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Mapping Building Information Modeling Capabilities with the Information Needs of Studies of Domestic Arthropod Ecology

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The presence of arthropods is a fact of life in most buildings. While many are innocuous, some may have negative impacts on human occupants' health or economic well-being, like cockroaches, bed bugs, and pantry moths. Understanding the behavior and ecology of domestic arthropods is critical for indoor pest management and sustainability, and can support Integrated Pest Management (IPM) plans. Building Information Modeling (BIM) has the potential to serve as the data analysis and simulation platform for domestic arthropod studies. This research maps the current and potential functions of BIM to the needs of domestic arthropod studies, and conceptualizes a system architecture for a BIM-enabled simulation engine and platform for this purpose. This platform will contribute to the digitalization of structural IPM and will serve as an educational tool for professionals and students.

Key Words: Building Information Modeling (BIM), domestic arthropods, arthropod simulation platform, indoor environment, sustainability

Introduction and Literature Review

Arthropods impact human life in buildings in many ways beyond the pleasures of watching them. They may have negative impacts on occupants' health, such as with diseases spread by bed bugs (Eliopoulos, Tatlas, Rigakis, & Potamitis, 2018). Cockroaches may cause sanitary problems and also negatively impact the mental health of occupants. Termites and other wood-boring insects can cause significant structural damage. Pantry pests may damage food. There is a factor of fear and disgust among humans for some arthropods, such as spiders (Vernon & Berenbaum, 2002). There can also be significant economic impacts in commercial or industrial settings. These problems support a thriving structural pest management industry, worth an estimated $10.4B in 2021 in the United States (Pest Control Technology, 2022).

Many strategies and techniques exist for pest management, depending on the context and the pests (e.g. Rajendran, 2020). However, a well-established framework for developing sustainable pest management plans is Integrated Pest Management (IPM). IPM is a holistic approach, which focuses on prevention. It can include evaluations of the building system and occupant behaviors, monitoring of pest presence and activity, thresholds or triggers for action, and actual control actions. Understanding what conditions will lead to pest populations or damage crossing the threshold for control actions is crucial to effective prevention. IPM planning is ideally begun during building design, and there are a variety of guides available for best practices at the design, construction, and operation phases of a building (e.g. Geiger & Cox, 2012).

Building Information Modeling (BIM) is a technology and process that enables analyses of construction processes and products through visualization and simulation (Sacks et al. 2018). BIM has been used for creating and managing information in the design, construction, and facilities management (FM) phases (Autodesk, 2022). While BIM's applications in design and construction are relatively well developed, its applications in the FM domain are still in early stages of development (Sacks, Eastman, Lee, & Teicholz, 2018; Teicholz, 2013). In the last decade, researchers have begun to explore how BIM can be utilized to assist FM tasks, such as providing information and more automated means and methods for building operation and maintenance (Gao & Pishdad-Bozorgi, 2019; Pishdad-Bozorgi, Gao, Eastman, & Self, 2018). With the capability to model parametric objects, BIM is more than a design tool and can be used for multiple purposes of building analysis. BIM software tools have interfaces to other applications such as those for energy analysis and cost estimation (e.g. Carvalho, Almeida, Bragança, & Mateus, 2021; Jalaei & Jrade, 2014). Using BIM, the relationships between components can be defined and stored in the attributes of each component. Using visualization capabilities and 4D simulation (Gledson & Greenwood, 2017), BIM can effectively communicate key building issues related to scheduling and sequencing (Badrinath, Chang, & Hsieh, 2016). BIM also has decision support capabilities, including clash detection (Hu, Castro-Lacouture, & Eastman, 2019), rules checking and validation (Lee, Eastman, Solihin, & See, 2016), change tracking over time (Kensek, 2015), and cost management with 5D BIM (Smith, 2016).

Internet of Things (IoT) is a unified framework for developing a common operative picture and control systems for a building through interconnected sensing and actuating devices (Gubbi, Buyya, Marusic, & Palaniswami, 2013). IoT consists of technologies such as sensing technologies, identification and recognition technologies, position technologies, data processing solutions, communication technologies and networks, and software and algorithms (Čolaković & Hadžialić, 2018). IoT and BIM integration can be used to create a digital twin for a building (Mohammadi & Taylor, 2020; Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, 2019; Taylor, Bennett, & Mohammadi, 2021), which enables the real-time data generation, analysis, and control of building systems. Successfully integrating BIM and IoT can yield real-time data for building systems, indoor environments, and occupant behavior and preference.

BIM has been used as a data platform for FM (e.g. Gotlib, Wyszomirski, & Gnat, 2020; Nour, 2010). Wang et al. (2013) developed a framework for engaging FM considerations in the design stage through BIM. In their research, BIM was used as a visual model and a database to provide integrated data for FM in the design stage throughout the building lifecycle. Kamal et al. (2021) described an integrated BIM-based framework for effective FM in hospital buildings. They utilized BIM to obtain consistent building information, visualized data, and quick data access. Kang and Choi (2015) developed a BIM database to connect external FM data with BIM data and provide relevant data based on user requests. Relying on BIM as a data source, an approach was presented by Hijazi et al. (2012) to obtain information on interior utilities. They mapped the semantic and connectivity information of BIM onto a new model called Network for Interior Building Utilities, which can provide a flexible way to manage interior utility network information. Ma et al. (2021) described a metadata-based image retrieval system by leveraging BIM and Geographic Information Systems (GIS) to obtain image information rapidly. In their research, BIM is utilized as a data platform for FM photos. Dong et al. (2014) developed a BIM-enabled information infrastructure to maintain data integrity for energy-saving applications.

Simulation engines have been developed using BIM for research studies in the FM domain. Wang et al. (2013) utilized BIM to predesign and simulate the maintenance work in FM. Kamal et al. (2021) created a 4D simulation model with BIM to visually illustrate the process of repairing failed equipment and zones affected by repair tasks. To understand the decision-making process of an endangered person in an emergency, Rüppel & Schatz (2011) employed BIM as a simulation engine to create emergency scenarios in a video game and simulate human behavior. Chen et al. (2014) used BIM to conduct firefighting simulations for reducing response time by helping firefighters quickly locate ladder trucks.

A BIM-IoT-based software tool has the potential to be a powerful tool for the critical FM task of pest management. Currently, BIM has never been used to support domestic arthropod-related research, education, or practice (such as pest management). This research aims to partially fill this gap by exploring the feasibility of using BIM for domestic arthropod studies, and creating a knowledge foundation for developing BIM-based data analysis and simulation platforms for them. To accomplish this, this research maps the information needs of domestic arthropod studies onto BIM's current and potential functionalities. It then creates a conceptual framework for a BIM-enabled simulation platform with functionalities for recording data, simulation for studies of arthropod behavior and ecology, supporting IPM during design and FM, and providing educational tools.

Methods

We identified the information related to environmental characteristics that is necessary for general study of behavior and ecology of domestic arthropods using basic knowledge of ecology and structural entomology. We then developed a comprehensive list of relevant elements of single-family residential structures. Using this list, we mapped the ways in which BIM and IoT can provide and manage the information needed for studying domestic arthropod behavior and ecology. We organized this mapping into four categories based on our synthesis of the disciplinary intersections, including 1) food sources, 2) water sources, 3) space for physical shelter, nesting or hiding, and 4) transport paths for hunting, socialization, and seeking new territory.

Results

BIM has parametric modeling capabilities that allow objects to be defined by their properties in the building model. The properties of an object in BIM can define its size, materials, location, relations with other objects, etc. Software applications, in the form of Revit plugins, for example, can be developed to automate the data extraction process (e.g. Chen & Nguyen, 2019; Suprabhas & Dib, 2017; Zotkin, Ignatova, & Zotkina, 2016). These capabilities provide as much detail on objects, materials, open space, and spatial relations as can be recorded in a BIM; and, allow a complete digital model of all static elements of a building, thus defining the physical spaces in which arthropods exist.

BIM provides static building data, while IoT can provide real-time data generated by sensing devices. IoT-enabled BIM, serving as the digital twin, is able to represent real-time data for indoor environments, building systems status, and occupant behaviors and preferences (e.g. Miller et al., 2021; Zibuschka, Ruff, Horch, & Roßnagel, 2020). For example, continuous sensor readings can provide real-time data about the temperature and humidity in different building spaces. By analyzing the data collected with IoT devices, we can also identify occupant behavior patterns, such as when and how often occupants clean their houses, and where and when occupants feed their pets. These capabilities can provide a complete digital model of all dynamic elements of a building and some about its occupants and their behaviors.

We categorized building-related information needs for domestic arthropod studies into four groups: food sources, water sources, space, and transport. Detailed explanations of each are described in each section of the BIM mapping. Much of the environmental information useful for studying arthropods can be readily acquired through a BIM database, using existing capabilities. Table 1 shows the mapping results between information needs in domestic arthropod studies and BIM capabilities.

Food

Arthropods may obtain food from a variety of sources in a building, depending on the needs of each species. We identified building materials, components, or objects in a building space that could provide food for any arthropods, as well as any the food created or brought by human occupants. Sources may include: structures and components with organic materials such as wood beams and wood furniture; primary producers and decomposers growing directly on structures such as fungi on wet drywall or algae on a consistently damp windowsill; food intended for human consumption; food waste and spillage created by occupants such as food litter in a trash can; and bodies and shed body parts from occupants such as human blood and skin cells.

Food sources related to building components, can be determined directly from BIM. For instance, some building elements are made of wood, which provides food for termites. We can acquire relevant information, such specific wood types and locations, from BIM, use this to determine potential food sources. Similarly, we can use BIM elements paired with IoT sensing of moisture to determine possible growth areas for mold. The behavior of human occupants cannot be acquired from BIM directly; but can be determined from sensing data generated by IoT. For example, some food sources are created by occupants, such as meals left out, or dishes not being cleaned. By analyzing the IoT usage data of appliances (e.g., dishwasher), utilities (e.g., water tap), and indoor environment (lighting, sound, humidity, etc.), a system built upon BIM can recognize potential food sources.

Water

Arthropods that need to drink can obtain moisture from a variety of sources among building systems and components. Water can be obtained from plumbing systems and condensation. Condensation is produced with temperature and humidity changes, and we can identify the components that may produce condensation by analyzing the real-time IoT sensor readings. High-risk areas for condensation, and the locations of plumbing system components, drains, and taps can be extracted with BIM existing functions based on location and type. Humidity is also important for many arthropods, particularly those like dust mites that obtain their water from the air. This can be determined from IoT sensor readings.

Space

Arthropods occupy space, and may need a variety of different spatial characteristics depending on the needs of any given species. Spatial characteristics and exposure to light, temperature, air currents, and open areas define types of exposure. We divided space in buildings into four sub-categories according to exposure: fully protected spaces, partially protected spaces, exposed spaces with surfaces, and open areas. The fully protected spaces and partially protected spaces are most often used for shelters by species that spend some or all of their time hidden, such as cockroaches. Partially protected spaces are also used as shelters but are not fully enclosed. These can be structures and objects, including the gaps between structural or decorative elements like sideboards and windowsills, and may be useful for temporary hiding or web building in transition zones. Exposed spaces with surfaces are utilized when leaving shelter, or by species that may not seek shelter. Open areas are the voids in a building where arthropods can easily fly. Each type of space can be derived from BIM elements with full 3D models, supported by information about environmental conditions and sources of light.

Transport

Arthropods require passage between spaces for hunting, finding mates, or seeking new territory or resources. They also may need ways of entering or exiting a building. Ambulatory arthropods require contiguous surfaces to move between zones. Flying arthropods are able to move through zones large enough to accommodate flight, indicated by open spaces and large voids connecting areas in a building. Access and exit points for a building may include utility passages, doors, windows, and vents. These are obtainable from BIM functions with spatial relations and component models.

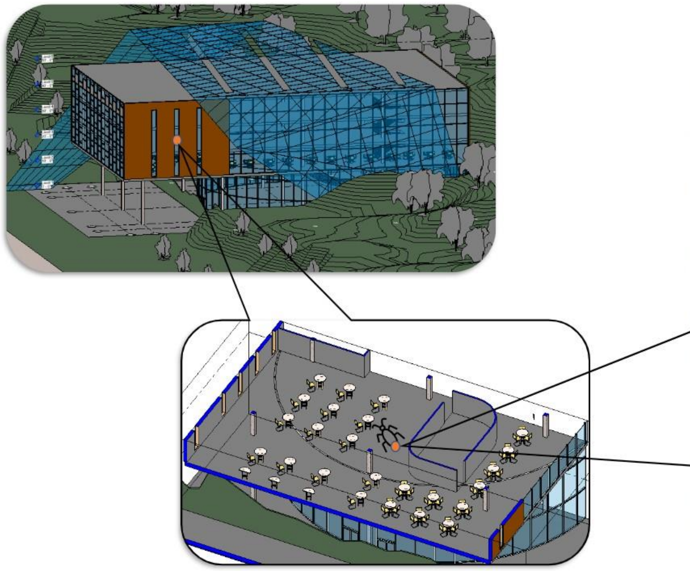
Discussion

We have conceptualized a BIM-enabled simulation platform with data storage and simulation functions for researchers to study domestic arthropods and to serve as an educational tool for biology students. Figure 1 shows an illustration of this framework for a BIM-enabled simulation platform. It would contain a 3D building information model, and the arthropod community's data. It would also contain a simulation engine (Figure 2), which would incorporate arthropod behaviors as simulation algorithms, a visualization of arthropod population dynamics, distribution, and possible movement patterns.

In the platform, the inputs for simulation include: food sources, water sources, space, and transport paths. Some of these data can be directly extracted from the IoT-BIM model. For example, some wooden structural materials can be a food source for some insects, and the data of the element locations, quantity, material properties can be extracted from the BIM model. A particular space's temperature and humidity can be extracted from the IoT sensing data. Some other input data may need manual input, such as food waste created by occupants and observations of insects.

The outputs of the simulation engine include: 1) the approximate current populations of species living in a particular building space during a given time period; 2) species population dynamics; 3) arthropod community dynamics; and 4) current and potential areas for expansion and exploitation.

These outputs have potential use in study of domestic arthropod behavior and ecology. They also have potential to be useful in designing and implementing IPM plans. IPM plan creation requires the identification of vulnerabilities and expectations for pest activity, so using these models to simulate and predict arthropod activity in a building as early as the design phase can have major downstream effects. Similarly, these outputs in conjunction with IoT monitoring will provide a major aid in IPM practice in FM. This tool can also support research into arthropod behavior and ecology in buildings, which will in turn support improvement to IPM practices.



Information	Details
Food Sources	
Materials	Wood / N/A
Location	Desk 21
Local Coordinates	(12, 45, 69)
Water sources	
Location	Pipe 15
Local Coordinates	(18, 66, 81)
Space	
Physical Shelters	
Location	Under Chair 18
Local Coordinates	<Matrix (3*8)>
Temperature	75 F
Humidity	81%
Other Space	
Room Number	5
Local Coordinates	<Matrix (3*8)>
Temperature	75 F
Humidity	80%
Transportation	
Hunting Zones	
Room Number	3
Moving Paths	<Matrix (3*N)>
Flying/Walking paths	
Room Number	3
Local Coordinates	<Matrix (3*N)>

Figure 1. A conceptual illustration of a BIM-enabled simulation platform

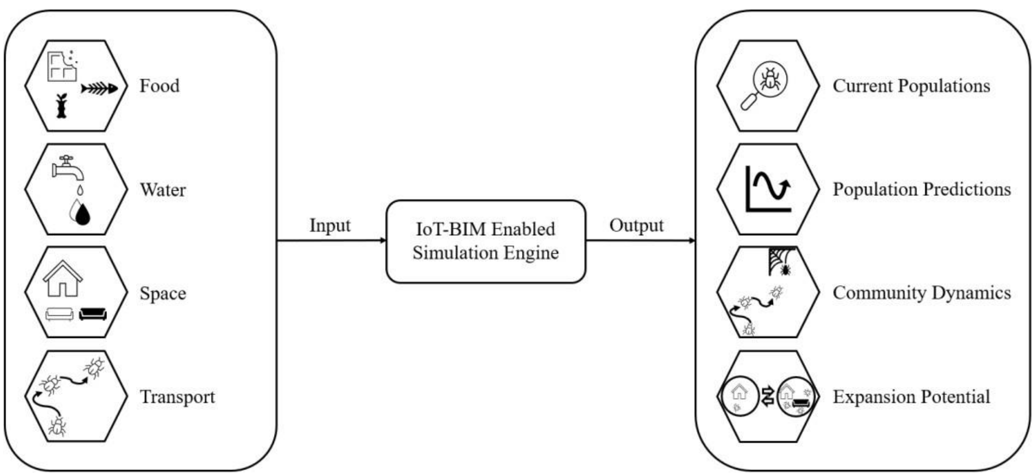


Figure 2. A conceptual simulation framework

Conclusions

This research maps BIM's capabilities with information requirements for studying and managing domestic arthropods. We have identified the information needs that can be obtained from an IoT-enabled BIM model and presented the mapping results in Table 1. This work provides a building block for establishing a BIM-enabled simulation platform for domestic arthropod study and management. The inputs for simulation include data about the arthropod's food sources, water sources, space, and transport. The outputs are predictions on arthropod behavior and ecology. The research team is currently developing a prototype for the simulation platform using the conceptual framework described in this paper. As new iterations of the tool are applied to specific organisms, additional variables and details will be developed and added. It is envisioned that this platform will serve as a research tool for arthropod researchers, as an educational tool for biology students, and provide support for IPM related FM tasks beginning in the building design phase, and carrying through the life of the facility.

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Table 1

Mapping between information needs in domestic arthropod studies and BIM capabilities

Type	BIM/IoT Type	Subcategory	General Description	Example Elements
Food	Structures	Materials	Digestible organic building materials	Wood foundation, siding
	Structures	Substrates for food growth	Moist areas that can grow mold, mildew, or bacterial films.	Wet drywall growing mold
	Furniture	Organic furniture	Furniture with organic components	Leather furniture upholstery
	Finishes	Organic finishes	Organic decorative items	Books, taxidermy, tapestry, art
	Finishes	House plants	House plants (or dried plants)	House plant
	Structures	Trap spaces	Places where arthropods tend to die	Window sill accumulating dead bugs
	Utilities	Standing water	Still water where things can grow	Spare bathroom, floor drain
	Occupants	Food	Storage or presentation of food	Pantry, dog food bowl
	Occupants	Food waste	Any storage of food waste	Kitchen trash receptacle
	Occupants	Pet waste	Any source of pet feces	Cat litter box
	Occupants	Bathroom waste	Removed elements of the body	Bathroom trash can
	Occupants	Occupant Body	Occupant bodies provide food	Human occupant, pets
	Occupants	Behaviors	Behaviors that make food sources available	Locations for food consumption , shedding of skin and hair
	Occupants	Hygiene	Cleaning habits	Vacuuming, dishwasher usage
Water	Structures	Condensation	Any location where condensation occurs	Leaky windows, poorly designed wall/vapor barriers
	MEP	Taps	Anywhere water is delivered.	Tap in sink
Space	Structures	Fully protected spaces	Gaps between structural or decorative elements	Space between cladding and sheathing, gaps behind sideboards

	Structures	Partially protected spaces	Areas that can be backed into but are still exposed.	Corners edges between wall and ceiling, windowsills
	Structures	Exposed spaces with a surface	No elements to back up against. Allow free moment by walking	Desk surface
	Structures	Fully open area	Spaces through which an insect can fly	Room space
Transport	Openings	Access points	Entry and exit for building	Door or window
	Structures	Walking paths	Contiguous surfaces	Walls, ductwork surfaces
	Structures	Flying space	Open space	Room space