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Integrated agent-based modeling and optimization in complex systems analysis

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Abstract

This paper presents two case studies on the use of agent-based modeling in the design of complex systems. In the first case study, elements of a self-organizing system are modeled as agents so that their interactions and system-level behavior can be analyzed and optimized to design a protective convoy. The use of agent-based modeling enables a fast simulation-optimization loop for the optimization of behavioral parameters. In the second case study, users of the system are modeled as agents, so the co-evolution of user and system behavior can be modeled in the selection of a seating layout. This modeling provides insight into the social desires of consumers, in addition to the structural properties of the seating layout, allowing a deeper understanding of customer satisfaction and system performance.

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1. Introduction

Agent-based modeling is potentially useful in both analyzing and designing complex systems^{1,2}. This capability, in part, stems from the study of interaction links between components of a system. Any link between system components can be characterized by a degree of dependence and degree of control. If links in a system have high dependence – that is, the performance of one component relies strongly on the performance of another – but very little control over that performance, then a system that exhibits such characteristics can be effectively modeled as a collection of interacting, autonomous agents. For complex systems, which typically have a large number of interconnections, agent-based modeling and simulation offers a viable approach. This is especially true of self-organizing systems, in which constituent parts have a great deal of local autonomy, but no direct control or even knowledge of overall system behavior.

It is important to note that humans and other entities that constitute the system's environment can also be modeled as agents³, thereby enabling analysis of the complex feedback loops that connect system performance and user behavior⁴. In these instances, it is not possible to derive smooth analytical functions for system behavior except for highly simplified representations of such systems. Agent-based modeling and simulation potentially provide a way to overcome this challenge and make the analysis more tractable. For example, the erratic behavior of untrained users, AI stand-ins for trained operators, and decision-making processes of consumers can all be modeled as agents working *with* and *within* the complex system⁴.

The data generated by agent-based simulations can potentially provide useful insights about the behavior of the system and uncover hidden interactions, including those that lead to unintended consequences. Higher-order interactions of agents, not apparent in an object diagram, can become apparent in a simulation as the indirect effects of agent-agent interactions propagate through the system in a time scale that engineers can understand and track. This approach can be helpful for influencing the “design of emergence,” by systems engineers interested in shaping interactions among complex system elements to achieve intended system-level goals.

The results from such simulations for various “what-if” conditions or parameter changes can be combined with powerful optimization methods to explore the design trade space under the control of systems engineers. This exploration allows for a more detailed elaboration of the trade space, and uncovering of interesting behaviors that can lead to asking deeper questions. This paper illustrates agent-based approaches to systems engineering with the help of two simple case studies. The first pairs agent-based modeling with a genetic algorithm in the design of a self-organizing system. The second relies on virtual users, modeled as agents, in the simulation and design of an interior layout. The research reported in this paper is applicable to Systems Engineering (SE) and Design. It rests on a theoretical base of three primary domains: complexity theory, agent-based modeling, and simulation optimization.

This paper is organized as follows. Section 2 presents the road to the present in agent-based modeling in relation to systems engineering and design. Section 3 presents innovative approaches to agent-based modeling and two case studies that exploit these methods in systems design. Section 4 presents findings and implications for future research.

2. Road to the Present

Complex systems are systems composed of parts whose many interactions are difficult to analyze⁵. In highly interdependent systems, the number of relationships among components rises nonlinearly with the number of components, and thus the analysis of these relationships can become unmanageable with increasing system size and dependencies and interactions among subsystems. It is difficult to break down or partition a system into manageable parts for analysis if there is no natural clustering and modularity. Higher-order interactions may not be apparent from mathematical calculations of system performance, and errors from diverse subsystems of the system can propagate throughout the system⁶. From a design perspective, it is important to minimize the number of interactions among system components⁷. However, increasingly customers, especially DoD customers, demand adaptable and resilient systems⁸. These requirements inevitably introduce complexity in the system being engineered. In such cases, systems engineers and designers need to explore alternate design approaches and strategies⁹. Agent-based modeling is an appropriate approach in this circumstance.

An agent is a discrete, situated, autonomous entity¹⁰. A simulation based on a collection of agents is called a multi-agent simulation. For a system to be truly *multi-agent*, it is necessary to restrict agents' knowledge¹¹. Therefore, in

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