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Hybrid systems modeling

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The '*Advances in the State of the Art of Modeling and Simulation*' special issue is in two parts. The first part comprises five papers on *hybrid systems* modeling,[1–3] which is the combined application of modeling and simulation with methods and techniques from disciplines such as computer science/applied computing, business analytics, data science, operations research, systems engineering, economics, humanities, and psychology. Examples include the combined application of qualitative system dynamics, problem structuring methods, forecasting, classical optimization techniques, process mining, data-mining, machine learning, game-theoretic modeling, etc. with computer simulation. The mixed method approach could be applied to different stages of a modeling and simulation study (problem formulation, model implementation, verification and validation, experimentation, etc.).

The second part of the special issue comprises two papers on *discrete event system specification*.[4,5] These two papers will be published in the next issue of the journal. The five hybrid systems modeling papers from this special issue are now introduced, together with an outline of specific methods and techniques that have been combined with modeling and simulation approaches.

Collins and Frydenlund[6] present a hybrid systems modeling approach that combines game theory, a branch of economics that is devoted to the study of conflict and cooperation between rational decision-makers, with modeling and simulation. The authors explore strategic group formation by drawing on cooperative game theory in agent-based modeling for group decision-making. They consider a game setting in which agents compete for resources with their neighbors. The authors state that by placing strategic group selection behavior in an agent environment, they benefit from empirical results that overcome some of the limitations of standard cooperative game theory (e.g., computational complexity). This is indeed the objective of hybrid systems modeling – to combine modeling and simulation approaches with methods and techniques from other disciplines with the view of developing the best possible representation of the underlying system under study.

The paper by Bell and Mgbemena[7] is again an example of a hybrid systems modeling approach, in which the authors combine data-mining techniques with computer simulation. More specifically, the authors have used agent-based modeling with classification and regression trees (CART), a type of decision tree, to understand customer behavior specific to retention in mobile telecommunication marketspace. The paper presents the *customer–agent decision tree (CADET)* method, which is a data-driven approach to agent-based modeling and simulation utilizing large and rapidly changing datasets.

The third paper in the special issue, by Kazi and Wainer,[8] not only has resonance with topics such as sustainability and circular economy, but the authors go further in contextualizing their work to the spatial analysis of ecosystem services. The authors have used a combination of discrete event systems (DEVS), formalism-based cell-DEVS modeling with geographic information systems (for data collection), web-based simulation for remote execution, and visualization of results using a geospatial visualization system. The paper discusses the design, implementation, and benefits of the hybrid approach, the cell-DEVS modeling and simulation environmental models, the integrated cell-DEVS architecture for web-based simulation, GIS visualization, and a case study.

The next paper, by Djitog et al.[9] is on the combined application of modeling and simulation methods with model-driven engineering for the development of a multi-paradigm hybrid systems modeling framework that is specific to healthcare. The authors identify the limitations of studying healthcare systems in isolation and using specific formalisms. They propose a framework that includes several formalisms (DEVS, petri nets, system dynamics, cellular automata, queuing networks) that allow the modeler to choose an appropriate formalism at a given level of

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abstraction. The framework has been applied to the study of the Nigerian healthcare system.

The last paper, by Barros,[10] is on the hybrid flow systems specification (HyFlow), a formalism that is designed to represent hybrid systems having both continuous and discrete characteristics. HyFlow achieves the representation of continuous variables using the concept of multisampling, while the representation of discrete events is based on DEVS. The author claims that this is the first modular representation of geometric integrators that can be seamlessly integrated with other families of hybrid models.

Future research in hybrid systems modeling

A defining characteristic of hybrid systems modeling is its reliance on interdisciplinary research in the methodology space. How could such research be effectively realized? We use the term ''hybrid teams'' to emphasize the need for interdisciplinary modeling and simulation groups that bring together problem stakeholders, researchers, and practitioners. They are essentially composed of individuals specializing in specific fields of study or, as in the case of problem stakeholders, having tacit knowledge of the underlying system of enquiry. When considered as a whole, such hybrid teams will have recourse to knowledge constructs (theories, methodologies, techniques, applications, etc.) that have not traditionally been applied to M&S studies. Such teams are arguably better poised to address challenges pertinent to hybrid systems as the very constitution of the team allows for opportunities to leverage from the diverse body of knowledge and individual expertise and skillsets, and makes it possible to work toward common end goals.

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