INTEGRATED METHODS OF MODELING AND SIMULATION APPLIED TO OPERATIONS PROBLEMS: ANALYSIS AND PRACTICAL APPLICATIONS

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The integrated use of simulation methods are rare in the literature, since most of the studies found focus on single method applications. This article contributes to better use of computer modeling simulation proposing combined use strategies of these methods what offers the potential to increase the strengths of these methods and reduce individual limitations. Three methods are discussed: Discrete Event Simulation (DES), System Dynamics (SD), Modeling and Agent-based Modeling and Simulation (ABMS). The article begins with a comparative analysis of these methods and in the following presents two practical applications. The integrated use of these methods opens the possibility to exploring old and new problems through a new perspective that can promote better solutions to real-world problems. We suggest the application of this strategy to problems involving complex systems with multiple levels of aggregation as supply chains, service operations, urban distribution problems, social networks, etc.

Palavras-chaves: Operations research, modeling, simulation, operations problems
1. Introduction

The modeling and simulation are essential to better understanding the systems, since the behavior of most systems is complex and transcends common sense.

Based on this premise, this article contributes to better use of computer modeling simulation proposing combined use strategies of these methods. This approach is rare in the literature, since most of the studies found focuses on single method applications or dyadic analysis. The proposed strategy offers the potential to increase the strengths of these methods and reduce individual limitations.

The focus of the article are the methods of computer modeling and dynamic simulation used to solve problems of operations, logistics and supply chain management by present a wide range of different applications and modeling possibilities as can be observed in figures 1 and 2. Three methods are discussed: Discrete Event Simulation (DES), System Dynamics (SD), Modeling and Agent-based Modeling and Simulation (ABMS).

Figure 1 - Applications of simulation modeling on abstraction level scale
The article begins with a comparative analysis of these methods, which presents the main differences between them, their strengths and weaknesses. After this, the benefits of integrated use are exemplified by two practical applications. One of them integrates Discrete Event Simulation (DES) with System Dynamics (SD) and the other integrates Agent-based Modeling and Simulation (ABMS) with System Dynamics (SD).

2. Comparative analysis of methods

This section presents and discusses the advantages, disadvantages and limitations of the methods considered. The considerations presented are based on the methods approach and in the analysis found in literature researched. Table 1 summarizes the analysis elements and the comparative approach adopted in the literature. And in the following the methods are discussed.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Comparative Approaches</th>
<th>Analysis Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brasilford and Hilton (2001)</td>
<td>Discrete Event Simulation (DES) and System Dynamics (SD).</td>
<td>Scope, variability, individual actions, entities, control, handing of time, objectives.</td>
</tr>
<tr>
<td>Morecroft and Robinson (2005)</td>
<td>Discrete Event Simulation (DES) and System Dynamics (SD).</td>
<td>Main building block, relationships, scope.</td>
</tr>
<tr>
<td>Mayo and Wichmann (2003)</td>
<td>Discrete Event Simulation (DES) and System Dynamics (SD).</td>
<td>Main building block, data, perspective, handing of time, level of modeling, flows etc.</td>
</tr>
<tr>
<td>Schieritz and Milling (2003)</td>
<td>Agent-based Modeling (ABMS) and System Dynamics (SD).</td>
<td>Main building block, unit of analysis, level of modeling, handing of time, mathematical formulation etc.</td>
</tr>
<tr>
<td>North and Macal (2007)</td>
<td>Discrete Event Simulation (DES), System Dynamics (SD), Dynamic Systems (SD), Agent-based Modeling (ABMS), participatory simulation, optimization, risk analysis and statistical modeling.</td>
<td>When to use, drawbacks and limitations.</td>
</tr>
</tbody>
</table>

Table 1 – Summary of comparative analysis found in literature

2.1. Discrete event simulation

The Discrete Event Simulation (DES) is a dynamic simulation method where state variables of the model change at discrete moments in time as consequence of specific event occurrence.
The elements that compose the system can be described as entities, activities, resources and controls. These elements define who, how, where and when it will be processed models (KELTON, SADOWSKI e STURROCK, 2007. Figure 3 shows a representation of the system from the method’s perspective.

Entities are items processed through the system, each entity can have characteristics that differ from each other, as the format, cost, priority, quality or condition (HARRELL, GHOSH e BOWDEN JR, 2004). According to Kelton et. al. (2007) these characteristics are called attributes.

Activities are tasks performed on the system that may be involved directly or indirectly with the entities process. Usually involve resource allocation and consumption of time.

Resources are means for the implementation of activities. Capacity, speed, cycle time and productivity are characteristics of resources (HARRELL, GHOSH e BOWDEN JR, 2004). Kelton et. al. (2007) call attention to other elements that are part of DES model, these are: global variables, queues and the simulation clock.

Based on the characteristics presented its is possible assert that the DES method is ideal for modeling systems that can naturally be represented in a process or sequence of operations, which have a strong element of variability and can be well defined by a probability distribution (LANE, 2000; BANKS, CARSON II, NELSON et al., 2004; NORTH e MACAL, 2007). Thus, the range application of the DES method varies from operational problems to tactical (BRAILSFORD e HILTON, 2001; BORSCHCHEV e FILIPPOV, 2004; MORECROFT e ROBINSON, 2005).

One of the method’s main advantages lies in the ease model’s representation trough the use of functions and predefined building blocks (SAKURADA e MIYAKE, 2009). The method's main drawbacks and limitations are related to the difficulty of model complex processes with multiple decision making levels, for example, simulate unpredictable paths of entities (MAYO e WICHMANN, 2003; NORTH e MACAL, 2007; SAKURADA e MIYAKE, 2009) as occurs in dynamic routing and scheduling problems.

According North & Macal (2007) another method's limitation is in its inability to capture changes in the structure of the system over time, the method's emphasis is the representation of fixed processes, whose relationships are typically defined at the beginning of the simulation.

2.2. System dynamics
The System Dynamics (SD) studies the behavior of systems over time. The method was developed by Jay Forrester (FORRESTER, 1961) from concepts of the theory of servomechanisms and points to a worldview where the inter-relationships and their structures influence the systems that surround us (SANCHES, 2009).

Vennix (1996) argues that the hierarchical structure of the SD models consists of four levels: closed limits, feedback loops, stocks and flows; goals, observed conditions, discrepancies between goals and observed conditions, and desired actions.

The System Dynamics has two fundamental languages: causal diagrams and stock-flows (STERMAN, 2000). These two languages allow the modeler graphically represent the system being modeled and in addition are the basis for the construction of computational models that allowing to simulate different policies and scenarios (STERMAN, 2000; MORECROFT, 2007; SANCHES, 2009).

Differently of others simulation approaches addressed in this work, SD is a continuous modeling and simulation method. However, the method's main differential lies in its represent capacity non-linear relationships between the several system variables (STERMAN, 2000). This characteristic is extremely useful to understand patterns systems and its long-term behavior, front the adoption of different management polices and scenarios (LANE, 2000; MAYO e WICHMANN, 2003; MORECROFT e ROBINSON, 2005; NORTH e MACAL, 2007; SANCHES, 2009).

As consequence the SD models are aggregates and have high abstraction level (MAYO e WICHMANN, 2003; BORSCHCHEV e FILIPPOV, 2004). Thus, one of the method’s limitations is the representation detailed processes how discrete event processes or activities that have fixed duration time (NORTH e MACAL, 2007).

Mayo & Wichmann (2003) and North & Macal (2007) point another method's limitation is in their inability to model complex entities which possess characteristics of decision and heterogeneity.

2.3. Agent-based modeling

Agent-based Modeling and Simulation (ABMS) is a computational method widely used to understand and analyze systems composed of many interacting individuals (NORTH e MACAL, 2007; GILBERT, 2008).

Agent-based models are particularly suited to tackle situations and support the study and of topics like decentralized decision making, local-global interactions, self-organization, emergence and effects of heterogeneity in the simulated system (AXELROD e TESFATSION, 2006; BANDINI, MANZONI e VIZZARI, 2009).

According to North & Macal (2007) the basic principle of the ABMS is that the systems are larger than the simple sum of its components, in fact, the behavior of the system emerges from the interrelations between these several components. Each one of these components has their own set of rules and behaviors, which provides them the ability to affect greater or lesser degree the system’s global behavior (NORTH e MACAL, 2007).

In general, these components are called agents in the literature. Foner (1993), Rocha (1999) and Bandini et. al (2009) warn that the notion of agent is controversial, since the term agent has been used by different science areas.
Franklin and Graesser (1997) define agents as systems situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future.

According Gilbert (2008) agents are distinct parts of a computer program that are used to represent social actors as individual people, organizations such as firms, or bodies such as nation-states.

North & Macal (2007) define agents as decision-making components in complex adaptive systems, an agent is an individual who has a set of attributes and behaviors. According the authors agent behavior are the heart of ABMS and the others model element, agent environments and data, are only addressed to set a stage for the agent activities.

According Wooldridge & Jennings (1995) agents are conventionally described as having four important features:

- autonomy: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state;
- social ability: agents interact with other agents (and possibly humans) via some kind of agent-communication language;
- reactivity: agents perceive the environment (which may be the physical world, a user via a graphical user interface, a collection of other agents, the Internet, or perhaps all of these combined), and respond in a timely fashion to changes that occur in it;
- pro-activeness: agents do not simply act in response to their environment, they are able to exhibit goal-directed behavior by taking initiative.

Gilbert (2008) defines environment as the simulated space where an agent is found including the physical elements and other agents. According Bandini et. al (2009) in the specific context of simulation the environment is typically responsible for:

- reflecting/reifying/managing the structure of the physical/social arrangement of the overall system;
- embedding, supporting regulated access to objects and parts of the system that are not modeled as agents;
- supporting agent perception and situated action;
- maintaining internal dynamics;
- defining/enforcing rules.

Unlike other paradigms or modeling methods discussed, many of the key concepts ABMS lack a universal definition as reported (JENNINGS, SYCARA e WOOLDRIDGE, 1998; SCHIERITZ e MILLING, 2003; BORSHCHEV e FILIPPOV, 2004). For the authors this deficiency occurs in function of the diversity of science areas that use the concept of agent.

Despite its importance, Jennings, Sycara and Wooldrige (1998) argue that this definition lack does not represent a serious obstacle to progress in technique. Axelrod (2006) sees in this diversity one of the strengths of ABMS, since it allows researchers to study problems that exceed the arbitrary boundaries between their disciplines. And the author presents the following arguments in favor of this perspective:

- ABMS can address certain problems that are fundamental to many disciplines;
ABMS facilitates interdisciplinary collaboration;
ABMS provides a useful multidisciplinary tool when the math is intractable;
ABMS can reveal unity across disciplines;

Bonabeau (2002) identifies three benefits of ABMS over other modeling techniques. The first benefit is the ability to capture emergent phenomena. The emergent phenomena have the characteristic that make them difficult to understand and predict, many times them can be counterintuitive.

The other benefit indentifies by the author is the ability to provide a natural description of the system. ABMS makes the model seem closer to reality (BONABEAU, 2002). For example, it is more natural to describe how shoppers move in a supermarket than to come up with the equations that govern the dynamics of the density of shoppers.

And finally, the third benefit is the modeling flexibility, ABMS also provides a natural framework for tuning the complexity of the agents: behavior, degree of rationality, ability to learn and evolve, and rules of interactions (BONABEAU, 2002). Another dimension of flexibility point by the author is the ability to change levels of description and aggregation.

Like the other methods ABMS has some limitations and drawbacks. The lack of consensus definitions, already discussed above, can provide a serious impediment to the method's adoption and development. One consequence of this limitation is reflected in the ABMS tools. Many of them are not user friendly. This feature was very important for the popularization of the two other methods discussed.

Other limitation is point by Axelrod (2006), according the author ABMS is hard to sell. Since most formal theorists equate models with mathematical models, it is not surprising that some of them are hard to convince about the appropriateness and value of an agent-based simulation (AXELROD, 2006).

Other important method's drawback is the high computational requirements of ABMS when it comes to modeling large systems (BONABEAU, 2002). ABMS looks at a system not at the aggregate level but at the level of its constituent units and simulating the behavior of all units can be extremely computation intensive and therefore time consuming (BONABEAU, 2002).

### 2.4. Comparative Analysis Summary

The considerations presented above are summarized in table 2 presented below. It is possible identify the main differences between the methods and the integration opportunities. These opportunities are strongly connected the methods' limitations and weaknesses.

<table>
<thead>
<tr>
<th>Perspective</th>
<th>DES</th>
<th>SD</th>
<th>ABMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>top-down</td>
<td>top-down</td>
<td>bottom-up</td>
</tr>
<tr>
<td>Level of modeling</td>
<td>detailed, micro</td>
<td>aggregate, macro</td>
<td>all levels</td>
</tr>
<tr>
<td>Main building</td>
<td>process</td>
<td>feedback loop and stock-flows</td>
<td>individual agent</td>
</tr>
<tr>
<td>Origin of</td>
<td>events and random process</td>
<td>levels and delays</td>
<td>events</td>
</tr>
<tr>
<td>dynamics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit of analysis</td>
<td>process</td>
<td>structure of system</td>
<td>Individual rules and</td>
</tr>
</tbody>
</table>
Table 2 – Main differences between the methods

<table>
<thead>
<tr>
<th>Structure of system</th>
<th>fixed</th>
<th>fixed</th>
<th>behaviors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handing of time</td>
<td>discrete</td>
<td>continuous</td>
<td>not fixed</td>
</tr>
<tr>
<td>Mathematical formulation</td>
<td>probability distributions</td>
<td>integral equations</td>
<td>discrete or continuous</td>
</tr>
<tr>
<td>When to use</td>
<td>to simulate systems that can be naturally described how process and having elements of variability and uncertainty</td>
<td>to understand patterns of transition from the system and its long-term behavior</td>
<td>to simulate systems that have emergent behavior, composed of interacting agents.</td>
</tr>
<tr>
<td>Main drawbacks and limitations</td>
<td>difficulty of model complex processes with multiple decision making levels and inability to capture changes in the structure of the system</td>
<td>inability to model detailed processes and complex entities</td>
<td>lack of consensus definitions, many of tools are not user friendly, hard to sell, high computational requirements to modeling large systems</td>
</tr>
</tbody>
</table>

For example, it is possible get a better understanding of system states, transient and regime, through the combined use of SD and DES. Processes that have complex or heterogeneous entities can be modeled through combination of DES and ABMS. In the next section some examples of these benefits will be presented.

3. Integrated use

To illustrate the benefits of an integrated approach two practical applications are presented in a summarized way. One application illustrates the integrated use of DES and SD methods in operations management of one amusement park. In the second practical application, SD and ABMS methods are combined to model a supply chain.

3.1. Operations management in one Brazilian amusement park

Loureiro (2009) proposed the integrated use of methods of Discrete Event Simulation and System Dynamics to describe and evaluate the dynamics of the processes of managing a service operation of one amusement park.

The DES method was employed to modeling the various systems to provide services offered by the amusement park, such as the rides, the food court, the ticket booths and turnstiles that can be naturally described as processes.

Already the SD method was adopted to model the long-term behavior of the park consumer market. The focus of this model was to examine the reaction of the amusement park consumer market in consequence of marketing and operational management policies adopted by amusement park managers.

To integrate the two models developed two different approaches were taken. The first approach was transforming the value of daily demand generated by the SD model in a distribution function of visitors’ arrival in the amusement park throughout the day. This function is based on the probability frequency of visitors’ arrivals and was determined through the process of collect and data analyze of DES method. The second approach was based on
the performance model of transport systems proposed by Lima (2004), the figure 4 shows this model.

![Figure 4 - Performance of transport systems including the dimensions of quality and sustainability](image)


The functions of service, customer satisfaction and resources have been adapted to express appropriate performance measures to the amusement park. Thus it was possible to determine the visitors' satisfaction level, the congestion rate of the park and operating costs involved. These values represent outputs of DES model which were used as inputs of the SD model. Figure 5 illustrates the process of integration of models.

![Figure 5 – Integration between DES and SD models](image)

Source: Loureiro (2009)

The operation of this integrated model was made through the analysis of scenarios where different management policies have combined with changes in the amusement park operating parameters. Three policies were proposed: investment in marketing, seasonal opening and increase the capacity. Moreover, it was evaluated scenarios where the system's daily demand equaled the system's maximum capacity.
The model allowed evaluating and verifying the effectiveness of proposed policies and their effects on system performance. Another advantage of this method lies in its ability to identify the component of DES model more sensitive to a change in management policies. This feature can help the decision on investments to increase capacity or changes in the system. Moreover, the proposed integrated model is not without drawbacks or limitations. It was found that the time consuming for the model running increased considerably. Another disadvantage lies in the complexity DES model developed that required the insertion of multiple decision points depending on the characteristics of the modeled entities.

One possible solution for these two problems would be the adoption of the ABMS method for modeling the services offered by the amusement park, since this method could describe more naturally the peculiarities of the system in question.

Ahmadi (1997) to corroborate this view, according to the author the amusement parks have four characteristics that affect the analysis and management of its operations. The first, the service package offered is not homogeneous, since the experience of visiting a park can include, for example, rides, games, shows, food and beverages. Second, the non-uniformity of customer preferences, customers can be segmented into different groups. Third, the significant variation in the attendance level in the park which depending on season, week day and day time. Fourth, the customer perception about the service, for example, delays, failures and queues.

3.1. Emergent structures in supply chains

The integrated use of ABMS and SD methods in supply chains is not new. Schieritz & Größler (2003) proposed a integrative approach where the supply chain was modeled with two levels of aggregation. Figure 6 shows the model proposed.

![Figure 6 – Macro and micro level of supply chain](source)

The macro level shows a network of agents that are potential supply chain participants where every link between two agents can be interpreted as a potential customer-supplier-relationship (SCHIERITZ e GRÖßLER, 2003). The SD method is used to model the agents’ schemata that represent the internal structure of an agent - the micro level.

The model proposed by Schieritz & Größler (2003) uses this framework to evaluate the effects of different order policies over on the configuration of the supply chain.
The results obtained by the authors showed that the use integrated of methods helped to overcome some individual limitations. In a system dynamics model the supply chain structure has to be determined before starting the simulation what represents a limitation of this method, using ABMS the supply chain structure can be model as an emergent system that resulting from the decisions of their agents which is much closer to what occurs in reality.

4. Conclusions

We have presented a comparative analysis of three modeling and simulations methods: Discrete Event Simulation (DES), System Dynamics (SD), Modeling and Agent-based Modeling and Simulation (ABMS). The results of this comparative analysis showed the individual benefits and limitations for each method and indicated some potential benefits of integrated use.

To illustrate these benefits, two practical applications were presented and discussed. One application illustrated the integrated use of DES and SD methods in operations management of one Brazilian amusement park and the second practical application showed a combination of SD and ABMS methods to model emergent structures in supply chains

The results of these two practical applications prove the benefits found on comparative analysis. However, some drawbacks also were identified. The modeling of some systems and the methods' integration can become very complex. Another limitation identified is the increased time required to run the model.

Apart these drawbacks, the integrated use of these methods opens the possibility to exploring old and new problems through a new perspective that can promote better solutions to real-world problems. We suggest the application of this strategy to problems involving complex systems with multiple levels of aggregation as supply chains, service operations, urban distribution problems, social networks, etc.

5. References


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