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A Comparison of DES and SD for Simulating Construction Operation

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Abstract: Different simulation methods and related software systems are used to model construction operations, such as Discrete Event Simulation (DES), System Dynamics (SD), Agent-Based Modeling (ABM), and Hybrid Simulation. After the introduction of the simulation methodology CYCLONE, which is more suited to model cyclic and repetitive operations, DES was adopted to address such limitations and has been used for over three decades to model a wide range of construction operations. SD has been recently introduced to augment the capabilities of DES. This paper focuses primarily on presenting qualitative comparison between DES and SD simulation methods from three perspectives: 1) system structure; 2) problem nature; and 3) simulation method. The study has identified ten potential aspects for comparison and pointed out the strength and weakness of each method. Six criteria selected form the conducted comparison, depicting the heterogeneous nature of construction projects, are found to cover most aspects of modeling construction operations using simulation. Selection of the appropriate simulation method is then performed based on those criteria. An example of earthmoving project is presented to show how the developed criteria can be applied. The findings of the study are expected to provide those involved in simulation with criteria-driven process for selecting the most appropriate simulation method for their respective operations.

1 Introduction

Decisions in construction projects are made at two levels: 1) strategic and 2) operational (Lyneis et al. 2001). The strategic definition in this paper is different from the definition pertaining to organizational management. The strategic level means achieving the project set objectives within the project strategic frame. This involves adjustment of certain parameters like cost, resource, and time to meet prior set goals (Rodrigues and Bowers 1996). On the other hand, the operational level is viewed here as the actions taken to meet the project goals set at the strategic level. It focuses on the daily operational details at the micro level of the project. The operational level is discrete in nature and one of its major disadvantages is the inability to function without communicating with project strategic targets. In this paper, two terms are used extensively, system and subsystem. System means the whole construction project (construction operations) while the subsystem means operation or process within the construction project.

Computer simulation is an excellent tool used to represent both management levels of construction operations. It assists in developing simulation models in the virtual world that mimics the real system. This valuable decision support tool allows studying system behavior and resources interactions to reach better planning. Through simulation, managers can have an insight into the resources' interactions and identify the influential elements in the system. Different scenarios of construction operation planning and execution can be experimented with and evaluated before commencement of real construction. Such experimentation would be costly and risky if executed in the real world. Many simulation techniques and philosophies exist, and being used to develop simulation models in different fields, such as DES, SD ABM, hybrid simulation, etc. Nevertheless, DES and SD are the most dominating simulation methods used over three decades in simulating construction operations with DES having greater advantage in term of applications over SD. DES enjoys a wide range of applications in construction simulation (Halpin 1977; Paulson 1987, Martinez and Ioannaou 1999; Hajjar and AboRizk 2002; Marzouk and Moselhi 2003). The successful application of DES method in construction operations simulation is mainly attributed to the fitting of the DES philosophy into the characteristic of construction operation elements at the tactical level, yet, DES focuses only on one side of the construction operation aspects (tactical) (Alzraiee et al. 2012b). SD is another simulation method developed to understand the system behavior (e.g., construction project) over time while considering interactions of system's variables. It models the system elements of a predefined boundary as one unit, and then monitors the interactions of those elements over the simulation time. One important feature of SD is its strong capabilities of modeling the causal and effect relationships that exist among the system variables. These feedback loops are significant in understanding the system and assist in identifying the problematic loops. SD was used to simulate construction projects (Ogunlana et al. 2003; Ford et al. 2004); however, it is used on a limited scale. Similar to DES, SD focuses only on one side of the construction operation (strategic). Adoption of any of the methods separately to simulation construction operations is less satisfactory to produce realistic models, since the construction systems, are of heterogeneous nature, which requires more than one simulation method.

The need to study and compare those two simulation methods arises from the increasing use of simulation tools in modeling complex construction systems. Simulation models play vital rule in achieving project objectives. The challenging question is on the process of selecting the appropriate simulation method/s. One of the main shortcomings of the current practice that challenges the modeler in simulating construction operations is the unclear procedures of analysis and absence of selection process between DES and SD methods. This paper presents a method to analyze construction operation elements that requires the application of simulation tool from three perspectives. The paper also presents common criteria to select the appropriate simulation method. The paper presents an overview of the main characteristics of construction systems that are candidate for simulation modeling. Then, it discusses and compares the DES and the SD techniques and their respective philosophies.

2 Characteristics of Construction Projects

Construction projects are of heterogeneous nature and having diverse characteristics. Using simulation tool in construction field requires the modeler to deal with: 1) decision level; 2) system complexity; 3) type of variable; and 4) relationship among variables (Alzraiee et al. 2012a). Selecting the appropriate simulation method starts by understanding the characteristics of the system being modeled. As demonstrated in Figure 1, a typical construction project system involves strategic and operational decisions taken at different management levels. This involves dealing with discrete and continuous variables too. The relationships among those variables are in a form of cause-effect relationships. In the following subsections, the paper discusses those characteristics that are essential for the development of realistic simulation models.

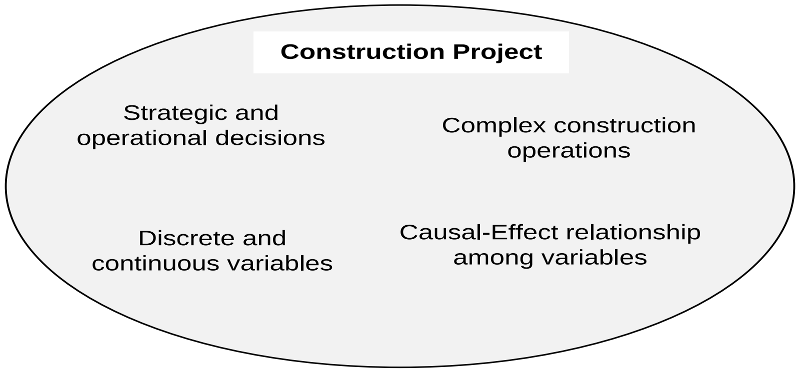

Figure 1: Construction Project Main Modeling Elements

2.1 Management Levels

The management science has classified the management decisions as strategic and operational (Schultz et al. 1987). Strategic decisions focus on determining the goals and the policies while the operational decisions focus on the practical execution of the strategic goals and policies. The current practice of simulation deals with these two levels separately. The interactions among the variables of the two levels are not captured using one simulation method. It is necessary for the modeler to analyze and understand the differences between those two decision levels ahead of the simulation formalization stage. Table 1 summarizes the main differences between those two levels. It can be perceived from the comparison shown in the table that both levels are different in all aspects, and mobilizing the appropriate simulation tool requires consideration of the two levels presented in Table 1.

Table1: Comparison between Strategic and Operational Management Levels (Adapted from Schultz et al. 1987)

Viewpoint	**Strategic**	**Operational**
Level	Macro	Micro
Assessment	Subjective	Objective
Nature of the problem	Unsaturated, one at a time	More saturated and repetitive
Information Needed	Small amount of specific information	Large amount of information
Planning Horizon	Long-term, but varies with problem	Short-term and more constant
Frame	Covers entire scope of project	Concern with only sub-project units
Level of detail	Broad and general	Narrow and problem specific
Evaluation	Difficult, because of generality	Easier, because of specificity
Perspective	Holistic and continuous	Reductionism and discrete
Focus	Strategic/Context	Operational

2.2 Discrete and Continuous Variables

Construction operations comprise of discrete and continuous variables. Usually, simulation tool deals with those two variables. In the simulation environment, continuous variables update their states at time points in time intervals while discrete variables update their states based on occurrence of events. The interactions between those variables are inevitable, and system behavior is mainly mapped based on that interactions. The relationship between the discrete and continuous variables is clearly depicted in Pritsker (1995) principals. For instance, a continuous variable that crosses a specified threshold values may cause an event to occur. This event is the warning light for actions to be taken to correct the situation and return the variable to its earlier state. Those actions may be of discrete nature. As a result, the discrete action induced to correct the change in the state of the continuous variables may change the function describing the continuous variable. This kind of interaction exists in construction operations and greatly influences the outcomes of the operation.

2.3 Interactions of construction Elements

Construction operations are of heterogeneous nature. Diverse external and internal factors influence the behavior of construction systems. The system behavior is mainly generated based on the interactions of the variables among each other in a form of causal-effect relationships and with external influential factors. Nevertheless, modeling and simulating all these aspects in integrative manner is a major challenge and of immense necessity in the same time to generate the real behavior of system in the virtual world. Simulating construction system based on fragmented approach is still dominant. Outcome of such models have failed to draw a clear picture of the real system behavior, and to present models capable of being used as base for enhancing the system understating.

2.4 Holistic Vs Fragmented

Construction operations can be simulated using two simulation philosophies that are holistic or fragmented. The holistic philosophy considers the whole elements of the system and tries to understand how system evolves. The holistic approach can utilize single simulation method (e.g.,SD) or a hybrid of simulation methods. The fragmented philosophy as the case with DES, considers one side of the system that regarded to be a representative to the whole system, and tries to simulate it (e.g. earthmoving operation is simulated with isolation from all surrounding factors). This approach usually requires detailed data and deals with issues of tactical nature. With the increasing of construction operations complexity, and the needs to enhance the certainty of projects in term of cost and time, more focus is needed to have a holistic approach that capable of accounting for tactical issues too. Recently, the research in construction simulation modeling efforts, have focused on exploring tools that are capable of setting a main framework (e.g., strategic) and then after, allowing elements of the construction project to interact within a previously predefined framework of goals. This evolution in simulation of construction operations has been adapted mostly from the fields of enterprise and manufacturing, and has proven to be successful in producing simulation models that emulating the real system behavior.

3 Simulation Methods: technique and philosophy

Different simulation methods developed to serve different purposes. The focus of this paper is mainly on studying the DES and SD simulation methods. The discrete and continuous variables are usually simulated using DES and SD respectively. Every method has its own strengths, weaknesses, and capabilities. In the following sub-sections, the paper presents in short the theory of each method.

3.1 DES

DES is widely established simulation method with applications in different fields. Essentially, the DES is a stochastic simulation technique better suited to queuing network systems. The DES model is composed of a collection of entities that act and interact together through flows in the system (Law and Kelton 2000). Such models are composed of a network of activities, resources and queues, through which entities flow with states update occurring when events take place usually at discrete points of time. Its computations are based on a list of events filled once every individual future event is scheduled and is depleted by firing elapsed events.

3.2 SD

The basic principle of SD is that the behavior of a system over time is defined by its structure (Forrester 1961). The powerful of SD method lies in the causal-effect loops that map the relationships among its variables. Those loops are the main source of dynamics behavior observed in the system, in addition, SD focuses on the systematic interactions of flows, inter-dependencies, and delays (Sterman 2000). SD is an elaboration to the continuous simulation with stress on system complexity and nonlinearity of feedbacks process. It is an approach to solve problems at top management level (Forrester 1975; Sterman 2000; Lyneis 2001). Two common forms of notations exist in SD, Causal Loop Diagrams that capture the conceptual relationships in the system, and Stocks-Flows diagram that describes the movement of entities from start to end of the process.

Rodrigues and Bowers (1996) and Sterman (2000) summarized the motivation to apply the SD modeling method in project management as follow:

1- The need to consider the whole project rather than sum of individual elements.
2- The need to examine non-linear scenarios described by balancing and reinforcing feedback loops.
3- System of highly dynamic
4- Involving both “soft” and “hard” data
5- The needs for experimenting the project behavior by applying different hypothetical scenarios, and
6- The failure of the traditional analytical tools (DES) to solve parts of the project management problems.

4 Comparison between DES and SD Methods

As stated earlier in the management levels section, the construction problem characteristics usually dictate using a combination of the simulation methods. Merely, examining the problem from one perspective can be misleading. Comparison between DES and SD were presented by Sweetser (1999), Lane (2000), Brailsford & Hilton (2000), Rabelo et al. (2005) as demonstrated in Table 2. The comparison between DES and SD found in literature is carried out from three viewpoints: 1) model development; 2) simulation method; and 3) model use.

Studying and analyzing of the DES and SD characteristics have pointed out that selection of the appropriate simulation method requires studying other aspects that influence the outcomes of the simulation model. Such as: 1) Defining problem that is more suited to simulation; 2) studying and analyzing the structure of the system; and 3) mapping the characteristics of simulation tools to those pertinent to the above two issues. Thus, it is necessary when embarking upon a need for developing sound simulation model, three perspectives should be examined to decide on which appropriate simulation method to rely on. The three perspectives are as follow:

1- System Structure (SS)
2- Problem Nature (PN)
3- Simulation Method (SM)

4.1 System Structure

System can be discrete, continuous, or combination of both. A preliminary step for system understanding starts with defining the system boundary. System has many interactions among its components. For instance, construction projects involve a substantial number of variables such as weather, change orders, labor skill, fatigue, etc, that influence the outcome of a model. Thus, it is necessary to define the system boundary that influences its behavior. The model boundary defines what variables should be included and what variables should be excluded. As to simulation methods, it can be notice that SD models involve process of variables classification into endogenous, exogenous, and excluded while DES models attempt to make approximation to context variables of the operation and consider them of no influence. The problem with construction project simulation is the surrounding environment that greatly influences the outcomes of the operations being modeled.

4.2 Problem Nature

The nature of operation being modeled has the upper hand in deciding on which simulation method is more suitable. The problem under simulation is somehow connected to the objectives of the simulation model. Addressing the problem means achieving those specified objectives. Many question arise when defining the problem, such as, is the problem spectrum, strategic impact on operation level or vice versa?, or is the operation context is more important?. Such questions are indispensible to frame out the simulation model as the mapping between variables depends on this stage. Framing the model problem is helpful to specify the boundary of the model and exclude unnecessary elements that are not of high influence and can make the model expensive to compute and hard to understand.

4.3 Simulation Method

Every simulation method designed to fit certain circumstances. Few researches have proven that one simulation method can replace another with giving similar results. Han et al. (2005), has developed a compatible SD simulation model to simple DES earthmoving operation model. The SD model generated results similar to that of DES. However, the SD model turned to be complex in structure for the small DES model. To what extend replacement of one method by another can be true to simulate complex problems as in construction projects has not been proved yet. Therefore, every simulation method can serve certain simulation aspects in system. For instance, SD takes a holistic approach of the main system and tends to integrate the subsystems. It focuses on policies, and uses feedback loops in the form of causal-effects relationship among system elements. Through reflecting these features on the characteristics of construction operation system, it can be said that those feature can serve specific areas in the system and limited in capturing other areas such as the lower level of the operation where entities, activities, and queues exist. These limitations bring us to the philosophy of DES, as stated earlier DES models systems as a network of queues and activities where state change occur at discrete points of time.

In summary, based on the literature and the differences between the DES and SD presented in Table 2, it is obvious that DES and SD are developed for different purposes and none is suitable to substitute another. One important note is that, impediments associated with DES are generally related to the upper level of the decision-making process and to the global aspects while impediments associated with SD are generally related to the lower level of the decision-making process. Therefore, it can be concluded that limitations associated with DES can be overcome by using SD and vice versa.

Table 2: Comparison between DES and SD Simulation Methods

Aspect of Comparison	**Category**	**DES**	**SD**	**Author(s)**
Problem scope	Problem Nature	Tactical operational	Strategic	(Sweetser 1999; Lane 2000; Rabelo et al. 2005)
Feedback effects	System Structure	Models open loop structures	Models causal relationships and feedback effects.	(Coyle 1985; Sweetser 1999; Brailsford and Hilton 2001)
System representation	System Structure	Analytic view	Holistic view	(Baines et al. 1998; Lane 2000; Rabelo et al. 2005)
Complexity	System Structure	Narrow and focus on complexity and details	Wider focus, general and abstract system	(Lane 2000)
Data type	System Structure	Quantitative	Qualitative	(Sweetser 1999; Brailsford and Hilton 2001)
Randomness		Random variables (Statistical distribution)	More deterministic	(Meadows 1980)

Validation	Simulation Method	Black-box approach	White-box approach	(Lane 2000)
Model Results	Simulation Method	Provide a statistically valid estimates of system performance	Provide a full picture, qualitative and quantitative of system performance	(Meadows 1980; Mak 1993)
State change	Simulation Method	At discrete points in time	Continuous	(Morecroft and Robinson 2005; Rabelo et al. 2005; Han 2008)
Level of model complexity	Problem Nature	Increases exponentially	Increases linearly	(Morecroft and Robinson 2005)
Modeling Elements A type	Simulation Method	Queue (unit)	Stocks (Unit)	Alzraiee et al. 2012b
Modeling Elements B type	Simulation Method	COMBI and NORM (Unit/Time)	Flows (Unit/Time)	Alzraiee et al. 2012b

5 Criteria for Selecting Simulation Method

The previous discussion paves the way on how to select the appropriate simulation method. The paper proposes six criteria for the selection process. Those six criteria are expected to be sufficient enough to classify any system or subsystem under the appropriate simulation method that should be used. The characteristics of each subsystem are assessed against:

- **Problem Scope and Focus -Operational or Strategic**
  It refers to scope and focus of the subsystem. If it has detailed data, focus on daily operation activities and complex in nature then they are consistent with DES. Subsystem with less details, address strategic level and highly abstract is more consistent with SD.

- **View-Reductionism or Holistic**
  Subsystem that promotes individuality with reductionism characteristics is consistent with DES while subsystem that concerns with global, homogeneity and holistic views is consistent with SD.

- **Data Nature-Quantitative or Qualitative**
  Subsystem of quantitative data nature, is better simulated using DES while subsystem of qualitative data nature is better simulated using SD.

- **State Change-Discrete or Continuous**
  Subsystem variables that tends to update states at discrete time points are better simulated using DES while subsystem variables that tends to update their states at equal time intervals is better simulated using SD.

- **Level of Details-Narrow or Broad**
  It refers to the available information about subsystem being modeled. Subsystem of narrow, numerous and focused information are more consistent with DES, generally such systems are stochastic. Subsystem of broad information with high level of abstraction are consistent with SD.

- **Level of Model Complexity-Increase Exponentially or Linearly**
  If complexity of subsystem tends to increase exponentially then it is more consistent with DES. When complexity of model subsystem tends to increase linearly then it is consistent with SD.

5.1 Illustrative Example

In order to show how the developed criteria can be applied on construction projects that require applying the simulation tool, the following earthmoving operations project is considered. The project involved moving earth from one location to another (earth dam construction site). During planning stage, the management has determined a productivity level (m^3/hr) of the fleet. The execution schedule was tight, and an allowable schedule pressure at any time point in the project was selected not to exceed 30% (schedule pressure equal to estimated time required to finish project divided by available time in the project schedule). Other aspects such as change in scope and overtime strategy were involved in the planning stage. The actual execution of the work involved processes such as loading off-highway trucks with earth, dumping, spreading, and compacting of earth. Precise simulation of this case should focus on the management policies (strategic decisions) as well as the execution process (operational).

Now, in order to model and simulate this project, the simulation model must consider those identified policies and processes. The entire project is decomposed into modeling elements (processes or polices). For instance, loading process is a modeling element arises from operational level, weather condition is a modeling element arises from the surrounding environment, and scope change is a modeling element arises from management policy. Those elements together generate the project near-real behavior, and any successful simulation model should include all the influential modeling elements. Table 3 presents an example of how any construction project can be decomposed into modeling elements. The table shows a selected short list of the processes/polices involved in the earthmoving project for purpose of illustrating how the criteria can be applied to select the appropriate simulation method. Each process or policy is tested against the developed criteria. For example, the *loading process* is tested against the six criteria. The characteristics of this process can be summarized as: (1) focuses on the execution level (operational), (2) narrow in perspective, (3) data are quantitative, (4) state change at discrete time points, (5) wide data details and (6) behaves exponentially. These characteristics of the modeling elements (*loading process*) coincided with the philosophy of DES method. Therefore, it is appropriate to model and simulate it using DES method. On the other hand, productivity policy such as *planned productivity,* is characterized by (1)strategic level emergent, (2) affect entire project holistic, (3) involve qualitative data, (4) state change at continuous time interval (continuous behavior), (5) narrow details and (6) linear in behavior. Thus, it is appropriate to model and simulate it using SD method.

Table 3: Decomposition of Earthmoving Project into Elements

	Criteria												
	Scope		**View**		**Data Nature**		**State Change**		**Level of Details**		**Complexity**		
Process/Policy	Strategic/ Policy	Operational	Holistic	Reductionism	Qualitative	Quantitative	Continuous	Discrete	Broad	Narrow	Linear	Exponential	Simulation Methodology
Loading	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	DES
Schedule deadline pressure	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	SD
Planned productivity	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	SD
Dumping	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	DES
Soil spreading	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	DES
Soil compaction	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	DES
change in	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	SD

Scope												
overtime	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	SD

6 Conclusion

The paper has presented an insight on the decision-making levels, project characteristics, and simulation methods. Understating issues arising from the interactions of strategic and the operation decision levels is important requirement for developing useful simulation models and assist in selecting the appropriate simulation method. Modeling and simulating construction operations should deal with modeling elements that influence construction operations' outcomes, such as variables' interactions, causal-effect relationships, and level of complexities. The comparison between DES and SD simulation methods is conducted based on those elements and from three perspectives: 1) system structure; 2) problem nature; and 3) simulation methodology. Developing simulation models through analysis of the three mentioned perspectives, provides a platform for insight understating and better designing of these models.

The modeler should accomplish the understating of the system nature that requires deployment of the simulation tool, it is a precondition to have good simulation model. This main requirement is less likely to receive attention as the modelers keep using the same simulation method with different systems that might require the use of other simulation methods. The model boundary (problem) is the second important step that can only be accomplished after understating the system. System boundary can be viewed, as the boundary of variables where the simulation model can be effective. Boundary definition of the system assists in identifying the relationships among the variables and the type of interactions. The third is to understand the interactions among variables and identify the positive and negative loops. These three elements (understanding of system, boundary definition, and interactions of variables) should be considered before starting to choose among simulation methods. Thereafter, simulation techniques and philosophies of the different simulation methods can be projected on the three elements to see which one is the most appropriate or which combination of methods can fit the operation being simulated. Six criteria (Scope, view, data nature, state, data quantity, and complexity), from the three comparison perspectives, provide simple and easy to use tool to select suitable simulation methods.

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