PAPER • OPEN ACCESS

Inspiration from animal's collective behavior for home energy demand management

To cite this article: L Badarnah *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 022013

Journal of Physics: Conference Series
2600 (2023) 022013
doi:10.1088/1742-6596/2600/2/022013

Inspiration from animal's collective behavior for home energy demand management

L Badarnah [1*], M Barakat[1], S Oliveira[2]

[1] School of Architecture and Environment, University of the West of England, Bristol, United Kingdom.
[2] Department of Architecture, University of Strathclyde, Glasgow, United Kingdom.

* Corresponding author lidia.badarnah@uwe.ac.uk

Abstract. An interdisciplinary approach towards managing energy demand through users' behavior is discussed, drawing on knowledge from studies on collective behavior in nature. Studies on home energy demand management have focused mainly on social, technical and, more recently, socio-technical aspects that are considered largely at the individual levels only. However, emerging trends in social studies call for explorations across different social and spatial scales beyond the individual levels. This work distinguishes several principles and mechanisms of collective foraging decision-making from nature that respond to demand, including aspects of self-organization and stigmergy. The scoping of potential biological systems and behavioral aspects emulation aims to provide a foundation for agent-based modelling (ABM). Collective behavior emerges from local interactions of the individuals within a group, and nonlinear interactions between individuals and their environment enable them to accomplish tasks, such as structural construction, without the involvement of centralized control systems. Response to demand in nature is significantly influenced by information flow, processing, perception, and communication and coordination patterns between individuals, groups, and their environment. By studying these interactions and adapting their principles to the context of home energy management, we can develop new, more efficient, sustainable, and resilient approaches.

1. Introduction

Studies on home energy demand management have focused mainly on social, technical and, more recently, socio-technical aspects that are considered largely at the individual levels only [1]. However, emerging trends in social studies call for explorations across different social and spatial scales beyond the individual levels [2]. For these aspects to be considered simultaneously in decision-making, there is a need to develop an energy demand management model that specifically builds on social behaviors at both individual and community levels and their interaction with technology in different spatio-temporal contexts. Different possible pathways exist for the future of community-driven smart grids, where more open and responsive approaches are needed to enable implementation [2].

This paper discusses an interdisciplinary approach towards managing energy demand through users' behavior, drawing on knowledge from studies on collective behavior in nature. Developing solutions by emulating strategies and mechanisms from nature, i.e. biomimetics, is a rapidly growing discipline in engineering and an emerging field in architecture with a primary focus on morphological applications [3]. This work distinguishes several principles and mechanisms of collective foraging decision-making from nature that respond to demand, including self-organization and stigmergy [4]. Collective behavior in nature refers to the coordinated and synchronized actions of groups of organisms in response to environmental demands, such as food availability, predator threats, or reproductive opportunities [5]. It is often observed in social animals, such as insects, birds, fish, and mammals, and it also occurs in non-social species, such as bacteria and plants [6]. Social interactions, individual states, environmental modifications, and information amplification/decay impact the adaptive response in collective behavior [7]. Different types of individuals have different degrees of willingness to act for the benefit of the collective, and there has been evidence that some contextual variables enhance cooperation while others do not [8].

Collective behavior emerges from local interactions of the individuals within a group [7], and nonlinear interactions between individuals and their environment enable them to accomplish tasks, such as structural construction, without the involvement of centralized control systems [9]. Response to demand in nature is significantly influenced by information flow, processing, perception, and communication and coordination patterns between individuals, groups, and their environment [10]. The environment plays a significant role directly and indirectly in the emergence of collective behavior, providing information about the quality and quantity of resources [11]. Decoding emergence in a complex biological system necessitates a thorough understanding of the following: interactions among individuals, information exchanges, information processing, behavioral algorithms and response [12]. Despite the advances in computational models that abstract emergence logic from nature, they are far from their biological counterparts' complexity, sophistication, and flexibility. Hence, before we observe significant evolving shifts, biological mechanisms may need to be explained more explicitly to be included in rich computational models [13].

Using Agent-Based Modelling (ABM), we can test the scoped potential biological systems and emulate human behavior. This computational method combines mathematical and biological system logic to investigate interconnected problems. ABM investigations in HEM have proven effective in decision-making [14]. However, there is a dearth of HEM ABM studies based on biomimicry logic, as evident in Figure 1. Applying biological models can help simulate human behavior, energy routines, and social identity factors to create artificial societies. By studying natural systems, we can minimize and shift energy consumption while meeting human needs. ABM can optimize energy demand and supply in homes and mimic complex interactions among a heterogenous population in community collective energy management [15].

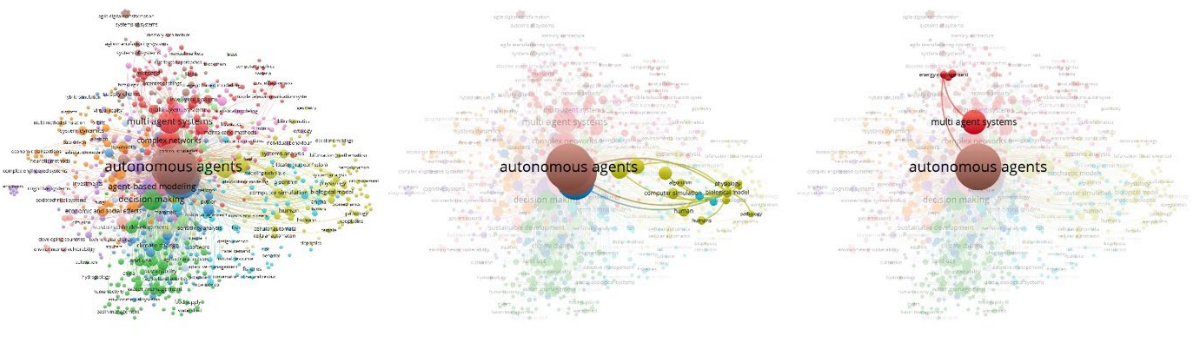

Figure 1. Adapted VOSViewer Co-Occurrence of Author and Index Keywords bibliographic map showing the gap in research focused on Biomimicry, HEM and ABMs.

In the following sections, we discuss the concept of the scoping approach to establish parallels between HEM, natural systems, and ABM, facilitating abstraction efforts and the transfer of knowledge between domains. Then, several examples of species exhibiting resource and demand management are outlined, and their potential applications to HEM are discussed. In the end, some coordination patterns, trigger variations, and performance capabilities are discussed in the context of potential application to an integrated control system for home energy demand management.

2. Scoping approach for collective logic

Animals of many species improve their ability to detect and respond to environmental changes by working collectively. Collective behavior in nature involves a complex interplay of coordination, communication, and decision-making that allows groups of organisms to respond to environmental demands in a coordinated and effective manner [16]. Interactions with others can assist individuals in overcoming their cognitive limits by providing them with context-dependent and spatially and temporally integrated information [7], which can lead to more accurate decision-making even in the face of distractions and uncertainty. In addition, collective behavior provides access to significant higher-order information-processing capacities that are difficult, if not impossible, to acquire alone [17].

This study employs a qualitative systematic review [18], using a thematic inductive and deductive approach [19] to identify the main principles of collective behavior in nature and their potential relevance to HEM. Figure 2 presents the main context of interaction between individuals and their environment through direct and indirect communication for a coordinated decision-making approach and the parallels and potential connections between HEM, collective behavior in nature, and ABM for an interrelated decision-making approach.

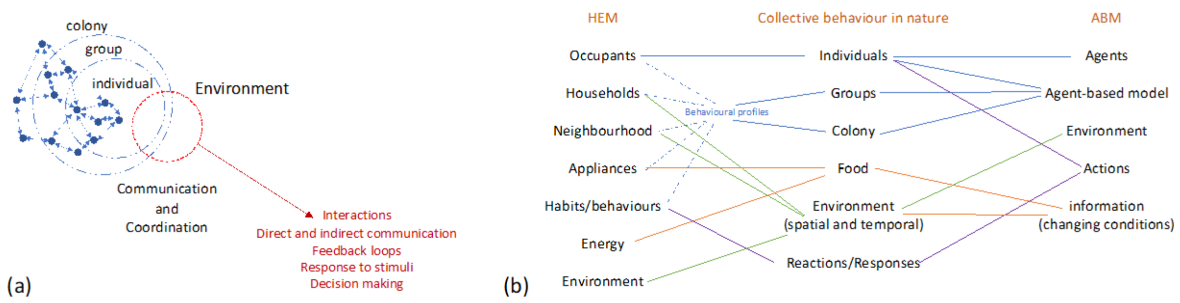

Figure 2. Context and parallels for collective coordination: (a) context of interaction, and (b) parallels and potential connections for an interrelated decision-making approach.

3. Collective resource and demand management in nature

Collective behavior and adaptive response to changing conditions are essential for enabling biological systems to manage resources effectively, where coordination and communication play crucial roles in enabling collective behavior in nature [5, 7, 10, 17]. Coordination refers to individuals' ability to synchronize their actions and movements, often using signals and cues. Communication refers to the exchange of information between individuals, which can involve signals, cues, or even complex vocalizations or displays. Decision-making is also important in collective behavior, as groups must make collective choices based on their shared perception of the environment and the demands placed upon them [11], which can involve simple decision rules, such as following the majority, and more complex decision-making processes involving individual preferences and interactions [17].

In nature, response to demand is often influenced by complex interactions between information flow, processing, perception, and communication and coordination patterns between individuals, groups, and their environment [5]. These interactions allow organisms to adapt to changing environmental conditions and respond to demand in ways that maximize their chances of survival and reproduction. One example of collective behavior in nature is seen in bird flocks, which can exhibit highly coordinated movements and formations in response to predator threats or environmental cues. Birds use visual signals, such as changes in wingbeats or body posture, to coordinate their movements, adjust position and velocity, and avoid collisions in a synchronized way without the need for centralized control. Another example can be found in ant colonies, which use chemical signals, such as pheromones, to coordinate their foraging and nest-building activities. As a result, ant colonies exhibit a high order of self-organization, communication, and division of labor [20].

Honeybees use signals (i.e. waggle dance) to communicate information about the location and quality of food sources, allowing other bees in the colony to adjust their foraging behavior accordingly [21]. They exhibit decision-making and information-sharing processes that could be used to optimize energy use in homes. Fish schools exhibit a coordinated motion that allows them to avoid predators and find food. This coordination emerges from simple interactions between individual fish, as each fish adjusts its position and velocity based on the movements of its neighbors and hydrodynamics effects.

These social insects exhibit collective behaviors through various means [22, 23] relevant to HEM, including (a) *decentralized control* in which individuals make decisions based on local information and interactions with their neighbors and environment rather than relying on a central control system. This approach can be applied to home energy management systems by allowing individual devices (e.g., thermostats, smart appliances) to make decisions based on local information (e.g., temperature, occupancy) and communicate with each other to coordinate their actions; (b) *Self-organization* in which individuals spontaneously form patterns or structures without the need for external guidance. This approach can be applied to home energy management systems by allowing devices to self-organize into groups or clusters (connectivity) based on their energy needs and preferences; (c) *Communication and coordination* used to achieve collective goals, such as foraging or predator avoidance. This approach can be applied by allowing occupants and devices to communicate and coordinate their energy use to optimize overall system performance and reduce energy waste; (d) *Learning and adaptation,* in which individuals modify their behavior based on feedback from the environment and their interactions with others. This approach can be applied by allowing occupants and devices to learn from the implications of their energy use behaviors on the neighborhood and adapt their behavior over time to optimize energy use and comfort.

4. Discussion: towards designing a collective-based energy management system

The principles of collective behavior in animals, such as decentralized coordination and decision-making, can inspire new approaches to home energy management that are more efficient, flexible, and adaptive. By allowing devices to communicate, coordinate, and learn from occupants' behavior, we can create more intelligent and responsive energy systems that better meet users' needs while reducing our overall energy consumption.

The triggers for coordination patterns in nature can vary depending on the specific system and context. However, some common factors that can influence coordination include environmental cues, social signals, and internal states that could potentially be relevant for coordination in the context of HEM: (1) *Environmental cues*: temperature, humidity, and other environmental factors can influence the energy demand of a home, as well as the availability of renewable energy sources such as solar power.; (2) *Social signals*: in a multi-user household and their networks, social signals such as occupancy, activity levels, and preferences can influence energy demand; (3) *Internal states*: the energy demand of a home can also be influenced by internal factors such as the health and wellbeing of the occupants. Different households require varied energy for heating, lighting, or ventilation.

Several studies have discussed visions and the need for an integrated approach that considers the different social, technical, and spatial levels in energy management, such as '*socially smart grids'* [2, 24], yet applications are still to be developed. Therefore, we propose that a successful collective home energy management system should have a nested hierarchical structure (see Figure 3) to enable a distributed control system and have several capabilities to be performed simultaneously between individuals and their environment, including (1) *sensing and monitoring*: the system must be able to sense and monitor a wide range of environmental, social, and internal cues to make informed decisions about energy consumption and production; this could include sensors for temperature, humidity, occupancy, activity levels, and energy consumption of appliances and devices, (2) *communication and coordination*: the system must be able to communicate and coordinate the energy use of different appliances and devices in the home to optimize comfort and reduce waste; this could include using algorithms to predict energy demand, coordinating the energy use of different appliances and devices, and adjusting energy consumption in response to changing conditions, (3) *user feedback and control*:

the system should allow for user feedback and control to ensure that the energy management strategies are aligned with the preferences and needs of the household occupants; this could include user-friendly interfaces for monitoring and controlling energy use, as well as the ability to provide feedback on the system's performance, (4) *adaptability and scalability*: the system should be adaptable and scalable to accommodate changes in the home environment and the needs of the occupants over time; this could include the ability to learn from user feedback and adjust energy management strategies accordingly and integrate new devices and technologies as they become available.

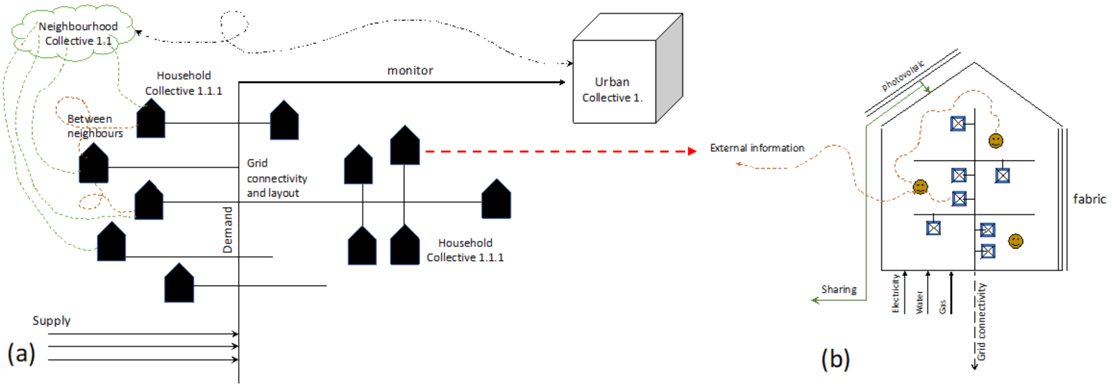

Figure 3. An integrated conceptual interpretation of collective demand management: (a) a hierarchical representation of collective social coordination at household, neighborhood, and urban levels; (b) a representation of a household-level interaction between users, appliances, and resources.

5. Conclusions

Principles of collective behavior from nature could provide meaningful ways to process information, communicate, and respond to a wide range of cues in the context of HEM, optimizing energy consumption and production in a coordinated and adaptive manner. By studying these interactions and adapting their principles to the context of home energy management, we may develop new, more efficient, sustainable, and resilient approaches.

There is a significant gap in the field of HEM concerning the integration of ABMs and biomimicry. Although ABM is commonly used, limited references explicitly consider biomimicry-based ABMs to simulate the system as a hierarchical system constituted of occupant routines and social identity (the neighborhood level) to shift peak load. We may discover new, sustainable energy resource and demand management methods by bridging this gap and drawing inspiration from nature. By distinguishing these mechanisms and principles, the study aims to develop a bottom-up energy demand management protocol that responds to the complex interactions between energy demand and use at the individual and community levels and enables collective coordination. It could also provide a collective basis for new ways of thinking about urban metabolism by establishing a better system's understanding of the interactions and inter-relationships between users, material, and their environment in different spatio-temporal contexts. Further investigating this nascent topic may lead to significant home energy demand and management advancements.

Acknowledgments

The work discussed is part of a project funded by EPSRC (grant number EP/V041770/1).

References

[1] Oliveira S, Badarnah L, Barakat M, Chatzimichali A, Atkins E. Beyond energy services: A multidimensional and cross-disciplinary agenda for home energy management research. Energy Research & Social Science. 2022;85:102347.

[2] Hargreaves N, Hargreaves T, Chilvers J. Socially smart grids? A multi-criteria mapping of diverse stakeholder perspectives on smart energy futures in the United Kingdom. Energy Research & Social Science. 2022;90:102610.
[3] Badarnah L. Form Follows Environment: Biomimetic Approaches to Building Envelope Design for Environmental Adaptation. Buildings. 2017;7:40.
[4] Sumpter DJ. The principles of collective animal behaviour. Philosophical transactions of the royal society B: Biological Sciences. 2006;361:5-22.
[5] Bradbury JW, Vehrencamp SL. Principles of animal communication. 1998.
[6] Dalziel BD, Novak M, Watson JR, Ellner SP. Collective behaviour can stabilize ecosystems. Nature Ecology & Evolution. 2021;5:1435-40.
[7] Couzin ID. Collective cognition in animal groups. Trends in cognitive sciences. 2009;13:36-43.
[8] Ostrom E. Collective action and the evolution of social norms. Journal of economic perspectives. 2000;14:137-58.
[9] Theraulaz G, Gautrais J, Camazine S, Deneubourg J-L. The formation of spatial patterns in social insects: from simple behaviours to complex structures. Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences. 2003;361:1263-82.
[10] Endler J. Evolutionary implications of the interaction between animal signals and the environment. Animal signals. 2000:11-46.
[11] Sulis W. Fundamental concepts of collective intelligence. Nonlinear Dynamics, Psychology, and Life Sciences. 1997;1:35-53.
[12] Bouffanais R, Bouffanais R. A biologically inspired approach to collective behaviors. Design and control of swarm dynamics. 2016:5-15.
[13] Miikkulainen R, Forrest S. A biological perspective on evolutionary computation. Nature Machine Intelligence. 2021;3:9-15.
[14] Yao R, Hu Y, Varga L. Applications of Agent-Based Methods in Multi-Energy Systems—A Systematic Literature Review. Energies. 2023;16:2456.
[15] Bonabeau E. Agent-based modeling: Methods and techniques for simulating human systems. Proceedings of the national academy of sciences. 2002;99:7280-7.
[16] Bradbury JW, Vehrencamp SL. Complexity and behavioral ecology. Behavioral Ecology. 2014;25:435-42.
[17] Deneubourg J-L, Goss S. Collective patterns and decision-making. Ethology Ecology & Evolution. 1989;1:295-311.
[18] Grant MJ, Booth A. A typology of reviews: an analysis of 14 review types and associated methodologies. Health information & libraries journal. 2009;26:91-108.
[19] Braun V, Clarke V. Using thematic analysis in psychology. Qualitative research in psychology. 2006;3:77-101.
[20] Camazine S, Deneubourg J-L, Franks NR, Sneyd J, Theraula G, Bonabeau E. Self-organization in biological systems. Self-Organization in Biological Systems: Princeton university press; 2020.
[21] Gordon DM. The ecology of collective behavior in ants. Annual review of entomology. 2019;64:35-50.
[22] Cook CN, Lemanski NJ, Mosqueiro T, Ozturk C, Gadau J, Pinter-Wollman N, et al. Individual learning phenotypes drive collective behavior. Proceedings of the National Academy of Sciences. 2020;117:17949-56.
[23] Alcock J. Animal behavior: an evolutionary approach, 10th edn Sunderland. MA: Sinauer Associates[Google Scholar]. 2013.
[24] Skopik F. The social smart grid: Dealing with constrained energy resources through social coordination. Journal of Systems and Software. 2014;89:3-18.