Proceedings of the 34th European Modeling & Simulation Symposium (EMSS), 019
19th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0029 © 2022 The Authors.
doi: 10.46354/i3m.2022.emss.019

Hybrid Simulation Design and Implementation

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Abstract

Hybrid Simulation in the Operational Research (OR) domain can be defined as the combination of two or more of the simulation methods of discrete-event simulation, agent-based simulation and system dynamics. This article examines how this combination might be achieved by reviewing the characteristics of the simulation methods, considering design view options and taking into account software tools for implementation. The purpose is to provide guidance on how hybrid simulation configurations can be designed and implemented.

Keywords: hybrid simulation; simulation design view, simulation software tools

1. Introduction

Co-simulation is defined as a simulation in which at least two different simulations are coupled (Hafner and Popper, 2017). In the Operational Research (OR) domain the term hybrid simulation (Brailsford et al., 2019) is often used to describe a combination of two or more of simulations with the main OR-based simulation methods being discrete-event simulation (DES), agent-based simulation (ABS) and system dynamics (SD). For example, Lättilä et al. (2010) provide a review of hybrid models of agent-based simulation and system dynamics

There is a small but growing number of practitioners who express a preference to develop hybrid simulations (Padilla, 2018). Examples of the use of hybrid simulation include Rondini et al. (2017), Mourtzis (2020), Vempiliyath et al. (2021) and Tian et al. (2022). This article examines the characteristics of the DES, ABS and SD methods to show when they might be applied to a particular problem situation. Then different design options for hybrid simulation are outlined and finally an evaluation is made of simulation software that can be used to implement hybrid simulation applications. The purpose of the article is to provide guidance on how hybrid simulation configurations can be designed and implemented.

2. Characteristics of SD, DES and ABS

Table 1 provides a review of the characteristics of the simulation methods of discrete-event simulation, system dynamics and agent-based simulation to provide a guide to their potential role in a hybrid simulation application.

In terms of purpose SD aims to investigate the patterns of behaviour in the system. DES is focused on the operational performance of processes in terms of flow rate and flow time. ABS is concerned with representing individual agent behaviour and from this it aims to show how individual behaviour leads to system behaviour.

Table 1. Characteristics of system dynamics, discrete-event and agent-based simulation

FACTOR	SYSTEM DYNAMICS	DISCRETE-EVENT SIMULATION	AGENT-BASED SIMULATION
PURPOSE	Investigate patterns of behaviour in system	Investigate operational performance of processes.	Directly represent agents and their behaviour.
DETERMINATION OF BEHAVIOUR	System behaviour determined by feedback and accumulation structures	System behaviour determined by stochastic nature and interdependency of processes.	System behaviour determined by interaction of autonomous components
AGGREGATION LEVEL	The system can be modelled with elements aggregated into flows	Each element can be modelled with a set of attributes.	Each element can be modelled with a set of attributes and operations.
CONCEPTUAL MODEL NOTATION	Influence Diagram Causal Loop diagrams	Process Flow Diagram Activity Diagram	Statecharts Unified Modelling Language (UML)
REPRESENTATION	Stocks and flows	Entities and Resources	Agents
PRESENTATION OF RESULTS	Statistics showing system performance. Plots showing behaviour patterns and feedback loops.	Statistics showing system performance. Animation showing individual process routing	Statistics showing system performance. Visualisations and animations of individual elements.
SOFTWARE TOOL	Stella, iThink, Vensim	Simio, Arena, Simul8	Anylogic, NetLogo, Repast
SOFTWARE CODING	Flow Diagrams	Visual Interactive Modelling interface	Java, NetLogo

In terms of the determination of behaviour, SD explains behaviour due to feedback by employing systems theory and emphasises the role of feedback and accumulation structures. DES explains behaviour due to uncertainty by combining an explanatory modelling approach in the mapping of interdependent processes with a descriptive modelling approach in describing the stochastic nature of systems. ABS explains behaviour by describing the interaction of autonomous components. In terms of the aggregation level the difference in the approach of SD, DES and ABS can be demonstrated by an example of a simulation of a new product development process. Here SD can model the quantity sold during a time period. The discrete-event approach is able to model each customer purchase and thus model individual purchase decisions through the ability of DES to carry information regarding each entity (customer) in the system. ABS could be employed to model individual customer behaviour when making a purchase decision.

In terms of conceptual model notation each approach employs different methods. Influence and causal diagrams map out the relationships in SD, DES employs process flow diagrams and activity diagrams and ABS employs statecharts and other diagramming methods associated with the Unified Modelling Language (UML) standard. In terms of representation the SD method models the real system using stocks and flow elements, the main representation in DES are entities and resources and ABS employs an agent representation. There is however a relationship between the concepts of stocks in SD with queues in DES and a relationship between flows in SD with processes in DES. Agents in ABS can be related to entities in DES which have self-contained decision logic. In terms of presentation of results all three methods provide statistical reports and graphical plots of variables over time. DES and ABS generally also provide animation of individual entities or agents. The use of software tools and software coding for hybrid simulation is covered in the later section regarding implementing hybrid simulation.

3. Hybrid Simulation Design

There are many definitions of hybrid simulation but here we take a broad view of hybrid simulation as the use of multiple SD, DES and ABS models and/or multiple SD, DES and ABS methods that are used for different aspects of the same simulation study. This definition is based on Morgan et al. (2017) that defines the use of a combination of DES and SD.

If we consider hybrid simulation in this way then there are a number of different modes of interaction between DES, SD and ABS that are possible. Table 2 presents these hybrid simulation designs based on Morgan et al. (2017) and extended to include ABS.

Isolationism is the use of a single method and model such as a DES model. The remaining 5 design options are categorised under the hybrid simulation approach. A parallel design uses more than 1 of SD, DES and ABS models to provide a complementary insight into the same system under investigation. A sequential design covers studies when the use of 1 model, for example an SD model, is followed by the use of an additional model, for example a DES model when it was decided that more detailed modelling was required in a particular area of the system. An enrichment design is when a base model is enriched with elements of a second method. An example is using SD to model continuous processes within a DES model. An interaction design is when 2 models using different methods exchange data between them. An integration design is when more than 1 method is applied in the same model and to the same problem situation, producing a single model with characteristics of both methods. These design options provide a useful guide to the different approaches possible when using simulation models in combination. For all but parallel hybrid simulation design there is likely to be required a mechanism for data exchange between models. The three main architectures are a manual (offline) interface in which data is transferred between models by saving data to a file such as an Excel spreadsheet. The second architecture is an automated (online) interface of the DES, SD and ABS models which may allow real-time exchange of data between the models. Finally, there is the integrated architecture which allows different methods to be used within a single model (Greasley, 2020).

4. Hybrid Simulation Implementation

In terms of implementation of hybrid simulation through software tools, the AnyLogic software package provides a multimethod modelling platform that allows the three simulation methods to be combined and is the most widely used computer simulation package in Hybrid Simulation (Brailsford et al., 2019). In Anylogic there is a clear delineation between the DES, SD and ABS components and so Anylogic models are classified as enabling an interaction hybrid simulation design (Brailsford et al., 2019). Another aspect of Anylogic is that it usually requires Java programming which may be a barrier to DES modellers only experienced in using Visual Interactive Modelling platforms such as Arena. Büth et al. (2017) show how an agent-based capability can be established using the Technomatix Plant DES simulation. Another potential software tool for providing a platform for an integrated hybrid simulation design for DES and ABS is Simio which provides an object orientation as its main paradigm (although a process orientation and event orientation are also supported). This means that instead of the traditional approach of having passive entities that are acted upon by the model processes, in Simio the entities can have intelligence and control their own behaviour (Pegden,2007). This is a key criteria for an agent-based simulation (ABS) and the Simio DES software provides capabilities in terms of permitting the embedding of algorithms (process logic) within the entity definition and provides a spatial display that permits free movement of entities. These object-oriented capabilities are built into the modelling environment, rather than an object-oriented programming environment which means that the skills required to define and add new objects to the system are modelling skills, not programming skills (Pegden, 2007). To demonstrate this capability Greasley (2019) outlines the implementation of a simple ABS model in Simio.

5. Results and Discussion

When developing a hybrid simulation, we need to relate the characteristics of the 3 simulation methods with the system we are modelling. This activity could take place after the overall conceptual model has been developed (i.e., at the modelling stage). However, Eldabi (2021) suggests attempting to establish whether a hybrid simulation model may be required or not at an earlier stage of the simulation study.

Table 2. Hybrid Simulation Designs (adapted from Morgan et al., 2017)

		HYBRID SIMULATION				
DESIGN VIEW	**Isolationism** Single view of system	**Parallel** 2 possible representations of the same system	**Sequential** Need to capture different parts/behaviours of the same system	**Enrichment** Need to capture different parts/behaviours of the same system	**Interaction** Need to capture different parts/behaviours of the same system	**Integration** Need to capture different parts/behaviours of the same system
JUSTIFICATION	Tried, tested and trusted methodology	Complementary insight into system to reveal plausible explanation of behaviour	Allows for emergent insights as knowledge of system improves	Benefit from characteristics of a second method without a second model	Capture interactive influences within the system whilst being grounded in each method	Capture interactive influences; present one concise and coherent view
MODELS / METHODS	1 /1	More than 1/ more than 1	More than 1/ 1 or more	1 / More than 1	More than 1/ More than 1	1 / More than 1
COMMENTS	Modeller should remain open to adopting another method as the project progresses	Same system modelled by each method (at least 2) for complementary insight	Each part captures different parts of the system or at a different level of detail	Frequency of interaction and whether it is triggered or regular depends on the master method	Models developed can operate independently but work together to contribute to the problem.	Methods function together as a single model

Eldabi (2021) presents a framework which includes the following steps:

- Identify the Overall Objective of the study: Define the problem situation and objectives and the need for hybridisation
- Systemic Review: Identify characteristics of the system and map them onto the 3 simulation approaches of SD, DES and ABS. Identify what the simulation modelling requirements are in the different parts of the system leading to specific modules.
- Model conceptualisation for each module: Draw up the conceptual models for each simulation approach within each module.

As can be seen from table 1 each of the three methods of SD, DES and ABS provides a different modelling perspective and modellers tend to specialise in one of the three methods. For example, ABS is widely used for complex systems that we cannot conceptualise well, so we build a model based on our theory of what governs that model (at an individual level) and observe what behaviour emerges from this theory. In DES we have a firmer definition of how the system operates (at a system level) based on empirical data and wish to observe the system behaviour under future scenarios.

DES and ABS are thus used together when we wish to model processes such as supply chains (DES) combined with decision making of supply chain actors (ABS) (Vempiliyath et al., 2021). People's behaviour, such as their emotional state, can also be modelled using ABS within a DES modelled customer service process (Tian et al., 2022). Another combination is to employ an SD model to analyse supply chain behaviour supplemented with a DES sub-model (Oleghe, 2020).

However, the definition of hybrid simulation used here implies a number of design options in addition to the combined use to model different aspects of the problem. For example, a parallel design view can provide complementary insight through multiple representations of the same system. This is demonstrated in Morecroft and Robinson (2006). Furthermore, a sequential design view can be used at different stages of a simulation study. For example, when SD is being used to understand the problem situation or to understand the reasons (causal relationships) that are leading to the DES results (Greasley, 2005). DES and ABS could be combined with a process flow defined in the DES and the ability of ABS to model individual entity logic (to represent human behaviour for example).

We also need to consider software tools for implementing hybrid simulation. Most are dedicated

DES, SD or ABS and so one barrier to the use of hybrid simulation is the lack of integrated software platforms that simplifies issues of data exchange and synchronisation between models. Anylogic is an exception here, integrating all 3 methods, but it does require Java programming which can be a barrier to practitioners. Simio is a DES package but it does incorporate two capabilities required for ABS at the modelling rather than programming level. These capabilities are the ability to incorporate algorithms within the entity definition and the ability to define a visual display incorporating free travel of entities (required due to the lack of prior definition of entity behaviour).

Finally, whatever software tools are available, only a minority of simulation practitioners are skilled in more than one of these methods. This bias to use a dominant modelling method that the modeller is more familiar with is identified as one of the weaknesses of modelling practice (Tako et al., 2019). Thus one of the aims of hybrid simulation should be to encourage simulation education and training to span all three approaches. Hoad and Kunc (2018) provide a case study of teaching system dynamics and discrete-event simulation together as an example of how this could be approached in practice.

6. Conclusions

Hybrid simulation offers the possibility of increasing the capability of the simulation model developer to provide a deeper understanding of systems behaviour. This requires an understanding of the purpose of each of the three techniques of SD, DES and ABS, the different design views that can be employed and the use of appropriate software to enable successful implementation.

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