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Perspective

Agent-Based Models as an Integrating Boundary Object for Interdisciplinary Research

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Many of the most complicated and pressing problems in hazards research require the integration of numerous disciplines. The lack of a common knowledge base, however, often prohibits clear communication and interaction among interdisciplinary researchers, sometimes leading to unsuccessful outcomes. Drawing on experience with several projects and collective expertise that spans multiple disciplines, the authors argue that a promising way to enhance participation and enable communication is to have a common model, or boundary object, that can integrate knowledge from different disciplines. The result is that researchers from different disciplines who use different research methods and approaches can work together toward a shared goal. This article offers four requirements for boundary objects that may enhance hazards research. Based on these requirements, agent-based models have the necessary characteristics to be a boundary object. The article concludes by examining both the value of and the challenges from using agent-based models as the boundary object in interdisciplinary projects.

KEY WORDS: Agent-based modeling; boundary objects; hazards; interdisciplinary research

1. INTRODUCTION

Hazards exist at the intersection of natural, physical, and human environments (Tierney, 2005). Thus, the strongest hazards-research teams often include physical scientists, engineers, and social scientists who can integrate their disciplinary expertise in innovative ways to generate new knowledge. These interdisciplinary teams are particularly needed in the study of hazards that result in large-scale and repeated damage, such as flooding, to understand how to break this cycle. Reducing future losses from such hazards requires understanding interactions of many complex factors, including, for instance, physical characteristics of the built environment, natural hazards exposure, and the behavioral options and decisions of individuals and communities. Adding to the complexity, how exposure to the hazard evolves over time creates temporal dynamics in the modeling problem.

A primary challenge for interdisciplinary teams is the lack of a common knowledge base to allow for clear communication and interaction among researchers from diverse disciplinary backgrounds. Specifically, while broad terminology may be similar among disciplines, the work *within* disciplines is nuanced, making it difficult for researchers collaborating *across* disciplines to make sense of the contributions in relation to their own work. Given the number of disciplines that contribute to hazards and disaster research, it is unlikely that a common knowledge base is possible, though developing common terminology can help. In addition, we argue here for the use of a central modeling framework

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(or "boundary object") as a means to further enhance communication and to enable interdisciplinary participation.

Past research has defined a boundary object as a core tool (or "shared space") that individual researchers can recognize in their own contexts, but is structured enough so that concepts can transcend the disciplines (Star, 2010; Star & Griesemer, 1989; Wenger, 1998). Its purpose is to facilitate communication among "communities of practice" but not necessarily to gain consensus (Star, 2010).

The objectives of this article are to (1) propose and justify requirements that boundary objects must fulfill in order to be useful in interdisciplinary disaster research and (2) identify candidate boundary objects. While multiple boundary objects potentially exist, based on our assessment of the requirements, agent-based models (ABMs) have all the necessary characteristics to form this central model.

ABMs are stochastic, bottom-up *in silico* models that apply particular focus on the actions and interactions of heterogeneous agents. Agents are typically thought of as human-like decisionmakers who can learn from their environment and other agents and make decisions in response. The decisions can be complex and grounded in sociological theory and decisions science[4] or follow basic rules.[5,6] Their decisions may then affect their environment, thus creating links among agents and between agents and their environment. The model's structure is purposely flexible and adaptable to the questions being posed and to the knowledge contributions by researchers. ABM's are useful in situations with many interacting parts where applying all core principles from multiple research fields would be problematic. ABMs are underused in hazards research, but we hope this discussion will encourage more researchers to learn about, use, and ultimately advance this modeling tool.[7]

2. REQUIREMENTS FOR INTERDISCIPLINARY HAZARD RESEARCH BOUNDARY OBJECTS

In this section, we describe four requirements for boundary objects to help expand interdisciplinary participation in hazards research. These requirements were iteratively derived by the author team, based on our prior collaborations, knowledge, and applications of ABMs across a variety of projects.

2.1. Requirement 1: The Boundary Object Must Be Flexible but Grounded in Theory

A basic definition of a boundary object is that it must be sufficiently flexible for multiple disciplines to recognize and contribute to the same model as if it were from their own discipline (Wenger, 1998). We have found that to get adoption from researchers, the core object must be firmly established in their literature. We believe this is the case for the following reasons. First, researchers who are unfamiliar with the method are able to independently learn about it using published material and prior research studies from their field. Second, we have found that there is more adoption from researchers when the general methods are already broadly accepted in the literature and grounded in theory. Agent-based models have been used extensively in a number of different fields over the past two decades. In addition, as computational capabilities have advanced, so too have the complexity of the problems being addressed using ABMs. An extensive perspectives literature exists on when ABMs are useful (Bonabeau, 2002), how the results of the models can be interpreted (Macal & North, 2010), and what model validation means (Windrum, Fagiolo, & Moneta, 2007).

2.2. Requirement 2: The Boundary Object Must Allow for Inclusion of Stochasticity and Relevant Antecedent Events

A unifying theme within hazards science is the concept of uncertainty. The heights and return periods of floods are unknown, the ability of infrastructures and ecosystems to withstand hazard forces are uncertain, and human response to these events varies tremendously. Scientists can use domain-specific methods to explore the range of the outcomes and patterns that emerge for pieces of the problem. For example, seismologists might use physics-based approaches whereas geographers might use large data

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[4] See An (2012) for a review.

[5] A useful example of this are the agents in sugarscape, a notional environment where agents seek to maximize sugar consumption. See Epstein and Axtell (1996).

[6] One reviewer observed that in many instances, systemic social and economic barriers may limit available choices for vulnerable individuals and groups when it comes to adaptation in hazardous areas. While it is unlikely that an AMB can meaningfully represent all structural inequities that are present in communities, it can apply assumptions and constraints on each agent that mimic some of the constraints faced by actual members of the community.

[7] See Reilly, Guikema, Zhu, and Igusa (2017) for a topical discussion and framework regarding applying ABMs to the problem of repeated hazards in communities.

sets combined with GIS to make inferences, but to represent the complexity and reality of the situation, all of these models need to be capable of including uncertainty. Uncertainty could be characterized both quantitatively, using standard probability theory, or qualitatively, where uncertainty is expressed descriptively through ranges of observational outcomes and trends.

The inclusion of antecedent events—essentially referring to what has happened in the past, and how those outcomes condition future states and decisions—can help explain some of the causes for the uncertainty. For example, soil moisture levels can help illuminate why some people are more likely to lose power during wind events, making precipitation, with its associated uncertainty, an important factor (Nateghi, Guikema, & Quiring, 2011). Similarly, through structured interview techniques, a sociologist could bring context to different evacuation behaviors for tsunamis (Lachman, Tatsuoka, & Bonk, 1961). Explanation for why these antecedent events occur and how to measure their forcing on future events is often difficult using domain-specific expertise and directly points to the need for interdisciplinary study.

ABMs can handle both uncertainty and antecedent events. Uncertainty can be captured through direct application of probability distributions, when known. This is useful, for example, when the return period of a particular hazard is known. When probabilistic estimates are unavailable, such as is typically the case for behavior, the entire parameter space that represents the range of possible scenarios should be examined using extensive sensitivity analysis (Thiele, Kurth, & Grimm, 2014). This will indicate the robustness of the results to different behavioral and other assumptions and identify conditions or scenarios leadings to undesirable outcomes.

2.3. Requirement 3: The Boundary Object Must Allow for Both Qualitative and Quantitative Information

Hazards research regularly generates both qualitative and quantitative information. Yet, most domain-specific questions lend themselves to one type or another. In interdisciplinary research projects, researchers in more numerically and algorithmically minded disciplines may have difficulty making sense of and including qualitative discoveries, whereas more qualitatively oriented researchers may have difficulty with the process of flattening complex ethnographic observations into statistical representations (Lach, 2014). Thus, for a boundary object to bridge this division, it must be flexible enough to contain both types of information.

Agent-based models are capable of using both types of data. Inclusion of quantitative data is highly compatible with *in silico* modeling. Hazard modeling and characteristics about the region, like home values, are more likely to be quantitative in nature. Qualitative information, such as how individuals prepare for and respond to disasters, can also be incorporated into ABMs through two mechanisms: (1) through the model's structure (e.g., through characterization of influences); or (2) through the options and decision rules assigned to agents. Because ABMs do not require homogenous decision making, agents assigned to different demographic groups could also be assigned unique behaviors reflective of observations from the social sciences. For example, persons with disabilities or serious health issues often require assistance or specialized equipment for evacuation (Rosenkoetter, Covan, Cobb, Bunting, & Weinrich, 2007), and they could be assigned a lower probability of evacuating in advance of a hurricane landfall or as being dependent on other services.

2.4. Requirement 4: The Boundary Object Must Allow for Temporal Dynamics

The manner in which individual actions map to outcomes in previous disasters creates a knowledge base that influences actions in future disasters. More precisely, individuals learn from their experiences and this may induce them into changing their mitigative or preparative decisions (Dillon, Tinsley, & Burns, 2014). This does not imply that all changes lead to better outcomes, however. An individual who evacuates under an order that is later determined to be unnecessary may be less likely to evacuate under future orders. Similarly, a long duration without a hazard may make some individuals complacent and eschew preparative actions (Fitzpatrick & Mileti, 1991). As a result, regional susceptibility to losses and harm changes over time in response to experiences (or lack thereof) had by members of the community.[8]

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[8] This does not, *per se*, preclude individuals who lack prior experience for a particular hazard (e.g., people new to a region). These individuals have their own (potentially limited) understanding of the hazard, and, over time, gather new information. This new information may be gained, e.g., from stories and experiences

Thus, including a temporal dimension in the model that reflects previous experiences and knowledge gains is critical for understanding the complexities of hazards. Agent-based models by nature are required to have the dimension of time. As outcomes are produced via the model, agents are able to "learn" (e.g., update a probabilistic estimate for the likelihood of damage given some hazard intensity), which can then influence future decisions. This temporal dimension directly results in emergent phenomenon being elicited from the system and is an element that is not integral to other potential candidate boundary objects for hazards research.

3. BENEFITS AND EXAMPLE OF USING AGENT-BASED MODELS AS BOUNDARY OBJECTS

We collectively have experience from many different interdisciplinary research teams. Here we draw on an example from a U.S. National Science Foundation (NSF) funded team focused on studying repeated disasters. We use this project to provide a concrete basis for discussing how boundary objects in general, and ABMs[9] specifically, can be of practical use for an interdisciplinary team and can help create new knowledge.

We are all part of an NSF Hazard-SEES project. The purpose of the NSF Hazard-SEES solicitation, which existed primarily between 2012 and 2015, was to make investments in strongly interdisciplinary research that would reduce the impact of hazards, enhance the safety of society, and contribute to sustainability. Our Hazard-SEES team spans eight institutions and includes researchers with expertise in engineering (civil and operations research), complex systems modeling, risk analysis, economics, behavioral science, climatology, epidemiology, and landscape architecture. The focus is on better understanding how repeated hazard events impact communities and their evolution over time. A key part of the research is also to experiment with, create, and ultimately implement a new approach for interdisciplinary hazards research using a boundary object. In our case, for the reasons provided in Section 2, we used an ABM. There are two purposes for the ABM in the project. The first is as a *model* to help enhance our understanding of how repeated events impact communities and their evolution, which has led to development of new knowledge. But it is more than this. It is also a "mechanism" to induce the interdisciplinary team to work in an integrated manner, by iteratively refining the model through integrating knowledge and generating and testing hypotheses across disciplines.

The ABM in our project includes individual household agents and models their decision-making processes about mitigation measures. It also models hazards (hurricanes and heat waves), health impacts, infrastructure performance, community damage from hazard events, and policy responses.

The ABM has been the focal point of collaboration during team meetings and conference calls because the core model spans different disciplinary knowledge bases and terminology. For example, in studying household response to repeated hurricanes and how this impacts collective vulnerability over time, we first built a simple model. We were able to include basic models of the hurricane hazard, household damage, and behavioral responses between hurricanes by having the complex system modelers work closely with the hurricane modeler, civil engineer, and behavioral scientist to formulate preliminary components of the model. We then iteratively improved each of these aspects, testing hypotheses about the importance of different types of behavior and different details about hurricane frequency and intensity and how this interacts with behavior. The team centered its discussions around the ABM, with the model providing an integrating platform for these discussions.

This approach required a substantial shift in how team members think about modeling and working together. The point of the model is not the model for the sake of prediction or inference as most of us were used to thinking of a model. Rather, in this project, the model became an integrating object, enhancing communication and collaboration. Not

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shared by neighbors or from governmental policies implemented to improve safety.

[9] In addition to ABMs, candidate boundary objects for disaster science may include geographic information systems (GIS) and simulation models. Although these tools partially adhere to the requirements of boundary objects put forth above, they also fail in some regards. GIS is useful when all the interdisciplinary data can be integrated spatially at one point in time (Cutter, Mitchell, & Scott, 1997). The benefits of a GIS model become limited when temporal dynamics is a critical part of the problem, as it is with repeated damage from recurring hazards. Simulation models are a better tool to capture communities evolving over time. However, a basic stochastic simulation model would try to capture the high-level behavior of the system but it would not model individual agents and their decision making within the system. That said, both GIS or stochastic simulation adhere to the requirements of being grounded in theory and accommodating both quantitative and qualitative data.

everyone on the team could fully make this transition, and some aspects of the work were not as integrated as we would have liked. However, overall, the ABM did serve the purpose of bringing the team together and enhancing our ability to collaborate across substantially different disciplinary boundaries in an integrated, interdisciplinary manner.

4. CHALLENGES OF USING AGENT-BASED MODELS AS BOUNDARY OBJECTS

If an ABM is a useful tool, then why are they not widely used as boundary objects for interdisciplinary hazards research? We argue there are three main, and interrelated, challenges to using ABMs as boundary objects: the simplifying assumptions required by ABMs sometimes run counter to field expectations, model validation and what this means for ABMs, and publishing results.

ABMs often require many of the contributing disciplines to make assumptions and, in many cases, to use simplified models. Often, these approximations are needed in order to integrate the new knowledge with the work of other. This can be difficult for researchers who stem from fields that build highly complex disciplinary models, but it is often necessary for computational reasons and so that the key attributes are not masked by nuance. Teams can also struggle with the proper level of detail to include in the model, with different disciplines having different established traditions and preference. For example, in our project, the hazard modelers were accustomed to working with considerable detail about real-world places whereas the economists came from a tradition in which more abstract models not directly tied to real places are the norm.

A related challenge is model validation. Both journal reviewers and team members from some disciplines often desire strong model validation similar to what tends to be done with physics-based models (e.g., hurricane storm surge models, hurricane wind field models, and earthquake ground motion models). This is often not possible with an ABM due to a lack of historical data at the level of spatio-temporal scale needed for full statistical model validation. As an alternative, many, including our team members, use extensive sensitivity tests to explore the robustness of the insights from the model to changes in input parameters.

These challenges contribute to the final challenge, which is publishing ABM-based research papers (Axelrod, 2006). Reviewers who stem from a specific domain may object to some of the (necessary) simplifying assumptions. An additional reason, as Axelrod (2006) states, is that "a reviewer with a not-so-legitimate problem with the submission can always use 'insufficient' checks for robustness as a cover for a negative review" (p. 1582). These reasons, combined with traditional notions of what model validation should be, can provide reviewers with easy cover for rejecting otherwise meaningful papers.

Through our work, we have found strategies that have helped us overcome this final challenge. For instance, we interpret the results in as much detail as we can and are careful to identify the factors that led to particularly unusual or interesting results. This provides the reader with confidence that the authors are not simply hitting a "run" button and "seeing what will happen," but rather have a deeper understanding of the problem and how the key components interact. Another strategy we have successfully used involves acknowledging that the purpose of the research is to understand the conditions and factors that could lead to certain outcomes, and not to precisely predict future outcomes. That is, we emphasize that ABMs are not prognosticators, but rather tools to explore how discipline-specific components interact and potentially lead to certain outcomes. We also recognize that transparency is important. Both input and output data, along with computational code, should be made publicly available when possible, and more repositories are becoming available to provide improved access to data and research code.[10]

We find that despite these issues, when team members unite to create something together, like an ABM, it can lead to a deeper understanding of where each member "fits." This in turn can induce researchers to appropriately scope their work, agree to common assumptions, and identify the best compromise regarding levels of detail.

5. CONCLUSION

Introducing ABMs as boundary objects in hazards research will not solve the multiple challenges of interdisciplinary research. Other fields, including business management and environmental conservation, attribute the lack of interdisciplinary research to problems with the peer-review process and differences in publishing norms (Campbell, 2005;

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[10] For example, at the Natural Hazards Engineering Research Infrastructure site: https://www.designsafe-ci.org/data/browser/public/nees.public/, accessed February 27, 2018.

Rafols, Leydesdorff, O'Hare, Nightingale, & Stirling, 2012). This is perhaps less a problem for the hazards field because multi- and interdisciplinary journals exist and provide respected outlets for the research. But other barriers still exist, of course.

In this article we have argued that by arming researchers with tools that include boundary objects, projects can be more successful and the output of such projects easier to communicate. Agent-based models are one particularly promising approach as a boundary object. They are accepted and established across many different disciplines, they are designed to integrate the various types of information available in interdisciplinary research teams, and they can handle the critical temporal and uncertainty aspects of the problem. Utilizing stronger boundary objects to better integrate interdisciplinary hazard-research teams has the potential to help these teams make deeper, more integrated progress on hazards research, pushing the field forward and reducing future disaster impacts.

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