Hybrid simulation for complex manufacturing value-chain environments

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Abstract

Hybrid simulation is nowadays a valid alternative for studying complex manufacturing environments. Some challenges exist in this context, as the ambiguous use of terms and definitions in the literature; and the demanding skills required for developing hybrid models. A structured literature review provides an overview of the use of hybrid simulation in manufacturing business performance and its most important advantages and drawbacks. A classification scheme for the 51 analysed papers is presented, including interfaced, sequential, enrichment, and integrated taxonomies.

Keywords: Agent-Based Simulation; Discrete Event Simulation; Hybrid Simulation; Manufacturing; System Dynamics; Taxonomy

1. Introduction

The complexity of modern manufacturing systems and the interactions in this context demand the use of simulation as an alternative to cumbersome mathematical models [1, 2]. Simulation is one of the most commonly used techniques in Operational Research (OR) [3]. It is very popular for modelling complex manufacturing systems [4, 5], assessing the impact of decisions [6], optimizing designs and operations, and assessing performance [7, 8]. There are many benefits in using simulation, as early insights on the behavior of complex systems [4], flexibility [2, 9], cost efficiency [10], easy development [2], few simplifying assumptions to the models [9], scaling-up of the models, quick running times, analysis of "what-if" scenarios, and ethical experimentation [2].

Recent demands from global business optimization, human decision making, and complexity of modern systems, push researchers for using hybrid simulation approaches, combining different simulation methods, for better understanding of complex interactions between processes of different nature [3, 8]. Adopting the definition in [3], hybrid approaches are those combining at least two of three simulation methods – System Dynamics (SD), Discrete Event Simulation (DES), and Agent Based Simulation (ABS).

Albeit there is a growing interest in hybrid simulation approaches, many questions remain unsolved. There is no unified use of terms and definitions in the literature [11], which introduces ambiguity. Literature in hybrid simulation is sparse, hampering the work of researchers interested in the topic. Also, many challenges arise when using more than one simulation method, as establishing information sharing between the models [12], converting time units [12, 13], and the skills required for building the models [14].

This work aims at providing insight on the use of hybrid simulation in manufacturing business performance; and the most important advantages and challenges of using hybrid simulation. We try to answer two research questions:

RQ1: Where and how has hybrid simulation been used in the context of manufacturing business performance analysis?

RQ2: Which are the key aspects and challenges for hybrid simulation approaches?

Particularly, focus is laid on exploring the different designs of hybrid simulation approaches which have been published in the context of manufacturing business performance (e.g. manufacturing supply chain, logistics), by following a structured literature review, focusing on the different combinations of methods (SD-DES, DES-ABS, SD-ABS, others). Furthermore, and focusing on the second research question, the key issues modelers should focus on when developing hybrid simulation models are explored.

The remaining of the paper is organized as follows. Section 2 includes a description of the three simulation methods. Section 3 highlights the steps in the structured literature review, the classification scheme for the different design approaches to hybrid simulation in the literature, and the challenges of hybrid simulation; and section 4 concludes the paper and provides guidance for future research.

2. Simulation methods

2.1. System Dynamics (SD)

SD was developed at the MIT, in the 1950s, by Jay W. Forrester [15, 16], and was initially called Industrial Dynamics [16]. It is a systems thinking approach [9], focusing on an aggregate view of the systems and emphasizes feedback mechanisms and their endogenous nature [12]. In SD, the structure of the real world determines behaviour over time [12, 15]. The endogenous behaviour results from feedback loops [16] creating dynamic complexity [17].

Processes are represented by stocks, flows between the stocks and feedback loops (balancing and reinforcing). SD focuses on policies instead of single events. All elements which influence the behaviour of the system have to be modelled endogenously [16]. SD models use finite differential equations to capture interactions between subsystems and the impact of delays [6]. Models are qualitative and quantitative: the qualitative aspect is related to developing the causal loop diagrams through discussion; variables must be quantified and the quantitative SD is used through stock-flow models. SD models are deterministic and do not require multiple iterations [15]. It is a "continuous" simulation method, in which time advances in small constant steps [18].

It is very important for understanding complex systems [19], in which time is an important factor [7]. It was primarily applied to supply chains (SCs), and later to economics, ecology, innovation, workforce management, software development, competition, and markets [17]. SD is adequate for representing the management environment, enabling practitioners to analyse strategic planning scenarios and simulation policies and operations [7]. Nonetheless, due to the continuous nature of SD, it is not capable of mapping discrete events which are common in many industries [20]. For a more comprehensive view of SD, please refer to Sterman [21].

2.2. Discrete Event simulation (DES)

DES dates back to the 1960s; it was introduced by Geoffrey Gordon in its idea for General Purpose Simulation System (GPSS) [22]. It is the most commonly used simulation method in manufacturing, for evaluating planning, routing and scheduling alternatives [9]. Modelling occurs from a macroscopic point of view [8]. The most important elements in DES are entities, activities, resources, queues, and events [19]. Entities are passive objects which may represent messages, tasks, and people; these entities travel through blocks of activities where they stay in queues, suffer delays, are processed, seize and release resources [22]. State variables change in discrete points in time, called events [15, 18]. Models require accurate data or accurate estimates on system's operation [1].

There are two world-views in DES: process-oriented and event-oriented [15]. In the process-oriented worldview, entities move through various processes, and each process requires resources and a certain amount of time for completion. Entities do not have a defined behaviour and are purely data containers. The flow of entities through the system is governed by rules assigned to system (probabilistic or condition-based), and not by a decision process internal to the entities. In the event-oriented worldview, the events are themselves the primary modelling element.

DES has been widely used at the operational level of organizations, for modelling production [20], and studying the system behaviour in response to detailed events in discrete points in time [5]. It is widely used for productivity analysis in manufacturing [13, 23], and logistics [24]. This method is particularly useful for problems with queueing simulations and variability is represented through stochastic distributions. DES models have a process oriented approach and are based on top-down modelling [24]. In spite of being a well-established method, DES does not address the stability of the system, which is very important when analysing the system in an aggregated level of planning [19]. More detailed information about DES can be found in [25].

2.3. Agent-Based simulation (ABS)

ABS is a more recent method [15], whose definitions are not yet universally accepted. There is a wide discussion referring to the properties that an object should have in order to be called an agent [22]. It adopts a bottom-up, microscopic approach, in which agents exhibit behaviour at the individual level [8, 26]. Agents live together in a certain environment, communicating with each other and with the environment, according to a number of logic rules. The macro-level behaviour of the system results from the individual interactions among agents [8]. It is possible to assess how agent diversity affects emergent behaviours of the system as a whole [15].

Agent's properties documented throughout time include proactiveness, purposefulness, situatedness, reactiveness, responsiveness, autonomy, social ability, anthromorphity, learning, continuity, mobility, and specific purpose. Agents can represent entities in a system, as human beings, animals, or institutions [16]. An agent's internal state is dynamic and changes as the agent's experiences accumulate and are recorded in memory [15].

ABS is increasingly used in business related areas, as manufacturing, maintenance and SC management [17]. As many details as possible are used to represent the individual features of the different elements of the system [12]. This is supported by the increased number of available databases and computational power, which allow micro simulations [17]. It is suitable for modelling adaptive and dynamic manufacturing systems [4]. Data requirements are high and often data collection may be difficult, e.g. when collecting data about human behaviour [23].

3. Hybrid simulation approaches – a literature review

This review reports publications targeting hybrid simulations in manufacturing business performance. To make the review as comprehensive as possible, the publication year was not restricted, which resulted in a span of publications across more than 30 years. The literature review followed a structured approach, based on the work by Jahangirian et al. [27], and adopted the steps in Fig.1.

The keywords' selection considered the dispersion of terms in the literature [11].; these included "manufacturing", "multi-method simulation", "hybrid simulation", "multi-paradigm simulation", "combined simulation". Three scientific databases were used: Scopus, Science Direct and Emerald Insight.

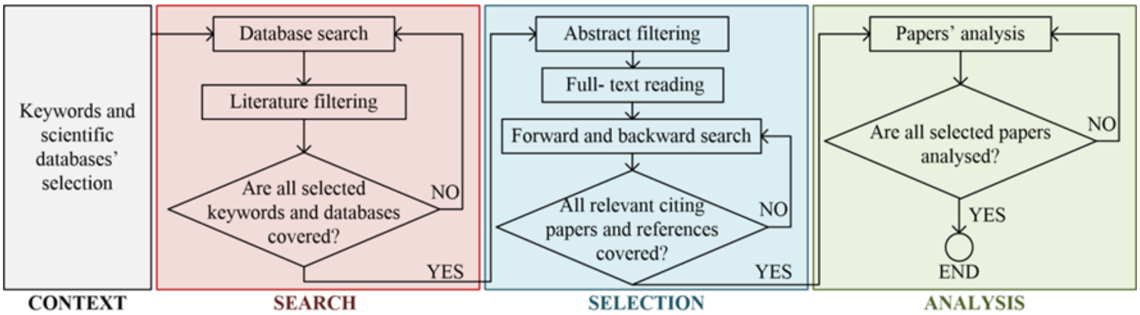

Fig. 1. Structured literature review approach.

Literature filtering included elimination of duplicates, non-English papers and unavailable papers. The following step included reading the abstract of all filtered papers. For a paper to be selected, it had to be explicit that more than one simulation method was used and that the context of the simulations was in manufacturing business. All papers selected based on the abstract were fully read and a backward and forward search (references and citing papers) were conducted to increase the range of papers. A total of 51 papers were fully analysed, distributed across different publication years. Database search was performed amid September and October 2016. Due to the space restrictions, only a part of the search results is presented in this work.

3.1. Classification scheme for the hybrid simulation approaches

Hybrid simulation approaches not only differ in model inputs, objectives and outputs, but also in the design of the simulation models, with different relationships between models from different methods. A taxonomy of classifications for the design of hybrid simulation models, based on the classification scheme proposed by Swinerd and McNaught [3] for hybridism using SD and ABS, is presented. The classification scheme is extended to all combinations of methods; and adding the enrichment taxonomy as presented by Morgan, Howick and Belton [28]. There are four taxonomies in the classification scheme: interfaced, sequential, enrichment, and integrated, as in Fig. 2:

- *Interfaced* (Fig. 2(a)) – Models from different methods are individually applied, and are uncoupled. There is comparison of results at specific points in time to discover opportunities of complementarity and compatibility.
- *Sequential* ((Fig. 2(b)) - Methods operate separately, one method follows the other, and methods are uncoupled but dependent and complementary. Results from the previous method are used in the following method.
- *Enrichment* ((Fig. 2(c)) - A single method is used, which is enriched with principles from other method(s).
- *Integrated* ((Fig. 2(d)) – Models from different methods are fully coupled. There is constant exchange of information and feedback mechanisms in more than one point in time between models from different methods.

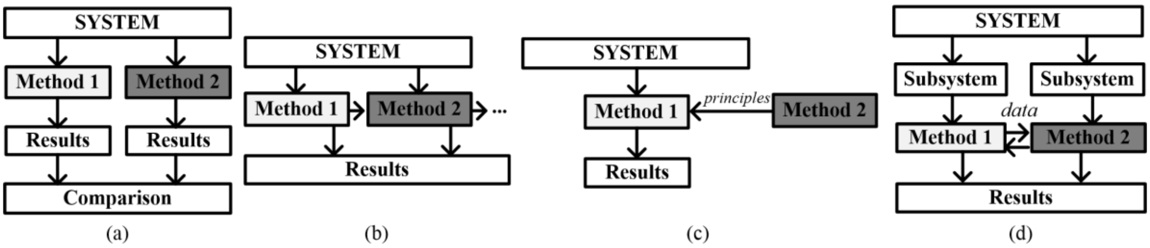

Fig. 2. Taxonomies in the classification scheme for the hybrid simulations. (a) Interfaced (adapted from [3]); (b) Sequential (adapted from [3]); (c) Enrichment (adapted from [28]); (d) Integrated (adapted from [3]).

3.2. Results from structured literature review

A total of 51 papers covering hybrid simulation approaches have been analysed. Among these, 7 were in the interfaced taxonomy, 7 in the sequential taxonomy, 6 in the enrichment taxonomy and 31 in the integrated taxonomy. In the interfaced taxonomy, models developed using different methods have the least interaction. Model outputs are compared in [26, 29-33] for assessing which modelling and simulation method best suits a particular part of the system In [29], the authors simulated a JIT/Kanban manufacturing process using SD and DES, and compared the obtained results; a similar approach was used in [30], but for studying a production line operating under constant work in process. Parunak et al. [33] developed agents and equations models for supply networks, and in [26], Demirel compares the capabilities of supply chain models built using SD and ABS. A different approach was used in [31], where the authors used systems thinking techniques within the context of DES, for capital investment decisions. Alternatively, guidelines for the integration of the models are presented in [34]. In the sequential approach, there are two lines of research. In the first, the authors start by selecting one method for modelling the system; however, these later realise the need of using another method for better analysis [35, 36]. In the second line of research, one of the methods is first used for developing a model; its' output results are then passed to a second model built using a different method, and often with different level of detail. In this approach, there may be feedback mechanisms, but the models are not simultaneously executed (e.g. in [37]). Different problems have been explored in the sequential approaches, as safety and productivity evaluation in manufacturing layouts [23], software project planning and management [35], evaluation and improvement of supply chain processes [38], assessment of green logistics practices in the automotive industry [37], evaluation of energy trade-offs in the supply chain [39], and production planning [36, 40].

Enrichment entails the use of principles of one method into other method. In some approaches, the authors use a software which is typical for one method, but applying principles [41, 42], or libraries [43] of other method. The realm of target problems in the enrichment taxonomy includes policies for managing job shop [41], warehouse operations [43], supply networks [44], and colliery operations [45]. The integrated taxonomy is the most commonly used in literature. A wide realm of problems has been addressed in the literature using this approach, including hierarchical problems [5, 46, 47], operational processes and SC phenomena [7, 48-50], enterprise simulation [6, 9, 20, 51-54], value chain analysis [55], agile manufacturing [56], material handling systems [4], SC management [57]. Regardless the topics under study, models in this taxonomy have feedback mechanisms and the models from different simulation methods are executed simultaneously. Table 1shows the results of the structured literature review, with the assignment of the papers to the different taxonomies.

Table 1. Results from the structured literature review

Taxonomy	**Methods**			**References**
	SD	**DES**	**ABS**	
Interfaced	●	●		[29-32]
	●		●	[26, 33, 34]
Sequential	●	●		[35-38, 40]
		●	●	[23]
	●	●	●	[39]

Taxonomy	**Methods**			**References**
	SD	**DES**	**ABS**	
Enrichment		●	●	[41, 43]
	●		●	[42, 44, 45, 58]
Integrated	●	●		[5-7, 9, 20, 46-55, 59, 60]
		●	●	[4, 8, 24, 56, 61-63]
	●		●	[12, 57, 64-66]
	●	●	●	[67, 68]

3.3. Aspects and challenges of hybrid simulation approaches

When developing a simulation, the method is chosen depending on the structure of the system and the objectives of the simulation [63]. It can be extremely time consuming developing models of complex systems using standalone simulation methods [63, 69]. In this situation, there is the need to use a hybrid approach [63]. Even though hybrid simulation approaches are more and more frequent, the combination of two methods only is justified when the developed models are of equal importance to the overall goal of the simulation [20]. In fact, combining models from different methods requires much effort and precision to establish which information should be shared and how often it should be shared [12]. Some common problems which arise in hybrid simulations and are not relevant in standalone simulation include the different time units in the models. Time units have to be converted so that proper data exchange is feasible and inconsistencies avoided [12, 13]. Also, developing hybrid models requires much knowledge about different simulation methods, high skills and flexibility from practitioners to find a good fit between models [14]. Choosing the appropriate methods to use is also a great challenge for hybrid simulations [11].

Despite the high demands of hybrid simulation, when its use is justified, many advantages can be achieved. One of the great benefits of hybrid simulation is flexibility [68]. The challenge of simulating a complex system using standalone simulation is overcome [63] and extracting the best features of the selected methods becomes possible [19]. It is possible to simulate different levels of aggregation when models using different methods are combined [12]; also, combining these models allows conjoint analysis of results, avoiding problems of model consistency, redundancy of components, model investigation effort [59]. Some of the purposes of hybridism include complementarity of the methods used [1, 11], coupling between methods, exploration of multilateral problems, stakeholder acceptability, need for a unique representation, validity, data availability and usability, expectation of unique insight, dimensions, and criteria [11]. Models combining discrete and continuous variables are convenient for explaining the dynamic behaviour of systems, confirming the validity of alterations to the system, predicting system behaviour, benchmarking competitive improvement strategies, checking novel adaptive control systems, and approximating a discretely changing variable using continuously changing variables [70, 71].

4. Conclusions and future research directions

Two important problems of the realm of hybrid simulation have been explored. The first was related to the lack of agreement in the terms used by different researchers, which introduces some misperceptions. A structured review was conducted, using different keyword combinations, to gather as much information as possible about hybrid simulation design in manufacturing business performance; aiding researchers in finding appropriate literature. A classification scheme allows understanding the different approaches to hybrid simulation design which have been used in the literature. The second problem included summarizing some key aspects and challenges of hybrid simulation.

Even though comprehensive, the review approach may exclude some relevant works. A broader range of databases should be used, and the scope of the review enlarged, so that other areas (e.g. healthcare, construction) may be included in the review. Furthermore, better inclusion criteria in the different taxonomies should be provided.

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