A Comparison of System Dynamics (SD) and Discrete Event Simulation (DES)

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System Dynamics modeling and Discrete Event Simulation both can be used to model corporate business decisions. However, there seems to be little dialog between the two communities of modelers. For instance, at the recent WinterSim simulation conference in Washington, DC, there were no presentations of System Dynamics models. Discussions held by the author with a number of practitioners in each field show that there is a general lack of appreciation of the strengths of each methodology. This paper provides a summary and comparison of the two approaches. The thrust of the paper is that the capabilities of each methodology uniquely suit them to different types of problems. The challenge to the modeler is to pick the tool most appropriate to the problem at hand.

Overview.
System dynamics (SD) offers a methodology to assist businesses and government organizations in strategy development, analysis of policy options, and analysis of dynamic processes where capturing information flow and feedback are important considerations. An SD model captures the factors affecting the behavior of the system in a causal-loop diagram. This diagram clearly depicts the linkages and feedback loops among the elements in the system, as well as all pertinent linkages between the system and its operating environment. This type of analysis can be valuable to a decision-maker as an aid in understanding a complex, inter-related system. To extend a decision-maker's understanding, SD simulation software lets a decision-maker adjust parameters of a system, add new linkages and feedback loops, or rearrange components of the system. The decision-maker can thus model a variety of scenarios and observe how the system might perform under different conditions.

While SD has some unique terms and concepts, it is similar in many respects to discrete event simulation (DES), another widely used analytical tool. A good DES model can replicate the performance of an existing system very closely and provide a decision-maker insights into how that system might perform if modified, or how a completely new system might perform. To achieve this fidelity to the performance of a real world process, a DES model requires accurate data on how the system operated in the past, or accurate estimates on the operating characteristics of a proposed system. DES models can represent a system in a computer animation that can provide a decision-maker an excellent overview of how a process operates, where backlogs and queues form, and how proposed improvements to the system might alter the system's performance. Like SD, DES also gives the decision-maker the capability to model and compare the performance of a system over a range of alternatives.

DES has capabilities that make it more appropriate to the detailed analysis of a specific, well-defined system or linear process, such as a production line or call center. These systems change at specific points in time: resources fail, operators take breaks, shifts change, and so forth. DES can provide statistically valid estimates of performance measures associated with these systems, such as number of entities waiting in a particular queue or the longest waiting time a particular customer might experience.

SD is well suited to modeling continuous processes, systems where behavior changes in a non-linear fashion, and systems where extensive feedback occurs within the system. As a matter of practice, SD is often used in strategic policy analysis. DES can also be used to model strategic issues, as well as non-linear relationships, feedback loops, and continuous systems. However, as a matter of practice, these issues are less commonly modeled. Whether an SD or DES approach is better at these issues is probably more a function of the particular situation being modeled and the needs and interests of the decision-maker, than the particular capability of either approach.

SD models often incorporate “fuzzy” qualitative aspects of behavior that, while difficult to quantify, might significantly affect the performance of a system. SD modelers, in practice, are comfortable than DES modelers with incorporating “best guesses” and expert opinion into their models. They tend to evaluate their models on the face validity of the model’s output, and whether the model provides the user an increased understanding of the system.

Some decision-makers might have a personal preference for the particular product associated with each approach. SD causal loop diagrams are an effective way of portraying feedback and linkages within a system. However, animation associated with a running SD simulation model is usually limited to updating graphs and numerical displays. Discrete event simulations include graphs and numerical displays, as well as a computer animation of the system. In these animations, icons represent entities moving through a graphical representation of the system. The process flow and on-screen movement in a DES animation can be a valuable tool in providing increased understanding of a process. However linkages and feedback may not be as explicit, or if there is very much of either, the animation may become very difficult to follow.

Definitions.

System dynamics (SD) is an approach to problem solving initially developed by Jay Forrester at MIT in the early 1960s. In the terminology of system dynamics, a ***system*** is defined as a collection of elements that continually interact over time to form a unified whole. ***Dynamics*** refers to change over time. ***System dynamics*** is, therefore, a methodology used to understand how systems change over time.

In one of the leading texts on discrete event simulation (DES), Law and Kelton define a system similarly as a collection of entities that interact together toward the accomplishment of some logical end.[i] DES, “concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time.”[ii] Therefore, like system dynamics, DES is used to gain an understanding of how an existing system behaves, and how it might behave if changes are made in the system.

Fine differences in these definitions point out some of the key distinctions between the two methodologies. SD is more focused on the analysis of systems. DES, in practice, more often models particular processes, not entire systems. Additionally, SD models continuous processes, and is less well suited to modeling discrete changes in systems. DES can model continuous systems, as well as mixed discrete and continuous processes, but is best suited to modeling discrete processes. Other distinctions between these methodologies will be discussed in the context of key SD concepts.

Key System Dynamics concepts and their relationship to Discrete Event Simulation.

Structure determines performance.

In SD, the components and relationships among the components of a system are called the ***structure*** of the system. A fundamental notion of system dynamics is that structure determines performance. With a clear understanding of the linkages between people, organizations, processes, and resources, the structure of a system can be optimized to improve performance. As part of this approach, the methodology attempts to make the important links between the objects in a system explicit. These links are modeled by feedback loops, where a change in one variable affects other variables in the system. This flow of information produces changes in the way the system performs over time. These changes are what make SD models "dynamic."

There's nothing in the literature of DES to indicate any disagreement on this approach. DES methodology is a disciplined means of capturing the structure of an existing or proposed system. However, the emphasis on structure in SD methodology, in practice, represents a subtler distinction. SD models frequently include "soft" variables, which may be difficult to empirically quantify. Identifying the system's structure is paramount, even if some components of the model rely on anecdotal data and the best estimates of subject matter experts. In the SD view, structure is paramount in determining system performance. In contrast, the creation of a DES model typically reflects a great investment of time in data analysis and distribution fitting to ensure the model is statistically valid. In DES, structure is important, but accurate historical data or estimates of future performance are required to populate the model and produce statistically valid results.

Mental models.

Another key concept in system dynamics is the importance of "mental models." Each person in a firm that interacts with a particular process carries a mental model of that process in his or her head. These mental models have been characterized as flexible, rich in information, and able to integrate data from a diverse array of sources. The emphasis on defining mental models is important because of the "fuzzy" types of systems of interest to SD modelers. Each person tends to view these systems in his or her own unique fashion.

A major part of the SD modeling effort is therefore associated with capturing these mental models a causal loop diagram that represents the system. The people attempting to improve a process or system map it explicitly by sharing their mental models. This mapping incorporates each person's insights and may also identify the inconsistencies or fallacies of a particular individual's mental model. Firms often reap an immediate benefit from the system dynamics modeling process simply in reaching a group consensus on the process or system map.

Instead of a causal loop diagram, DES models are often built from a process map, or flow chart. These process maps can also assist firms by clarifying important processes and relationships. The important distinction is that SD more often models abstract, general systems, such as a market for a particular good. Getting a group of experts to agree on a causal loop diagram of such a system is rarely easy. DES models, in contrast, typically have a narrower focus, such as modeling a production line or a call center. In these instances, process maps are just as important, but the systems under study tend to be easier to define.

Systems orientation.

SD models attempt to capture all of the aspects of process within a closed system. The variables are therefore "endogenous" or contained within the system represented by an SD model. The effect of feedback within the system plays a significant role in the values of the model's parameters over time. Feedback loops are explicitly displayed in the model's causal loop diagram. Because of the importance of modeling feedback, SD software packages make the incorporation of feedback loops a "point and click" process.

Although there are certainly exceptions, DES models more often reflect systems where entities are processed in a linear fashion. Feedback plays less of a role in these systems. DES modelers often invest a great deal of effort analyzing historical data to capture process means, variances, and distributions, but once entered into the model these parameters often remain fixed. There is less emphasis in DES models on identifying events that might trigger changes in the model's parameters. Feedback loops can, of course, be built into discrete event simulations, however, their presence is less common than in SD models.

The role of computer simulation.

Both SD and DES routinely employ computer simulation. In SD, model building is an iterative process involving the model builder and the people who routinely work with the system under study. They begin by identifying the basic structure and relationships within the system (often referred to as "stocks" and "flows"), and then assign functions and numerical values to these relationships. Once the group has reached some agreement that the system under study has been adequately described in a causal loop diagram, a computer simulation is run of the model to see if the output reflects the group's intuitive understanding of the system. The model is then iteratively revised and re-run until the group feels comfortable that the important elements of the system are captured and the model's output reflects their view of reality. The computer model helps to provide an increased understanding of how the system's performance depends on its structure. This part of system dynamics is much like discrete event simulation.

Once the system under study is appropriately captured in a computer simulation, that simulation can then be developed into a management "flight simulator." These are learning laboratories that permit managers to run the system dynamics model in a gaming environment. Well-crafted management flight simulators can be an effective tool to help managers gain insight into a firm's business operations via "learner directed learning." These simulators also help new managers quickly gain an appreciation of the firm's business environment. Some management flight simulators include aspects of artificial intelligence or expert systems by incorporating software agents that learn and adapt to the user to more realistically simulate real-life situations.

Computer simulations of DES models can serve the same purposes. However, DES models are less used as training tools for non-technical managers, and more the domain of simulation experts. Proper analysis of DES output requires some statistical background, and this may explain why it is less used as a training tool.

Differences also exist in the underlying mathematics that drive the software package appropriate to each approach. SD models the behavior of systems using differential equations. Because of the nature of these mathematical functions, SD is well suited to modeling continuous systems. For instance, SD software can easily model the flow of fluids in a water treatment plant, or perform strategic analysis, where the model user is more interested in overall system performance rather than the finite behavior of a particular process within the system. SD is less well suited to providing a detailed representation of a system where there are discrete changes in state variables, or mixed systems of both discrete and continuous processes. For instance, an SD model cannot easily model inter-arrival rates of discrete entities in a system. In contrast, DES models use a simulation clock that advances time in fixed increments or advances time to the next scheduled event on a simulation calendar. Discrete changes in system parameters are easily modeled. Therefore, a discrete event simulation would provide more reliable estimates of backlogs that might occur in an assembly line, or of the longest waiting time experienced by particular customers of a firm.

Validity.

SD proponents would argue that usefulness in the user's eyes is the appropriate standard by which to evaluate these models. One of the chief benefits claimed from system dynamics models is the increased understanding they provide of the system being modeled. The fact that a group of senior managers, for instance, shares insights and reaches a collective understanding of the firm's operating environment is valuable for its own sake.

Many writers on system dynamics shy away from holding their models to a strict standard of statistical predictive validity. A possible explanation for this restraint lies in the fact that system dynamics models could be characterized as a collective "best guess" based on a particular group's understanding of a system at a certain point in time. Additionally, since the real systems the models represent are inherently dynamic, changes in the real system could quickly outdate the model. Additionally, human behavior often plays an important role in system dynamics models and this is inherently more difficult to quantify

Discrete event simulations, in contrast, have a stronger empirical basis because they usually model concrete, observable processes. DES models usually reflect extensive analysis of historical data. When detailed historical data does not exist, assumptions are highlighted and vetted with the model's users. However, this approach opens the methodology to the criticism that DES models can become "prisoners of the past." As factors affecting the behavior of the system change over time, the ability of DES models to predict behavior declines.

A Comparison of SD and DES models of a production process.
Figures 1 and 2 highlight some of the similarities and differences of the two approaches. Both diagrams represent models of a production process. The SD model (figure 1) is a causal loop diagram. The DES model (figure 2) is a process flow model of the same process. The models are different because the two methodologies are, in practice, used for different purposes.

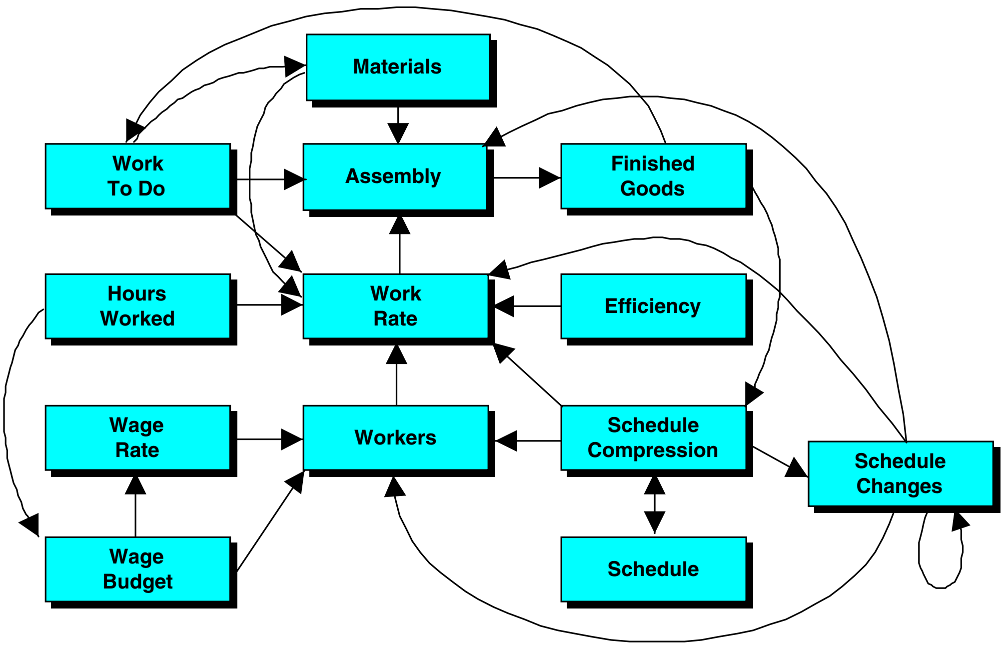

Figure 1. SD diagram of a production process.

In the SD representation, Work to do, Assembly, and Work Complete represent the essence of the production process. The other elements of the diagram show depict the numerous factors that influence work rate, as well as a myriad of other relationships important to the overall system. For instance, schedule compression, schedule changes, and worker efficiency might have a negative effect on productivity. Additionally, schedule pressure, delay and disruption, and the wage budget may have a negative effect of the labor force. The intensity of these feedback loops and the speed with which feedback affects the operating parameters of the system could all significantly influence the line's overall productivity. Overall, the system dynamics model of the work process is a rich, highly interdependent model that identifies a number of physical and human characteristics that all affect the overall flow of work through the system.

This model is excellent at capturing the behavioral and qualitative relationships within the structure of a system. The effect of schedule compression on worker productivity and the firm's ability to hire and retain workers are undoubtedly important considerations to the managers of that process. Yet these factors defy precise measurement. It may be difficult and indeed impossible, to empirically verify the strength and intensity of some of the feedback loops depicted without an enormous amount of research. SD modelers, in practice, are comfortable making educated guesses or obtaining estimates from experienced managers who are knowledgeable in the process. In the SD view, the fact that these relationships may be difficult to quantify does not diminish their importance in understanding the system and predicting its behavior.

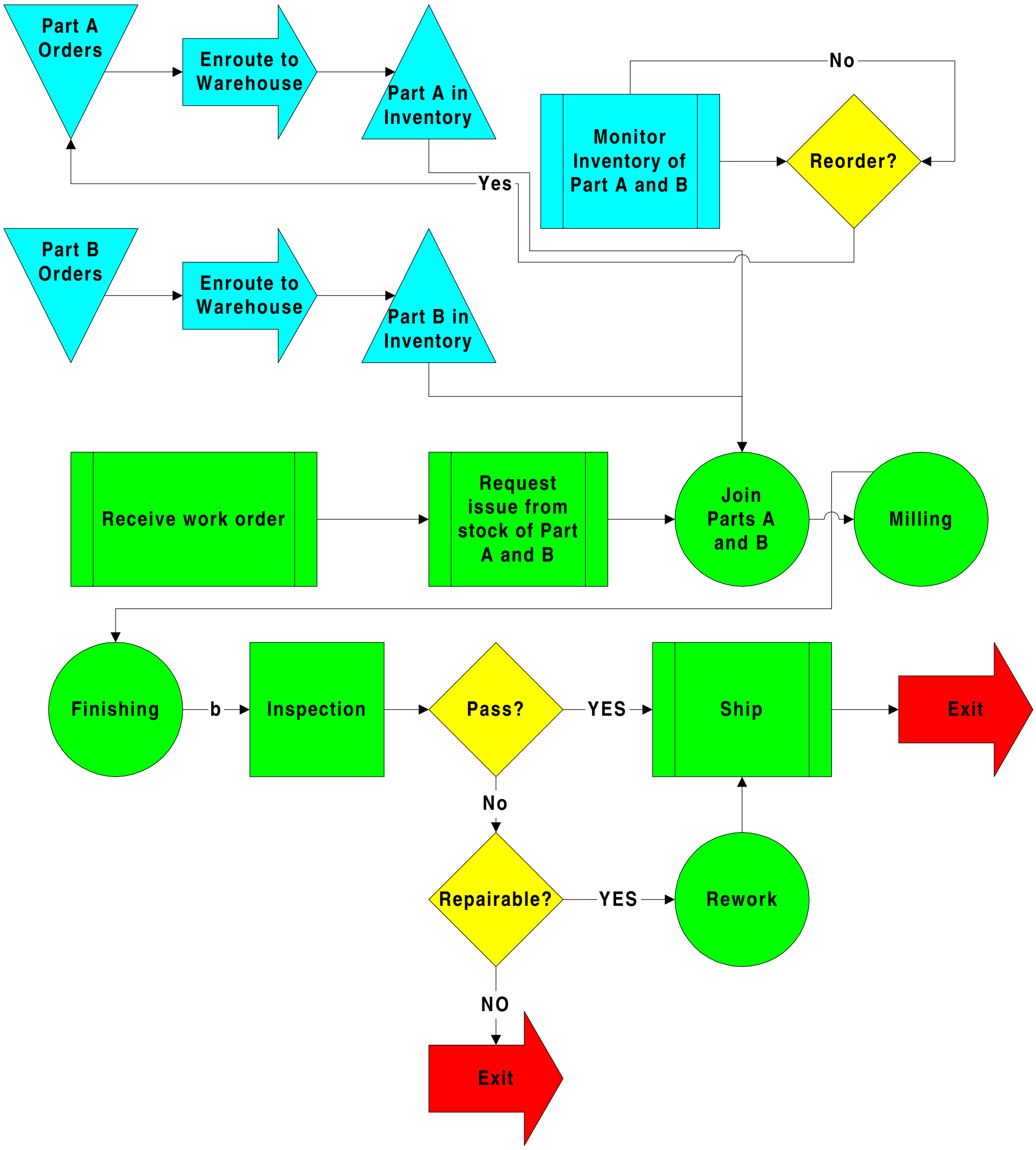

Figure 2. DES diagram of a production process.

In contrast, a DES representation of the same system would typically focus on observable and measurable aspects of production (figure 2). The process has a clear beginning, and ending. Entities move through the system in a linear fashion. There are no feedback loops. While the same factors that affect productivity can be built into the DES model, these factors are typically not included. Instead, the

DES model reflects a detailed analysis of historical data on the the system's behavior. In the absence of historical data, data from the performance of similar systems might be used. The effect of factors present in the SD model, but omitted in the DES model, is captured in the statistical distributions associated with each process included in the DES representation.

The two different diagrams reflect the profoundly different approach of each methodology. To the extent the factors present in the SD model produce dynamic changes over time, the DES approach may be misleading to a decision-maker. However, the DES model will produce a statistically valid representation of the historical behavior of the system under study. Using this as a starting point, the DES model could then be updated with new information are changes in the system occur or are anticipated.

Summary.

In deciding which approach is best suited to model a particular problem, the key questions are which type of model best represents the system under study, what questions does the decision-maker wish to address, and for what purpose will the model be used. System dynamics methodology is best suited to problems associated with continuous processes where feedback significantly affects the behavior of a system, producing dynamic changes in system behavior. DES models, in contrast, are better at providing a detailed analysis of systems involving linear processes and modeling discrete changes in system behavior. DES models are used when the goal is a statistically valid estimate of system performance. SD is more often the tool of choice for a training vehicle. There is certainly a large area of overlap between the two approaches. Many problems could be modeled with either approach and produce results that would look very similar. Both methods, used appropriately, can help provide increased understanding and serve as an aid to decision-making.

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[i] Law, Averill M., and Kelton, W. David. Simulation Modeling and Analysis (1991:McGraw-Hill, Inc. New York). p. 1.

[ii] Ibid. p. 7.