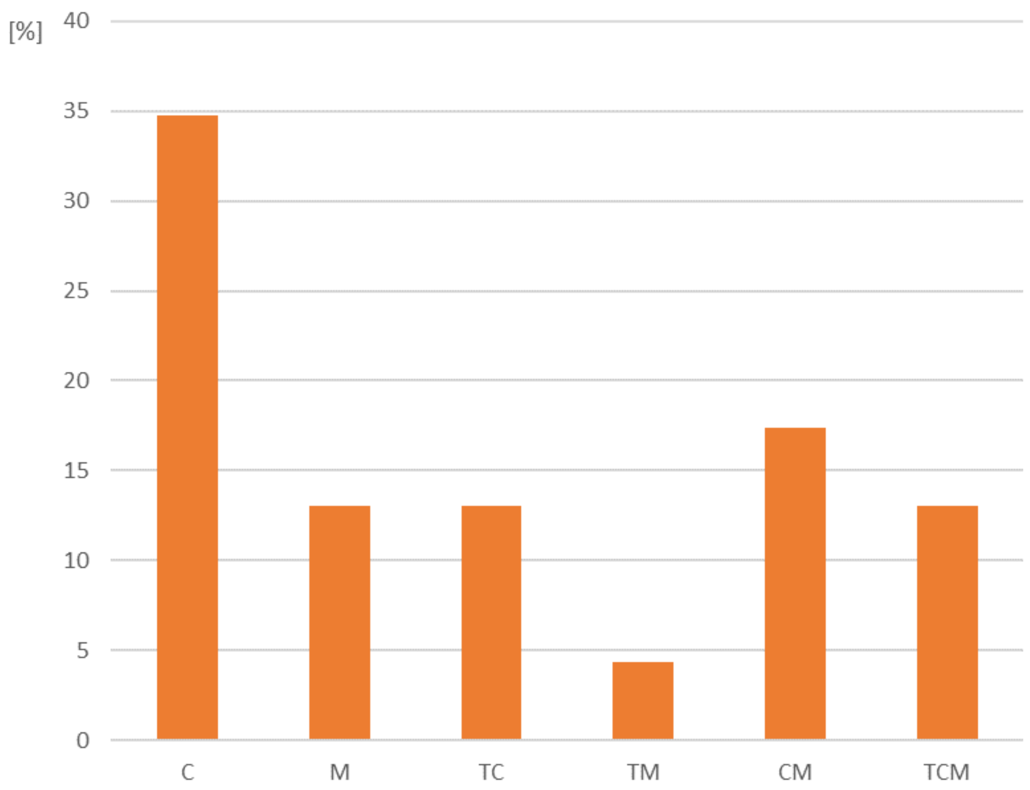

Figure 5. Fraction of the main sources of domain knowledge in the reviewed publications (Berger and Mahdavi 2020a).

Thereby, the following resources are considered:

- Theories or theoretical underpinnings (T)
- Codes, standards, and guidelines (C)
- Measurement, case-based original data (M)

Some reviewed studies rely on multiple sources of domain knowledge, such as both theory and codes/standards/guidelines (TC), both theory and original data (TM), both codes/standards/guidelines and original data (CM), or all three sources (theory, codes/standards/guidelines, and original data (TCM)).

As shown in Figure 5, none of the reviewed publications rely solely on a relevant behavioral theory. Only about one third (30%) of the research efforts include theoretical underpinnings.

About 40% of the reviewed papers rely solely on information based on codes, standards, and guidelines and do not include any behavioral theory or original data. Few research efforts (35%) rely on original data that is obtained through measurements, surveys, observations, or interviews.

Only a minority of the research efforts (about 13%) simultaneously include behavioral theories, information from codes, standards, and guidelines, and original data.

Hence, a main shortcoming is considered in the lack of available empirical data to capture different building types and locations and validate the ABM approaches. Moreover, the results of their computational studies are rarely validated against information from the "real world". Sophisticated computational formalisms as such are insufficient in providing real insights in occupant-environment interaction phenomena.

Supplied with proper, detailed, and robust domain knowledge on behavioral processes, they would however provide highly useful building design and operation support platforms.

Ongoing and future research efforts must not only seek the embellishment of ABM simulation formalisms, techniques, and platforms, but also engage in collaborative and extensive efforts to gather, structure, and analyze observational data from both field and laboratory investigations.

4.5.2 Challenges regarding knowledge base assumptions

As alluded to before, theoretical foundations are often missing in research efforts focusing on occupant behavior modeling. This obviously applies also to the ABM applications in the built environment domain. To put such applications on a solid foundation, a deeper understanding of occupants' patterns of perception and behavior in real environments is necessary. Real environments are, however, both complex and dynamic. A key feature of this complexity lies in the multi-aspect nature of indoor-environmental exposure situations. Whereas most available building design guidelines (and their underlying knowledge base) are mono-dimensional (i.e., they consider indoor-environmental variables one at a time), real environments are inherently multi-dimensional. Specifically, indoor-environmental conditions must be assessed and evaluated while simultaneously considering thermal, visual, auditory, and air quality aspects.

A number of past and ongoing research efforts study the impact of indoor-environmental conditions, such as thermal, visual, acoustic, and air quality, on occupants' behavior and perception (Schweiker et al. 2020, Berger et al. 2020b, Mahdavi et al. 2020). Thereby, research efforts focus on both single-domain and multi-domain approaches to better understand occupants' behavior. Single-domain research analyses the impact of one indoor-environmental stimuli in isolation (i.e., thermal domain) whereas multi-domain efforts address the influence of two or more indoor-environmental factors (i.e., thermal and visual domain) on occupants' behavior and perception. Schweiker et al. (2020) reviewed around 200 multi-domain approaches. Thereby, the majority of the reviewed studies is not based on profound theories of related disciplines (i.e., physiology, sociology, neurology, or psychology). Underlying theoretical concepts can help to understand and link certain findings with regard to human perception and human physiology.

Future research work can aim to develop an overall multi-domain comfort model. A conceptual schema (Mahdavi 2019) for a research design framework toward a multi-domain comfort model is shown in Figure 6. Thereby, a two-phase approach is suggested. Within a first phase, considerations to extend existing domain-specific comfort models by concurrent observation of the effects of variance in other domains. The second phase addresses a strategic and parametric analysis of the enriched single-domain models toward the definition and specification of a global IEQ (indoor-environmental quality) construct. Development of a unified model of human perception and behavior is of course a major challenge. Nonetheless, efforts in this direction are necessary, if future developments in ABM applications are going to be more reliable from the scientific point of view and more effective from the design decision support point of view.

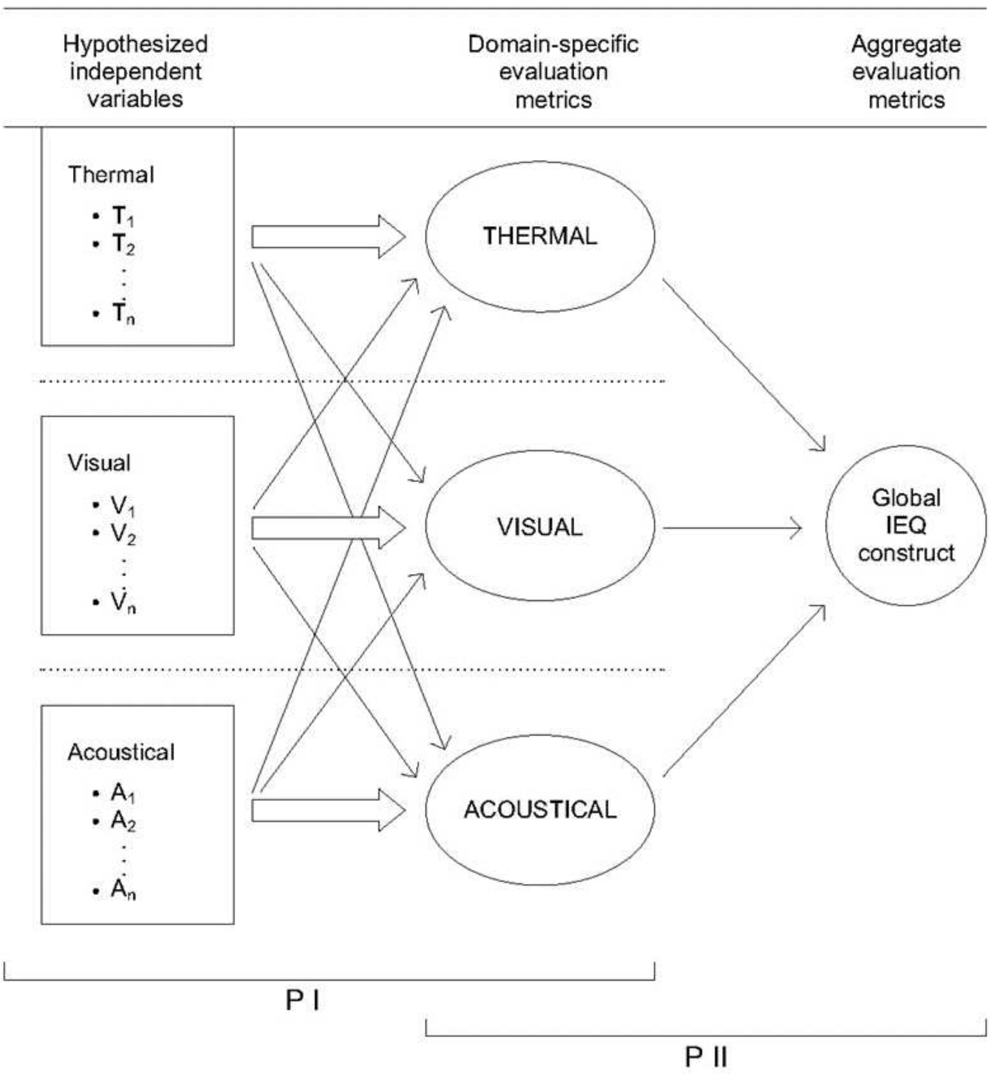

Figure 6. Conceptual schema for research design and evaluation geared toward a general multi-domain comfort model (Mahdavi 2019).

5 CONCLUDING REMARKS

The presented thesis demonstrates a review effort that focuses on agent-based modeling applications in the field of energy and indoor-environmental performance in buildings. Several research efforts are identified and analyzed in detail. A number of different representational methods and implementation environments and toolkits are discussed. Thereby, ABM formalisms are considered to provide a flexible way to capture occupants' dynamic behavior and patterns. Nonetheless, certain limitations and shortcomings, such as the lack of profound theoretical underpinnings or empirical data, are observed.

As alluded to before, various research work is continuously developing in the field of occupant behavior modeling. The IEA EBC Annex 79 "Occupant-centric building design and operation" (2020) specifically focuses on integrating and implementing occupancy and occupant behavior into the design process and building operation. Thereby, both energy performance and occupant comfort are aimed to be improved. Ongoing research activities in the framework of IEA EBC Annex 79 address different approaches and methodologies (including agent-based modeling) in the field of occupant modeling. In this collaborative framework, theoretical and empirical findings of occupants' behavior and perception are explored to enhance future research activities in this field.

6 APPENDIX

6.1 List of Figures

6.2 List of Tables

6.3 Matrix

Matrix 1 including general information about reviewed publications (Part I).

GENERAL INFORMATION							
Reference	Keywords	Type of article	Year of publication	Domain	Thematical Focus	Main output	Type of the model
Alfakara and Croxford (2014)	agent-based modelling, occupant behaviour, dynamic building simulation tools	Symposium Proceeding	2014	thermal comfort, energy consumption	the proposed approach deals with the impact of occupants' behavior (including users' interaction with the building) on energy consumption of residential buildings (in the context of summer overheating)	cooling load, internal temperatures	simulation framework
Andrews et al. (2011)	buildings, design automation, human factors, simulation, usability	Journal Paper	2011	visual comfort, energy use, energy costs	the study focuses on occupants' visual comfort, energy performance and energy costs of buildings	visual discomfort, occupants' interactions with windows and lights	simulation framework
Azar and Menassa (2010)	agent-based modeling, building energy consumption, energy usage characteristics, energy estimation software, energy calculation software	Conference Proceeding	2010	energy consumption	the paper studies the influence of different types of occupants and interactions among occupants on the buildings' energy consumption	energy consumption (electricity and gas consumption)	simulation framework
Azar and Menassa (2012)	energy use, energy estimation, occupant behavior, agent-based modeling	Journal Paper	2012	energy consumption	the paper studies the influence of different types of occupants and interactions among occupants on the buildings' energy consumption	energy consumption (electricity and gas consumption)	simulation framework
Barakat and Khoury (2016)	occupant multicomfort level, office buildings, energy efficient buildings, high-energy performance, building operation phases, building design, acoustic comfort levels, thermal comfort levels, visual comfort levels, agent-based modeling, energy consumption reduction, academic buildings, acoustic satisfaction, HVAC	Conference Proceeding	2016	thermal, visual and acoustic comfort	the paper studies occupants' influence of thermal, visual, and acoustic comfort levels on the buildings' energy consumption	probability of occupant behavior actions	conceptual agent-based modeling framework
Chen et al. (2016)	NA	Conference Proceeding	2016	occupant behavior, lighting energy consumption	the paper presents an web-based agent-based modeling application	lighting energy consumption	presentation of an agent-based modeling web application
Luo et al. (2017)	occupancy simulation, occupancy pattern, model performance evaluation, verification, occupant presence and movement, occupant behavior	Journal Paper	2017	occupant behavior	the study mainly focuses on the performance evaluation of the Occupancy Simulator (a web-based agent-based modeling application)	occupant behavior	performance evaluation of an agent-based model
Chen et al. (2018)	occupant behavior, occupant presence and movement, agent-based modeling, occupancy model stochastic model, meeting event model	Journal Paper	2018	occupant behavior	the proposed approach focuses on occupants' behavior (movement and presence) in buildings	occupant behavior	presentation of an agent-based modeling web application
Jia et al. (2017)	NA	Conference Proceeding	2017	thermal comfort, visual comfort, air quality comfort, energy consumption	the proposed ABM simulation framework is used to study the impact of occupants' behavior on energy consumption in commercial buildings	energy consumption	simulation framework
Jia et al. (2018)	occupant behavior, building energy simulation, sensors, agent-based modeling	Conference Proceeding	2018	thermal comfort, visual comfort, air quality comfort, energy consumption	the proposed ABM simulation framework is used to study the impact of occupants' behavior on energy consumption in commercial buildings	energy consumption	simulation framework
Jia and Bharathy (2018)	building energy model, energy simulation performance, current virtual model, dynamic occupant information input, practical occupant information input, ABM, model interactions, building components, actual data involvement, model testing, robust occupant behavior model, agent-based modeling, energy-related behaviors, office building energy simulation, building energy simulation improvement	Conference Proceeding	2018	thermal comfort, visual comfort, air quality comfort, energy consumption	the study focuses on validating the proposed ABM framework by Jia et al. 2017, 2018	energy consumption, occupant behavior	validation of an ABM simulation framework

Matrix 1 including general information about reviewed publications (Part II).

GENERAL INFORMATION

Reference	Keywords	Type of article	Year of publication	Domain	Thematical Focus	Main output	Type of the model
Langevin et al. (2014)	NA	Conference Proceeding	2014	thermal comfort, energy use	the study presents an approach to simulate occupants' adaptive thermal behavior with regard to energy and comfort effects of occupant behavior in an office setting	energy consumption, user behavior	simulation framework
Langevin et al. (2015)	human-building interaction, occupant behavior, agent-based modeling, thermal comfort, thermal acceptability	Journal Paper	2015	thermal comfort, energy use	the paper focuses on the description and validation of the proposed ABM	energy consumption, user behavior	simulation framework
Lee (2013)	agent-based modeling, building simulation, building technology, energy efficiency, human behavior, simulation coupling	Dissertation	2013	thermal comfort, energy consumption	occupants' influence on the energy use in office buildings is studied	energy consumption, occupant behavior	simulation framework
Lee and Malkawi (2014)	occupant behaviors, behavior simulation, simulation coupling, agent-based modeling, simulation accuracy, energy efficiency, thermal comfort	Journal Paper	2014	thermal comfort, energy consumption	occupants' influence on the energy use in office buildings is studied	Energy Use Index, Percentage of hours that comprise occupants' comfort level	simulation framework
Linkola et al. (2013)	agent-based modeling, behavioral factors, residential water use, buildings	Journal Paper	2013	water use of occupants	the proposed approach focuses on the impact of occupants' behavior on water consumption in residential settings	water consumption, frequency of water fixture usage	conceptual agent-based modeling framework
Papadopoulos and Azar (2016)	building performance simulation, agent-based modeling, energy consumption, human actions and behaviors, uncertainty analysis, multiple linear regression, surrogate models	Journal Paper	2016	occupant behavior, thermal comfort	the impact of occupants' behavior and building systems interactions on buildings' energy consumption of office buildings is studied	energy consumption	simulation framework
Azar and Papadopoulos (2017)	NA	Conference Proceeding	2017	energy consumption	the paper focuses on the uncertainty of occupants' behavior and the influence on the buildings' energy performance	energy consumption	simulation framework
Putra et al. (2017)	locus of control, building energy modeling, occupant behavior, load shedding, agent-based modeling	Journal Paper	2017	thermal and visual comfort	the models' main purpose is to analyse the impact of thermal and visual comfort levels and adaptive behavior on the energy consumption of buildings	energy consumption (electricity use)	simulation framework
Schaumann et al. (2017)	multi-agent system, occupant movement and shared activities, narrative-based model, use scenario, hospital setting	Journal Paper	2017	occupant behavior (movement and shared activity)	the proposed approach addresses occupant behavior (including occupants' movements and activities) in a hospital setting	occupant behavior	simulation framework
Thomas et al. (2016)	distributed simulation framework, adaptive thermal comfort behavior, building occupants, indoor building environments, comfortable living environment, adaptive thermal comfort models, behavioral patterns, agent-based model, zone-wise thermal comfort level, office building, energy simulation model, lightweight communications, marshalling, LCM, distributed computing framework, distributed workstations, energy saving potential	Conference Proceeding	2016	thermal comfort, energy consumption	the paper focuses on the effect of adaptive thermal behavior on the overall buildings' energy consumption	energy consumption	simulation framework
Wang et al. (2016)	lighting usage, office building, occupant behavior, conditional probability model, crowd effect	Journal Paper	2016	visual comfort	the paper deals with the impact of occupant behavior on the lighting energy usage in office buildings	lighting energy consumption, occupant behavior	conceptual agent-based modeling framework
Zhang et al. (2010)	office energy consumption, agent-based simulation, energy management technologies, energy management strategies	Research Article	2010	energy consumption	the ABM research effort focuses on occupants' impact on energy consumption in an office setting	electricity consumption	conceptual agent-based modeling framework

Matrix 2 including thematical assessment as well as main sources of domain knowledge of the reviewed publications (Part I).

	Thematical Assessment					Main sources of domain knowledge		
Reference	Building type	Number of occupants	Simulation run period	Region	Comments	Theory-based	Codes/ Standards/ Guidelines	Measurement/ Survey/ Case-based original data
Alfakara and Croxford (2014)	flat	2	3 months (in summer)	UK	limited to few occupant interactions with the building, no validation performed		X	
Andrews et al. (2011)	office	up to 10	1 day	US	no cross-reference to thermal, acoustic, or air quality comfort levels is considered	X		X
Azar and Menassa (2010)	office	10	60 months	Madison-Wisconsin, US	three types of occupants with different energy consumption profiles, no validation included		X	
Azar and Menassa (2012)	office	10	36 months	Madison-Wisconsin, US	three types of occupants with different energy consumption profiles, no validation included		X	
Barakat and Khoury (2016)	office	NA	NA	NA	statistical analysis using Rstudio is conducted			
Chen et al. (2016)	office	NA	NA	Miami, US	web application that generates occupancy schedules		X	
Luo et al. (2017)	office	13	1 year	Miami, US	occupancy data is collected to obtain information about occupants' behavior		X	X
Chen et al. (2018)	office	16	1 year	Miami, US	the study builds upon Chen et al. (2016) and Luo et al. (2017)		X	
Jia et al. (2017)	office	1	4 weeks	Florida, US	integration of ABM and BEM is manual (however, co-simulation is under development)		X	X
Jia et al. (2018)	office	single-occupied offices	4 weeks (in November)	Florida, US	indoor environmental data including temperature, humidity, and illumination is collected		X	X
Jia and Bharathy (2018)	office	single-occupied offices	NA	Florida, US	indoor-environmental data (temperature, humidity, illumination, CO2 concentration) is collected, a survey is conducted to obtain information about occupants' behavior		X	X

Matrix 2 including thematical assessment as well as main sources of domain knowledge of the reviewed publications (Part II).

	Thematical Assessment					Main sources of domain knowledge		
Reference	Building type	Number of occupants	Simulation run period	Region	Comments	Theory-based	Codes/ Standards/ Guidelines	Measurement/ Survey/ Case-based original data
Langevin et al. (2014)	office	about 70	2 months (January and July)	US	three different behavior scenarios (baseline, typical, set point float) are included	X	X	X
Langevin et al. (2015)	office	24	4 and a half work weeks	US	validation is included	X	X	X
Lee (2013)	office	1	1 year	Philadelphia, US	agents learn which behavior is more efficient to maximize the comfort and minimize the energy use	X	X	
Lee and Malkawi (2014)	office	1	1 year	Philadelphia, US	agents learn which behavior is more efficient to maximize the comfort and minimize the energy use	X	X	
Linkola et al. (2013)	residential setting	12 households	1 year	US, Netherlands	statistical information about average water consumption in the US and the Netherlands is obtained	X	X	
Papadopoulos and Azar (2016)	office	101 (100 occupants, 1 facility manager)	1 year	Abu-Dhabi, UAE	a sensitivity analysis is included		X	
Azar and Papadopoulos (2017)	office	101 (100 occupants, 1 facility manager)	NA	NA	the study is based on the approach by Papadopoulos and Azar (2016)		X	
Putra et al. (2017)	office	NA	NA	Philadelphia, US	different types of occupants are considered, including building manager, tenant representatives, and tenants	X	X	X
Schaumann et al. (2017)	hospital	4	NA	NA	building users' behavior is led by a set of procedures			X
Thomas et al. (2016)	office	about 2400	6 months (3 winter months, 3 summer months)	Chicago, US	influence among occupants is considered in terms of energy-conscious behavior		X	
Wang et al. (2016)	office	up to 20	126 days	NA	prior to the modeling of the occupant behavior model, a questionnaire is conducted and measurement data of office spaces is collected			X
Zhang et al. (2010)	office	NA	NA	Nottingham, UK	three types of agents are included: light and computer agents are modeled as passive agents in addition to agents that represent building users			X

Matrix 3 including information about representation of people and environment of the reviewed publications (Part I).

	REPRESENTATION OF PEOPLE		REPRESENTATION OF THE ENVIRONMENT		
Reference	**Domain knowledge**	**Implementation tools**	**Case study**	**Implementation tools**	**Coupling tools**
Alfakara and Croxford (2014)	occupants' interactions with the building include window and cooling system operation; "concept of seniority" is incorporated; two different behavioral scenarios (including a base-case scenario and an improved-case scenario) are compared in terms of the impact of energy-conscious behavior	Repast Symphony	a case study is performed in a flat (including four rooms) in a high-rise building	TAS	NA
Andrews et al. (2011)	the occupant behavior model is based upon the Theory of Planned Behavior (TPB) and the Belief-Desire-Intention (BDI) framework; a survey is conducted to collect occupants' behavior information	NetLogo	a simplified five-zone office building is used to simulate daily occupant light use patterns	Radiance	NA
Azar and Menassa (2010)	three different types of occupants: High Energy Consumer, Medium Energy Consumer, and Low Energy Consumer with different energy usage profiles are considered; occupants can operate blinds, lighting, equipment, and hot water; the influence on energy use habits among occupants ("word of mouth effect") is included	AnyLogic	a case study in an office setting including ten occupants in Madison-Wisconsin is performed	eQuest	NA
Azar and Menassa (2012)	three different types of occupants: High Energy Consumer, Medium Energy Consumer, and Low Energy Consumer with different energy usage profiles are considered; occupants can operate blinds, lighting, equipment, and hot water; the influence on energy use habits among occupants ("word of mouth effect") is included	AnyLogic	a case study in an office setting including ten occupants in Madison-Wisconsin is performed	eQuest	NA
Barakat and Khoury (2016)	three groups of building users, namely green, neutral, and non-green users, with different thermal, visual, and acoustic comfort preferences are considered	AnyLogic	NA	NA	NA
Chen et al. (2016)	the occupant behavior patterns are based on the OB XML Schema that is built upon the OB DNAS framework; occupants' movement and presence in built spaces is captured	Occupancy Simulator	a case study office building in US is selected	NA	NA
Luo et al. (2017)	the occupant behavior patterns are based on the OB XML Schema that is built upon the OB DNAS framework; occupants' movement and presence in built spaces is captured	Occupancy Simulator	a case study office building including 13 occupants is simulated	EnergyPlus	obFMU
Chen et al. (2018)	occupancy patterns are based on the OB XML schema that builts upon the OB DNAS theoretical framework	Occupancy Simulator	a case study in an office building in the US is performed	EnergyPlus	obFMU
Jia et al. (2017)	occupants can adapt the state of windows, doors, blinds, and heaters; thermal, visual, and air quality comfort levels are considered	PMFserv	a case study in a single-occupied office area in Gainesville, Florida (US) is performed	EnergyPlus	manual coupling
Jia et al. (2018)	a GSP (Goals, Standards, and Preferences) tree is used to describe occupants' behavior	PMFserv	a case study in a single-occupied office area in Gainesville, Florida (US) is performed	EnergyPlus	manual coupling
Jia and Bharathy (2018)	occupants can adapt the state of windows, doors, and blinds	PMFserv	five single-occupied office spaces in a university building are selected	EnergyPlus	manual coupling

Matrix 3 including information about representation of people and environment of the reviewed publications (Part II).

	REPRESENTATION OF PEOPLE		REPRESENTATION OF THE ENVIRONMENT		
Reference	**Domain knowledge**	**Implementation tools**	**Case study**	**Implementation tools**	**Coupling tools**
Langevin et al. (2014)	occupants react according to the Perceptual Control Theory (PCT); different adaptive behaviors with regard to thermal comfort are considered	MATLAB	a case study office building is simulated in five different climate regions in the US	EnergyPlus	BCVTB
Langevin et al. (2015)	occupants react according to the Perceptual Control Theory (PCT); different adaptive behaviors with regard to thermal comfort are considered; a one-year field study is conducted to collect information about occupants' behavior	MATLAB	a case study office building is simulated for validation purposes	EnergyPlus	BCVTB
Lee (2013)	occupants' behavior is adopted from the Reasoned Action Model (including behavioral, control, and normative beliefs); occupant actions include the interactions with windows, doors, blinds, fans, and heaters	MATLAB	a case study office building is simulated in different climate regions in the US	EnergyPlus	MLE Legacy and BCVTB
Lee and Malkawi (2014)	occupants' behavior is adopted from the Reasoned Action Model (including behavioral, control, and normative beliefs); occupant actions include the interactions with windows, doors, blinds, fans, and heaters	MATLAB	a case study office building is simulated in different climate regions in the US	EnergyPlus	MLE Legacy and BCVTB
Linkola et al. (2013)	agents' decision making process is based on the TPB (Theory of Planned Behavior) and the BDI (Belief-Desire-Intention) framework	NetLogo	two case study buildings in the US and the Netherlands are selected including three different household scenarios (single, couple, and family)	NA	NA
Papadopoulos and Azar (2016)	different occupancy characteristics (including lighting and equipment use patterns as well as cooling and heating thermostat set points) are considered	AnyLogic	a case study office building is selected including occupants and facility manager	EnergyPlus	MATLAB, MLE+
Azar and Papadopoulos (2017)	occupants' actions include the use of lights, equipment, and control of cooling and heating set points	MATLAB	a simulation in an office building including occupants and facility managers is performed	EnergyPlus	MLE Legacy and BCVTB /MATLAB
Putra et al. (2017)	a questionnaire about occupants' preferences and behavior is conducted; the occupant behavior model is built upon the BDI framework	NetLogo	the proposed simulation framework is applied to case study office buildings equipped with different building controls	EnergyPlus	NA
Schaumann et al. (2017)	information about occupants' behavior is obtained via interviews and field observations	Unity 3D	a case study in an simplified hospital layout including different types of spaces (i.e., patient rooms, offices, nurse areas, medecine spaces) is performed	Autodesk AutoCAD	NA
Thomas et al. (2016)	the occupant behavior model includes three different types of occupants with different thermal comfort preferences and is based upon the model by Azar and Menassa (2013, 2015)	AnyLogic	the proposed simulation framework is applied to a case study office building	EnergyPlus	LCM based communication
Wang et al. (2016)	a self-conducted questionnaire gives information about occupants' light switching behavior; the occupant behavior model considers same rights to access lights within the offices among all occupants and the light use behavior adapts as soon as occupants are interacting with each other (occupants are not allowed to turn the lights off in case other occupants are still in the office working)	NA	the study includes a simulation of occupants' light usage in an open-plan office setting	NA	NA
Zhang et al. (2010)	empirical surveys and observations of occupants' behavior are conducted to collect information about building users' behavior; three different types of agents are considered: the energy user agent (represents an occupant), the computer agent (passive agent), and the light agent (passive agent)	AnyLogic	a case study building at the University of Nottingham, UK focusing on the electricity consumption is simulated	NA	NA

6.4 Annotated Bibliography

Alfakara and Croxford (2014).

Alfakara and Croxford (2014) propose an approach to simulate the impact of occupant behavior on energy consumption, specifically on the case of summer overheating, in a residential setting using an ABM. Thereby, the study links an energy simulation software with an ABM environment.

The simulation framework is applied to a residential setting including two occupants. The occupants are able to control the mechanical cooling system (on/off) as well as operating the windows (open/close). The ABM is programmed using the tool Repast Symphony (Repast 2020). Thereby, the study incorporates a "concept of seniority". It represents a hierarchical decision-making model in which the most senior agent has the privilege to make behavioral decisions in the built environment. Moreover, two types of occupants with different behavior characteristics are considered.

The simulation is performed over a period of three months in summer using the software TAS (Thermal Analysis Simulation) (TAS 2020). The results show a 30% cooling load difference between the two different occupant behavior types.

The proposed simulation framework is limited to a small number of occupants and includes few occupant interactions with the environment. The sources of information about domain knowledge are not described in detail and no validation is performed.

Andrews et al. (2011).

The study by Andrews et al. (2011) focuses on visual comfort requirements of occupants as well as energy performance and energy costs. Thereby, the authors present an ABM simulation framework that builds upon an approach developed by Fujii and Tanimoto (2003). This approach includes four different submodels, namely a building performance simulation submodel, a human action simulation submodel, a mediating submodel that links the building and the occupants, and an external industry-standards building system model. For modeling occupants' behavior, the human action simulation submodel combines the Theory of Planned Behavior (TPB) (Ajzen 1991) and the Belief-Desire-Intention (BDI) framework (Rao and Georgeff 1998). This modeling approach is already tested, calibrated, and validated using survey responses of building occupants as well as data from a case study building.

In order to test different light design options and related visual comfort of building occupants, the authors couple an ABM (using NetLogo (Wilensky 1999)) with a lighting simulation tool (using Radiance (2020)). Thereby, the authors model a five-zone office building including up to ten occupants and simulate the daily occupant lighting use.

Andrews et al. (2011) emphasizes the lack of empirical data describing occupants' preferences and sensitivities as well as monitoring data.

The study provides an interesting approach with regard to visual comfort. The outputs are not limited to energy performance parameters but include also a cost factor. However, the study has limitations as the simulation run period is fairly short (one day) and the cross-reference to other comfort requirements (such as thermal, acoustical, or air quality) is not considered.

Azar and Menassa (2010).

Azar and Menassa (2010) present a research effort that links an ABM with a conventional energy simulation tool. The authors study the influence of different occupants' behavior and change over time on the buildings' energy estimation.

In this context, three different types of occupants ("High Energy Consumer", "Medium Energy Consumer", and "Low Energy Consumer") are defined that represent different energy usage profiles. Thereby, the occupants' energy use characteristics include the operation of blinds, lights and equipment, as well as the consumption of hot water. Moreover, a change of occupants' energy use characteristics over time is incorporated in the ABM. Thereby, the "word of mouth" effect (Allsop et al. 2007) is included that describes the probability of influence on energy use habits from one occupant to another.

The presented simulation framework is applied to a student office in Madison-Wisconsin, US including ten students over a period of 60 months. The study uses the energy simulation tool eQuest (2020) and the ABM tool AnyLogic (2020). The simulation results showed a difference of 11% gas consumption and 39% electricity consumption between the "Low Energy Consumer" and the "High Energy Consumer". Furthermore, the number of "Low Energy Consumers" increases over the simulation time so that the overall energy consumption decreases.

The authors propose an approach that addresses not only the integration of multiple occupant types with different energy use characteristics but also the interaction and influence among the occupants. However, the study does not comprise a comprehensive data collection to better assume occupants' behavior and perception.

Azar and Menassa (2012b).

Azar and Menassa (2012b) propose an approach to model occupants and their impact on energy consumption using an ABM. For this purpose, different patterns of occupants' energy consumption behavior as well as the interaction and influence among occupants are modeled. Thereby, three different types of occupants, including high, medium, and low energy consumer, are considered. Moreover, a change of occupants' behavior over time is included in two aspects. One aspect focuses on the integration of energy conservation trainings and workshops that inform occupants about energy saving techniques and practices. Another aspect refers to the consideration of the "word of mouth" effect (Allsop et al. 2007). This effect describes the influence between occupants with regard to their energy consumption habits. In this model framework, each occupant intends to influence the surrounding individuals and change their energy consumption behavior.

A case study example is presented to implement the proposed simulation framework. Thereby, ten occupants are simulated in an office area in a university building in Madison-Wisconsin, US. The occupants can adapt and use lights, equipment, blinds as well as hot water. This study uses the energy modeling software eQuest (2020) and the ABM environment AnyLogic (2020).

The study demonstrates an ABM approach that addresses both the influence and the change of people's behavior over time on energy consumption. Nonetheless, the approach does not provide a collection of actual building data. Thus, the study is limited to a technical validation. Moreover, the simulated environment involves a single office area. Future research studies could address the interaction of occupants in multiple areas and environments.

Barakat and Khoury (2016).

The research effort by Barakat and Khoury (2016) studies occupants' influence of different comfort levels, including thermal, visual, and acoustical comfort, on the energy consumption of buildings.

For this purpose, three groups of occupants (green, neutral, and non-green) with different thermal, visual, and acoustic comfort preferences are defined. Occupants are able to operate windows, shades, lights, and HVAC settings. Note that the state of windows, shades, and lights can be adjusted in two ways, namely open/closed or on/off whereas the HVAC settings include four levels (high, medium, low, and off). Moreover, the study incorporates three levels of noise from outside (high, medium, and low). The presented ABM framework is applied to an office area using the ABM software environment AnyLogic (2020).

The results of the study show a statistical analysis using the tool RStudio (2020). Thereby, the probability of occupants' behavior and actions (considering the three different occupant types) is analyzed.

The study proposes a conceptual ABM framework that addresses occupants' thermal, visual, and acoustic comfort preferences. The proposed framework does not describe the sources of domain knowledge to assume certain occupant behavior patterns.

Chen et al. (2016).

Chen et al. (2016) present a web-based agent-based modeling application “Occupancy Simulator”. The Occupancy Simulator is developed at the Lawrence Berkeley National Laboratory (Occupancy Simulator 2020). It is an open-source tool and is built upon the web framework Ruby on Rails (2020). As the application is limited to commercial buildings, it cannot be used for residential settings.

The occupant model is built upon the occupant behavior XML Schema (Hong et al. 2015a) and the occupant behavior DNAS (Drives, Needs, Actions, Systems) framework (Hong et al. 2015b).

Within a case study the usage of this application and its integration with EnergyPlus (2020) and obFMU (Hong et al. 2016b) is presented. Occupant schedules and lighting energy consumption of an office located in Miami, US are analyzed. Specifically, a researcher office including four occupants is simulated for a period of one year using the Occupancy Simulator.

The proposed web application can capture occupants' movement and presence in built spaces. However, occupants' walking time and distance between spaces is not yet considered.

Luo et al. (2017).

The study by Luo et al. (2017) mainly focuses on the performance evaluation of the Occupancy Simulator (2020) proposed by Chen et al. (2016).

For this purpose, occupancy data is measured in an actual office building at Carnegie Mellon University, US. Over a period of three months, information about occupancy behavior patterns of about 60 building users are collected using occupancy sensors. Moreover, a statistical evaluation of the measured data is conducted.

The measured data is used to test the verification of the proposed simulation model. Thereby, a case study office building including 13 occupants is simulated over a period of 12 months using the before identified occupancy patterns.

The authors suggest to use and measure detailed occupancy data of different space types in an office building to validate the occupants' data provided by the Occupancy Simulator (2020).

As the study's main focus is the evaluation and verification of the proposed occupant behavior model, no link between an ABM and a building performance simulation model is discussed.

<u>Chen et al. (2018).</u>

This research effort builds upon the publication by Chen et al. (2016) and Luo et al. (2017).

The occupant model is built upon the OB XML Schema (Hong et al. 2015a) and the occupant behavior DNAS framework (Hong et al. 2015b). The authors include three events to represent occupants' behavior (movements and presence), namely status transition events (occupant arrives or leaves the building), movement events (occupants' movements within the building), and meeting events (occupant has a meeting for a certain time within the building). In order to simulate these events, the Reinhart's Lightswitch-2002 model (Reinhart 2004) and the Markov chain model by Wang et al. (2011) are used.

Moreover, a case study is conducted including 16 building users in an office building in the US. Thereby, the percentage of time that occupants are spending inside the office spaces is assumed according to the measured data by Luo et al. (2017). The simulation runs over a period of one year. ObFMU (Hong et al. 2016b) is suggested for co-simulating with a building performance simulation tool, such as EnergyPlus (2020).

An interesting ABM approach is presented that uses a free available web-based application. However, occupants' behavior is considered not to be dependent of indoor-environmental conditions. Moreover, a case study that connects the occupant behavior model with an energy simulation model is not provided.

Jia et al. (2017).

Jia et al. (2017) propose an ABM simulation framework to study the impact of occupants' behavior on energy consumption.

The study considers occupants' thermal and visual comfort as well as indoor air quality preferences. Occupants can improve the environmental conditions by adapting the state of windows and doors (open or close), as well as blinds and heaters (on or off). Within the ABM, agents' (occupants') behavior actions are based on a decision-making algorithm depending on values (occupants' cognition) and contexts (occupants' environmental perception).

The ABM is built by the use of the tool PMFserv (Performance Moderator Functions testbed) (Silverman 2006b) and is linked with the widely used energy simulation tool EnergyPlus (2020).

A case study for a single-occupied office area in Gainesville, Florida (US) is conducted to apply the simulation framework.

The number of simulated occupants is limited to one individual so that no interaction among occupants could be considered. Moreover, the simulation coupling is done manually and the study does not conduct a validation. The authors mention that relevant actual data is already collected and will be incorporated in future research.

Jia et al. (2018).

This research effort studies the impact of occupant behavior on the buildings' energy use and builds upon the approach presented by Jia et al. (2017). The main focus is to improve the proposed ABM and expand the energy simulation scale. Thereby, the occupants' thermal, visual, and air quality preferences are considered. A "Goals, Standards, and Preferences (GSP) tree" is used to describe agents' behavior (an agent refers in this study to a building user). This value system implies the agents' inner mindset and values (e.g., safety or health issues). Within the ABM, agents make decisions based on the utility that is a function of values and contexts. Values are derived from the GSP tree. Contexts represent the environmental parameters including the thermal, visual, and air quality comfort.

To test the simulation framework, several single-occupied offices are simulated over a period of four weeks. Occupants' interactions with the built environment include the operation of windows, doors, blinds, and heaters.

The study collected indoor environmental data, but no validation is provided. Moreover, the integration of the ABM and the energy simulation model is limited to a manual operation. As many other publications, the simulation framework addresses only one building type.

Jia and Bharathy (2018).

The study by Jia and Bharathy (2018) focuses on the validation of an ABM framework and builds upon previous work by the authors (Jia et al. 2017, 2018). The simulation framework addresses three main aspects. One aspect describes the building occupant that is represented as an agent with a certain perception and behavior. Moreover, an actual building, namely a university building in Florida, US, is selected as a simulation environment. The third aspect describes occupants' interaction with the built environment. The authors describe the ambient environment as the key factor that triggers occupant behavior in terms of maintaining thermal, visual, and air quality comfort. The tool PMFserv (Silverman 2006b) is used to define the human behavior model.

For the purpose of validating the proposed ABM framework, environmental data, such as temperature, humidity, illumination, and CO2 concentration, is measured. In addition, information about occupant behavior is collected using a paper-based survey over a period of two to four weeks. The survey is filled by the occupants in a 15 minutes' interval to determine occupants' interactions with the building. Five single-occupied office spaces in a university building are selected in which occupants can adapt the state of windows, doors, and blinds. Furthermore, a comparison of the collected (measured) data and the simulated results is presented. Thereby, actual and simulated window blind operations and illumination levels, that represent the main influencing factor for operating windows, are shown for one working day (9am till 6pm). In addition, actual and simulated door operations and the main influencing factors, namely CO2 concentration and indoor temperature, are presented and analyzed. The simulation accuracy is between 70% and 97%, whereby the blind operations represent the highest accuracy.

As the study's main focus is the validation of an ABM simulation framework, the integration with an energy simulation tool is not provided. Moreover, the model is limited to three different occupant actions and one building type.

Langevin et al. (2014, 2015).

Langevin et al. (2014, 2015) present a co-simulation framework that focuses on occupants' comfort and behavior predictions. The Human and Building Interaction Toolkit (HABIT) couples an ABM (defined in MATLAB (2020)) with an energy performance simulation tool (EnergyPlus 2020) by using the Building Controls Virtual Test Bed (BCVTB) (2020).

The ABM includes agents that represent building occupants who react according to the Perceptual Control Theory (PCT) (Powers 1973). As soon as agents' thermal perception is outside the thermal acceptable range (adopted from the ASHRAE Sensation Scale (ASHRAE 2020)), a behavior action is required.

A one-year field study in an office building is conducted to collect information about occupants' behavior and comfort and to validate the ABM scheme. The field study is conducted in an office building in Philadelphia, US, from July 2012 till July 2013. A total of 45 individuals (occupying different office types and having different control possibilities) participated in the study. Thereby, the participants are asked to fill an online questionnaire three times per day over the period of two weeks and a retrospective questionnaire. The questions related to thermal preferences, acceptability, and behavioral actions. In addition, indoor-environmental data (ambient and globe temperature, relative humidity, air velocity) and occupant actions (use of heater, personal fan, and windows) were measured.

Five adaptive occupant behavior actions with regard to thermal comfort are considered (clothing adjustment, personal use of heaters and fans, thermostat use, window opening/closing).

Moreover, the presented simulation framework is applied to a case study building. Thereby, an office building (provided as a prototype building by the US DOE (2020)) is simulated in five different climate regions in the US over a period of two months (January and July). Different behaviors are defined in three scenarios: "Baseline", "Typical", and "Set Point Float".

The study proposes a co-simulation framework that integrates an ABM with a building performance simulation. The incorporated ABM is validated using information and data from a field-study in an office building. As the research effort focuses only on occupants' thermal comfort, other indoor-environmental aspects, such as visual, acoustic comfort or air quality comfort can be considered in future research as well.

Lee and Malkawi (2014), Lee (2013).

The research efforts study the influence of occupant behavior on the energy use in an office building. Thereby, the authors incorporate three processes, namely to define behavior, to identify behavior triggers, and to measure and quantify behavior, in a human behavior model. The behavioral, control, and normative beliefs associated with occupants' behavior are adopted from the Reasoned Action Model (Fishbein and Ajzen 2010). Moreover, the study includes a cost function that supports the agent in performing the appropriate decision to maximize occupants' comfort and minimize the energy use. Once an agent performs an action, the influence of its behavior is evaluated. In this way, the agents learn which behavior is more efficient in terms of maximizing the comfort and minimizing the energy use. Occupants' behavior actions include the use of windows, blinds, space heater, and personal fan as well as the adjustment of clothing and activity level. The behavior actions are triggered by the occupants' thermal comfort preferences that are adopted from the PMV model by Fanger (1970).

The ABM framework is applied to an office area in Philadelphia, US, including a single occupant. The case study example was simulated hourly over a period of one year. Thereby, the ABM is defined using the tool MATLAB (2020) and the software EnergyPlus (2020) is selected for simulating buildings' energy consumption. The authors include a simulation coupling by using the BCVTB architecture (BCVTB 2020) and MLE+ (2020).

Lee and Malkawi (2014) study occupants' behavior in different climate regions (Phoenix, Calgary, and San Francisco). The results show that the overall occupant comfort level is rated as the highest in a moderate climate (San Francisco). The study suggests a human behavior model that encompasses theoretical concepts as well as code-based assumptions. However, the study does not provide measured data to validate the simulation framework. Moreover, the interactions between occupants are not considered.

Linkola et al. (2013).

The proposed ABM approach focuses on the impact of building users' behavior on water consumption in residential settings. In this context, the authors propose an ABM that integrates four aspects to describe the agents' behavior and their surroundings. One aspect describes the model environment in terms of water use appliances. Another aspect represents agents' decision-making process that is based on a previous research approach (Andrews et al. 2011) by combining the Theory of Planned Behavior (TPB) (Ajzen 1991) and the Belief-Desire-Intention (BDI) framework (Rao and Georgeff 1998). As per the concept of the TPB, occupants' behavior is led by behavioral, normative, and control beliefs. Other aspects cover agents' interaction with water use fixtures and adaptive occupant behavior.

Two case study buildings in the Netherlands and the US are selected to apply the suggested ABM framework. For this purpose, statistical information from both countries is collected to assume the average water consumption. The authors use the widely known tool NetLogo (Wilensky 1999) to implement the ABM. Thereby, three types of household configurations, namely singles (full-time working adult), couples (two retirees) and families (two working adults and two students) are considered. A number of practices of daily water usage (such as personal hygiene, toilet use, cooking, drinking, washing laundry, and dish washing) are included.

Linkola et al. (2013) presents an interesting approach to use ABM in the context of occupants' water use behavior patterns. The study does not include a calibration or validation as no empirical data of occupants' behavior is available. Moreover, occupants' change over time is not considered within the ABM.

Papadopoulos and Azar (2016).

Papadopoulos and Azar (2016) present an approach to couple building performance simulation and agent-based modeling to study the impact of occupants' behavior on buildings' energy consumption.

Building occupants are described as agents that influence the built environments' performance. The human behavior model considers two types of occupants (building user and facility manager) that interact with building systems. Occupants' light and equipment use as well as control of heating and cooling setpoints are included in the ABM. The acceptable comfort levels are derived from the building code ASHRAE (2020).

The tool AnyLogic (2020) is selected to define the ABM and the software EnergyPlus (2020) is used for simulating the energy performance. A co-simulation is implemented by using MATLAB (2020) and MLE+ (Bernal et al. 2012, MLE+ 2020). Moreover, a regression-based surrogate model is integrated to train, test, and validate the model using MATLAB (2020).

A case study building is selected to deploy the simulation framework. A total of 100 building occupants and one facility manager are simulated in a commercial building over a period of one year. The building represents a prototype building provided by the US Department of Energy (DOE 2020).

The presented study does include a technical validation (i.e., performing a sensitivity analysis). However, actual building data is not measured so that a validation of the simulation framework is not provided. The authors provide a detailed description about the technical implementation of the modeling approach whereas the integrated ABM is not extensively discussed.

Azar and Papadopoulos (2017)

The paper studies the uncertainty of occupants' behavior and the related influence on buildings' energy consumption. In this context, the authors propose a simulation framework that couples an ABM with building energy simulation using a regression surrogate model.

The presented methodology is based on a previous research effort by Papadopoulos and Azar (2016). Thereby, an office building including 101 occupants (100 building occupants, 1 facility manager) is simulated according to the proposed framework. Occupants' actions include the adaption of heating and cooling setpoints, as well as the use of lights and equipment. Moreover, an uncertainty analysis is conducted to analyze the variation and uncertainty of occupants' actions. Different scenarios are simulated to study the impact of different control options (full occupant control, full facility manager control, shared control among occupants and facility manager). The results show that the variation and flexibility of energy consumption is low in case of full occupant control (considering 100 occupants). However, the energy performance results vary much more if only the facility manager has control over the building systems.

The occupant actions included in the study are rather limited and can be further expanded. Moreover, no data or information about occupant behavior is collected and no validation is conducted.

Putra et al. (2017).

The study by Putra et al. (2017) addresses the influence of thermal and visual comfort and adaptive occupant behavior actions on buildings' energy consumption. The authors propose an ABM framework that defines adaptive occupant behavior in terms of a multi-attribute utility function (that reflects the proposed BDI framework (Andrews et al. 2011, Rao and Georgeff 1998). Thereby, adaptive behavior is related to environmental conditions (thermal and visual conditions) and occupants' actions intend to minimize the four aspects: environmental impact, effort, cost, and discomfort.

Moreover, a questionnaire about occupants' preferences and behavior is conducted to collect behavioral information. Three types of occupants are included, namely building occupants, tenant representatives and building manager.

The tool NetLogo (Wilensky 1999) is used to implement the ABM and EnergyPlus (2020) is selected to simulate buildings' energy performance. The simulation framework is applied to two office buildings that are located close to Philadelphia, US. A number of scenarios are simulated to test different communication types, control options, and clothing behavior in both buildings.

The proposed ABM framework includes three types of occupants, though the building type and location options can be further expanded. In addition to occupants' comfort preferences, the impact of energy costs is also considered.

<u>Schaumann et al. (2017).</u>

The research effort by Schaumann et al. (2017) focuses on occupant behavior in a hospital setting. Thereby, it is assumed that user behavior is mainly led by a set of medical procedures. Prior to the simulation approach, detailed information and data about procedures in hospital settings are collected by conducting interviews with professional experts, field observations, and reviewing relevant literature. Within the suggested multi-agent model, agents' behavior is led by narratives. As the hospital environment is mainly a process-driven setting (similar to for example airports), narratives are assumed to represent occupants' behavior in an appropriate way.

A case study in an abstract hospital layout including different types of spaces (such as patient rooms, offices, nurse areas, medicine spaces) is performed. The proposed approach includes different types of building users, such as doctors, nurses, patients, and visitors. The simulation output visualizes occupants' movements within the hospital setting in colored lines.

The environment is modeled using Autodesk AutoCAD (2020) and the tool Autodesk 3DS Max (2020) is selected for modeling the building users. Users' activities, narratives, users' profiles as well as space profiles are modeled using the C# programming language. The tool Unity 3D (2020) is used for simulation and visualization purposes.

The authors suggest to integrate the multi-agent narratives model with energy simulation tools. In addition, future research can focus on validating of the proposed simulation approach.

Thomas et al. (2016).

Thomas et al. (2016) present a simulation framework that focuses on the impact of adaptive occupant behavior on energy consumption by coupling an ABM with an energy simulation. Specifically, occupant behavior patterns that influence the thermal comfort level are studied.

For this purpose, the occupant behavior model is adapted from Azar and Menassa (2013, 2015). This model includes three different types of occupants with different thermal comfort preferences. Moreover, interactions among the occupants are considered so that one occupant can influence another in terms of energy-conscious behavior.

EnergyPlus (2020) is used to simulate the energy performance. In order to couple the occupant behavior model and the energy simulation model, the authors use a LCM (Lightweight Communications and Marshalling) (2020) communication.

The coupled simulation framework is applied to a case study building (office) in Chicago, US. Thereby, the simulation runs over a period of six months (three summer months and three winter months) and includes about 2400 occupants.

The authors present a simulation framework that incorporates simulation coupling between the occupant behavior model and the energy simulation model. However, the study is limited to a technical validation and only one building type is considered.

<u>Wang et al. (2016a).</u>

The approach presented by Wang et al. (2016a) focuses on the impact of occupant behavior on the lighting energy consumption. Specifically, the occupants' usage of lights is analyzed in an office area.

Prior to the definition of the occupants' light switching behavior model, a questionnaire is conducted and actual data in office spaces is collected in the course of previous publications (Ren et al. 2015, Wang et al. 2016b). The questionnaire results reveal that two main aspects trigger occupants' behavior related to the light usage. One aspect refers to the influence of personal movement (i.e., light usage when leaving or entering a space). Another aspect addresses the adjustments of lights level to maintain an adequate lights level at the workplace. Different probabilities are considered to turn the lights on or off if an occupant is entering or leaving an office space as well as if an occupant perceives the illumination as too dark or bright enough.

In the course of the ABM, the authors assume that all occupants have the same right to access the lights within the office space and all occupants show the same behavior in open offices as in private offices. Moreover, occupants' light use behavior adapts as soon as occupants are interacting with each other.

A simulation of the occupants' light usage model is performed in an open-plan office including up to 20 occupants. The simulation is repeated 100 times to analyze the variability and stability of the results. The analysis of the results show that a higher number of occupants within the office space entails an increase in lighting energy consumption and the lighting usage is more constant with less randomness.

The study is limited to a conceptual framework that is not linked to building performance simulation and considers only the occupants' visual comfort.

Zhang et al. (2010).

Zhang et al. (2010) present an ABM approach to simulate energy consumption of an office area. A case study building at the University of Nottingham, UK, is selected to perform simulations focusing on the electricity use. Specifically, one floor including several rooms is simulated. Prior to the case study, information about occupants' behavior as well as data of the actual energy consumption of the building was collected. The ABM framework considers occupants' movements, their use of computers (turning on/off), and their energy-conscious behavior. The lights are switched on automatically once an occupant enters a room as light sensors are integrated in the entire building. The software AnyLogic (2020) is deployed to implement the ABM.

The study includes not only building occupants as user agents, but also passive agents related to building systems, namely computer agents and light agents. The behavior of computer agents (on/off/standby) and light agents (on/off) is influenced by the user agents' behavior.

As empirical data is collected, a validation is conducted by comparing the simulation results and the actual building data. The simulation results are further used to analyze the electricity consumption in detail. Thereby, the results reveal that a high percentage (55%) refers to the electricity consumption of lights in contrast to the electricity consumption of computers (7%).

The authors point out the lack of sophisticated theories about occupants' behavior and the time and cost-consuming process of conducting relevant behavioral information through questionnaires.

The study presents an interesting approach to implement an ABM. However, the model is applied to one building type (office) only and does not incorporate a change of occupants' behavior over time.

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