Simulation in Composites Manufacturing

Charles Harrell and A. Brent Strong
Brigham Young University
Provo, UT

The Problem of complexity

Don't you just hate the feeling of being in a situation that is just beyond (or sometimes way beyond) your understanding? That feeling might happen when something goes wrong with your computer or, perhaps with the electronics in your car. It might also happen when your boss gives you a change in your work assignment. Perhaps it happens just by contemplating the world that surrounds us. Those feelings of uncertainty and tension are often caused by the complexity of the situation; and that complexity seems to be increasing at an alarming rate. This article is about coping with and simplifying complexity. In particular, the kind of complexity that has arisen in manufacturing, often because of the need to simultaneously satisfy so many requirements. The complexity that arises because we are involved in the manufacture and use of a highly complex material–composites: a material made from multiple components that is chosen because it can be tailored to meet specific needs. With that tailoring, we get added complexity.

Planning and managing today's manufacturing systems pose nearly insurmountable challenges for manufacturers. Often competing objectives (cost, throughput, cycle-time, etc.) must be met while satisfying multiple constraints (budgets, schedules, technology, etc.). Furthermore, the manufacturer must deal with numerous interdependent variables that all seem critical for proper operation: number of resources, routings, product mix, schedules, etc. Assuming, for example, that you have five jobs that can be performed on five different machines, you have 120 (5!) different ways in which the jobs can be produced—and this is a simple situation. Something clearly needs to be done to help the manufacturer deal with this complexity.

Simulation as an answer to complexity

Simulation has proven to be an effective tool in helping to sort through the complex issues surrounding manufacturing decisions. Kochan (1986) notes that, in manufacturing,

> The possible permutations and combinations of workpieces, tools, pallets, transport vehicles, transport routes, operations, etc., and their resulting performance, are almost endless. Computer simulation has become an absolute necessity in the design of practical systems, and the trend toward broadening its capabilities is continuing as systems move to encompass more and more of the factory.

As manufacturers face increasingly more complex decision making for improving the entire supply chain, simulation will continue to be an essential tool for effectively planning production and delivery processes.

World-class manufacturers (hopefully some of us) not only have clearly defined goals and objectives, but they know what it takes to achieve these goals. This requires a thorough understanding of and control over the cause-and-effect relationships of different production decisions (what Deming calls “profound knowledge”). In even the smallest manufacturing systems success requires understanding how the system operates, knowing what you want to achieve with the system, and being able to identify key leverage points for best achieving desired objectives. To illustrate the nature of the manufacturing challenge, consider the following scenario:

> ABS Pipe Co. is a manufacturer of a highly specialized type of filament wound pipe and is able to sell its finished products for nearly ten times the cost of the raw materials. What’s more, the company enjoys virtually unlimited demand for its product so the sky is the limit. In the manufacturing process the raw materials are combined using a proprietary process, are wound onto a mandrel, are then heated and cured into pipe. The pipe is then stenciled with labels and stacked and bundled for shipping. The secondary operations are performed off-line. The process sequence is shown in Figure 1.
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> Due to various inefficiencies, the system is able to run only about 60 percent of its theoretical capacity, costing the company millions of dollars a year in lost revenue. In an effort to improve manufacturing productivity, management studied each step in the process. It was fairly easy to find the slowest step in the line, but additional study showed that only a small percentage of lost production was due to problems at this “bottleneck” operation. Sometimes a step upstream from the bottleneck would have a problem, causing the bottleneck to run out of work, or a downstream operation such as the strapping machine would go down temporarily, causing work to back up and stop the bottleneck. Sometimes the bottleneck would get so far behind that there was no place to put incoming, newly made pipe. In this case the workers would stop the entire pipe-making process until the bottleneck was able to catch up. Often the bottleneck would then be idle waiting until the curing oven heated up and was functioning properly again and the new pipe had a chance to reach it. Sometimes problems at the bottleneck were actually caused by improper work at a previous location.
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> In short, there is no single cause for the poor productivity seen at this plant. Rather several separate causes all contribute to the problem in complex ways. Management is at a loss to know which of several possible improvements (additional or faster capacity at the bottleneck operation, additional storage space between stations, better rules for when to shut down and start up the filament winder, better quality control, or better training at certain critical operations) would have the most impact for the least cost. Yet the poor performance of the system is costing enormous amounts of money. Management is under pressure to do something, but what should it be?

This example illustrates the nature and difficulty of the decisions that an manufacturer. Manufacturers must make decisions that are the “best” in some sense. To do so, however, requires that they have clearly defined goals and understand the system well enough to identify cause-and-effect relationships.

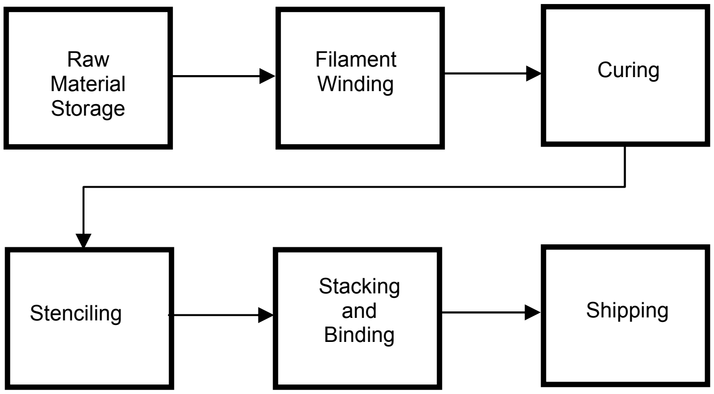
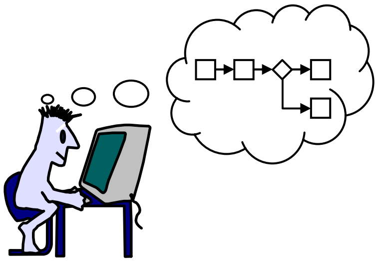


Figure 1. Process Flow for ABS Pipe Co.

Problems of this complexity are best solved using computer simulation. A natural reaction to the thought of using simulation is “Uh-oh, it sounds too difficult.” **No one wants to use a tool that is more difficult to use than the problem for which it is intended to solve**. Today, however, simulation tools are easier than ever and in a matter of minutes a system like ABS Pipe Co. can be modeled and analyzed. Not surprisingly, most of the effort in simulation is gathering data and preparing presentations. However, the amount of this detail needed is not too great and the effort required to find prepare for the simulation is valuable in understanding the process.

The Oxford American Dictionary (1980) defines simulation as a way “to reproduce the conditions of a situation, as by means of a model, for study or testing or training, etc.” Simulation is typically conducted using a computer program and helps evaluate and improve a process or system. Simulation in composites manufacturing is typcially performed on one of two levels: (1) process simulation, and (2) system simulation. Each of these two levels of simulation is summarized here.



Simulation mimics a process or system using a computer model in order to evaluate and improve performance.

Process Simulation

Process simulation is used to analyze what happens to material and tooling under a defined set of conditions. A filament winding process, for example, might be modeled to simulate pressure forces on the mandrel or the pattern of fiber laydown. Process simulation for some processes, such as plastic injection molding, has been conducted for years. Mold filling, cooling, and warpage analyses are very powerful in providing diagnostics and troubleshooting quality problems for understanding the injection molding process and its effect on part properties.

Software is available to model process control and performance characteristics for a number of different processes and can be useful for determining machine settings, including some parts of the filament winding process. Users can enter information on part design and quality requirements, and the software interprets simulation results to come up with suggested machine set-up conditions. For injection molding these include cooling times and profiles for temperatures, ram velocities, and injection and holding pressures. For filament winding these include the speeds of the payoff device, the turning of the mandrel (thus giving the angle of laydown), the number of fibers in the bundle (to give the width of the laydown), and the number of wraps at each angle.

The benefits of process simulation have been significant, enabling process engineers and molders to quickly optimize machine set-up, reduce cycle times, and monitor and correct the various machine processes during production.

System Simulation

When it comes to analyzing and improving the entire production process, we must turn to system simulation. System simulation is becoming increasingly recognized as a quick and effective way to design and improve the operational performance of manufacturing systems. For a comprehensive treatment of the use of simulation technology for improving manufacturing systems see Harrell, et al. 2004.

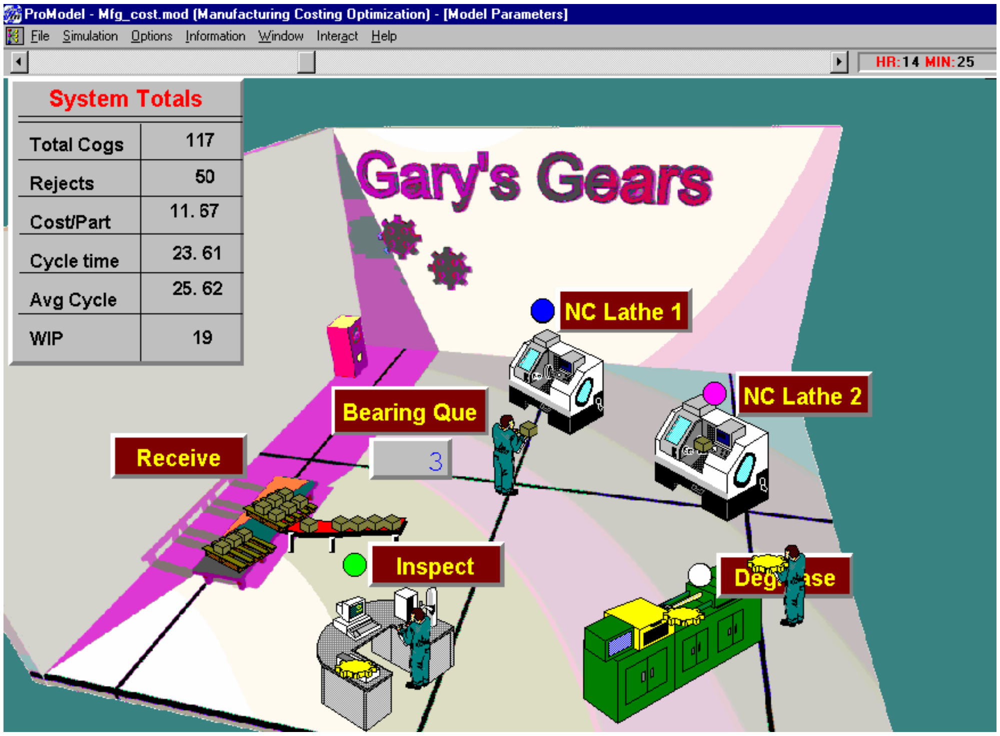
To anaylze a manufacturing system, one of the following methods might be chosen:

- Construct a simple flow chart,
- Develop a spreadsheet model, or
- Build a computer simulation model.

The choice depends on the complexity of the system and desired precision in the answer. Flow charts and spreadsheet models are fine for modeling very simple processes with little or no interdependencies or variability. However, what is seemingly a simple process might be quite complex because of interations that are often overlooked unless we consciously are forced to think about the details and subtleties of the process. Hence, a computer simulation is often used even for seemingly simple systems and is always needed for any complex and for understanding interactions of the system over time.

This type of dynamic simulation has been defined by Schriber (1987) as “the modeling of a process or system in such a way that the model mimics the response of the actual system to events that take place over time.” Thus by studying the behavior of the dynamic model, we can gain insights about the behavior of the actual system.

In practice, manufacturing simulation is performed using commercial simulation software such as ProModel or ProcessSimulator that have modeling building block (called modeling constructs) that are specifically designed for easy entry of data that describe the dynamic behavior of systems. Using the modeling constructs available, the user builds a model that captures the processing logic (that is, why each step follows after another) and the constraints of the system being studied. As the model is “run,” performance statistics are gathered and automatically summarized for analysis. Modern simulation software provides a realistic, graphical animation of the system being modeled to better visualize how the system behaves under different conditions.



System Totals	
Total Cogs	117
Rejects	50
Cost/Part	11.67
Cycle time	23.61
Avg Cycle	25.62
WIP	19

Figure 4. System Simulation Typically Includes Animation (http://www.promodel.com)

During the simulation, the user can interactively adjust the animation speed and even make changes to model parameter values to do “what if” analysis on the fly. State-of-the-art simulation technology even provides optimization capability—not that simulation itself optimizes, but scenarios that satisfy defined feasibility constraints can be automatically run and analyzed using special goal-seeking algorithms.

Because simulation accounts for interdependencies and variability, it provides insights into the complex dynamics of a system that are unobtainable using other analysis techniques. Simulation gives manufacturers unlimited freedom to try out different ideas for improvement, risk free—with virtually no cost, no waste of time, and no disruption to the current system. Furthermore, the results are both visual and quantitative with performance statistics reported on all measures of interest.

The procedure for doing simulation follows the scientific method of (1) formulating a hypothesis, (2) setting up an experiment, (3) testing the hypothesis through experimentation, and (4) drawing conclusions about the validity of the hypothesis. In simulation, we formulate a hypothesis about what design or operating policies work best. We then set up an experiment in the form of a simulation model to test the hypothesis. With the model, we conduct multiple replications of the experiment or simulation. Finally, we analyze the simulation results and draw conclusions about our hypothesis. If our hypothesis was correct, we can confidently move ahead in making the design or operational changes (assuming time and other implementation constraints are satisfied). As suggested in the figure of the Process of Simulation Experimentation, this process is repeated until we are satisfied with the results.

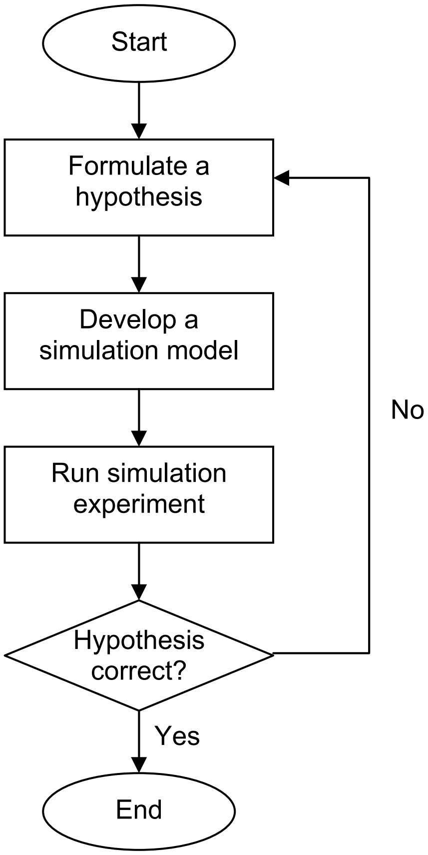


Figure 5. The Process of Simulation Experimentation.

Simulation is essentially an experimentation tool in which a computer model of a new or existing system is created for the purpose of conducting experiments. The model acts as a surrogate for the actual or real-world system. Knowledge gained from experimenting on the model can be transferred to the real system. Thus when we speak of doing simulation, we are talking about "the process of designing a model of a real system and conducting experiments with this model" (Shannon 1998).

Everyone is aware of the benefits flight simulators provide in training pilots before turning them loose in actual flight. Just as a flight simulator reduces the risk of making costly errors in actual flight, system simulation reduces the risk of having systems that operate inefficiently or that fail to meet minimum performance requirements. Rather than leave design decisions to chance, simulation provides a way to validate whether or not the best decisions are being made. Simulation avoids the time, expense, and disruption associated with traditional trial-and-error techniques.

Simulation Applications

Simulation has been applied successfully in a number of applications in the composites and plastics industries. All of the major manufacturers of filament winding machines provide simulation capabilities for laydown, overlap, and machine operation. Cave, et al. (2002) show how simulation was successfully applied to optimize the scheduling for a plastic rotational molding machine. Nembhard, et al. (1999) demonstrate the integration of real-time process control charting with simulation modeling to illustrate the effects and benefits of SPC charts for quality improvement efforts. Other typical applications of simulation include

- Work-flow planning
- Capacity planning
- Cycle time reduction
- Staff and resource planning
- Work prioritization
- Bottleneck analysis
- Quality improvement
- Cost reduction
- Inventory reduction
- Throughput analysis
- Productivity improvement
- Layout analysis
- Line balancing
- Batch size optimization
- Production scheduling
- Resource scheduling
- Maintenance scheduling
- Control system design

Many layout and improvement decisions in manufacturing are left to chance or are driven by the latest management fad with little knowledge of how much improvement will result or whether a decision will result in any improvement at all. For example, work-in-process (WIP) reduction that is espoused by lean manufacturing or just-in-time (JIT) advocates often results in a disruption of operations because it merely uncovers the inherent problems in the system. It is like finding the rocks (variability, long setups, etc.) hidden beneath the inventory water level that necessitated the WIP in the first place. To accurately predict the effect of lowering WIP levels requires being able to see below the surface of the water and understand the reasons for the rocks being there in the first place. Ideally you would like to identify and remove production rocks before arbitrarily lowering inventory levels and exposing production to these hidden problems. “Unfortunately,” note Hopp and Spearman (2001), “JIT, as described in the American literature, offers neither sonar (i.e., models that predict the effects of system changes) nor a sense of the relative economics of level reduction versus rock removal.”

Another popular manufacturing management technique is the theory of constraints (TOC). In this approach, a constraint or bottleneck is identified and a "best guess" solution is implemented, aimed at either eliminating that particular constraint or at least mitigating the effects of the constraint. The implemented solution is then evaluated and, if the impact was underestimated, another solution is attempted. As one manufacturing manager expressed, "Contraint-based management can't quantify investment justification or develop a remedial action plan" (Berdine 1993). It is merely a trial-and-error technique in which a best-guess solution is implemented with the hope that it works and doesn't mess something else up.

Simulation helps evaluate the performance of alternative designs and the effectiveness of alternative operating policies. A list of typical design and operational decisions for which simulation might be used in manufacturing includes the following:

Design Decisions

1. What type and quantity of machines, equipment, and tooling should be used?
2. How many operating personnel are needed?
3. What is the production capability (throughput rate) for a given configuration?
4. What type and size of material handling system should be used?
5. How large should buffer and storage areas be?
6. What is the best layout of the factory?
7. What automation controls work the best?
8. What is the optimum unit load size?
9. What methods and levels of automation work best?
10. How balanced is a production line?
11. Where are the bottlenecks (bottleneck analysis)?
12. What is the impact of machine downtime on production (reliability analysis)?
13. What is the effect of setup time on production?
14. Should storage be centralized or localized?
15. What is the effect of vehicle or conveyor speed on part flow?

Operational Decisions

1. What is the best way to schedule preventive maintenance?
2. How many shifts are required to meet production requirements?
3. What is the optimum production batch size?
4. What is the optimum sequence for producing a set of jobs?
5. What is the best way to allocate resources for a particular set of tasks?
6. What is the effect of a preventive maintenance policy as opposed to a corrective maintenance policy?
7. How much time does a particular job spend in a system (makespan or throughput time analysis)?
8. What is the best production control method (kanban, MRP, etc.) to use?

By using a computer to model a system before it is built or to test operating policies before they are actually implemented, many of the pitfalls that are often encountered in the start-up of a new system or the modification of an existing system can be avoided. Improvements that traditionally took months and even years of fine-tuning to achieve can be attained in a matter of hours. Because simulation runs in compressed time, weeks of system operation can be simulated in only a few minutes or even seconds.

Even if no problems to a system design are found through simulation, the exercise of developing a model is, in itself, beneficial in that it forces one to think through the operational details of the process. Simulation can work with inaccurate information, but it can't work with incomplete information. If you can't define how the system operates, you won't be able to simulate it. Often solutions present themselves simply by going through the model-building exercise—before any simulation run is made. System planners often gloss over the details of how a system will operate and then get tripped up during the implementation phase by all of the loose ends. The expression "the devil is in the details" has definite application to systems planning. Simulation forces decisions on critical details so they are not left to chance or to the last minute, when it may be too late.

Simulation Economics

Savings from simulation are realized by identifying and eliminating problems and inefficiencies that would have gone unnoticed until system implementation. Cost is also reduced by eliminating overdesign and removing excessive safety factors that are added when performance projections are uncertain. By identifying and eliminating unnecessary capital investments, and discovering and correcting operating inefficiencies, it is not uncommon for companies to report hundreds of thousands of dollars in savings on a single project through the use of simulation. The return on investment (ROI) for simulation often exceeds 1,000 percent, with payback periods frequently being only a few months or the time it takes to complete a simulation project.

The real savings from simulation come from allowing designers to make mistakes and work out design errors on the model rather than on the actual system. The concept of reducing costs through working out problems in the design phase rather than after a system has been implemented is best illustrated by the rule of tens. This principle states that the cost to correct a problem increases by a factor of 10 for every design stage through which it passes without being detected (see Figure 6).

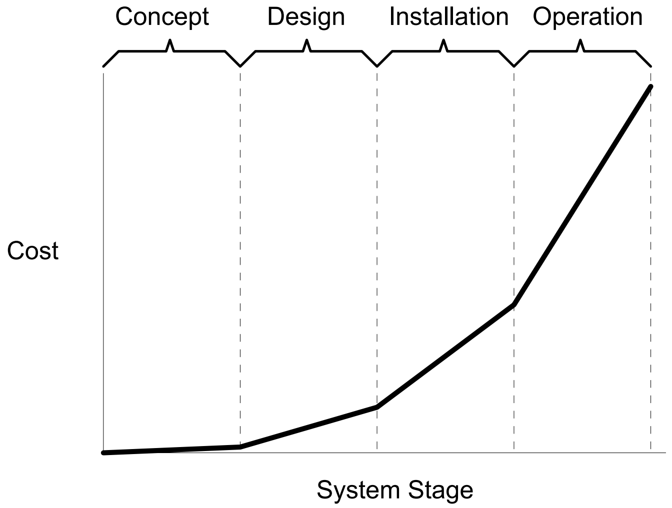


Figure 6. Cost of Making Changes at Each Stage of System Development.

Many examples can be cited to show how simulation has been used to avoid making costly errors in the start-up of a new system. One example of how simulation prevented an unnecessary expenditure occurred when a Fortune 500 company was designing a facility for producing and storing subassemblies and needed to determine the number of containers required for holding the subassemblies. It was initially felt that 3,000 containers were needed until a simulation study showed that throughput did not improve significantly when the number of containers was increased from 2,250 to 3,000. By purchasing 2,500 containers instead of 3,000, a savings of $528,375 was expected in the first year, with annual savings thereafter of over $200,000 due to the savings in floor space and storage resulting from having 750 fewer containers (Law and McComas 1988).

Even if dramatic savings are not realized each time a model is built, simulation at least inspires confidence that a particular system design is capable of meeting required performance objectives and thus minimizes the risk often associated with new start-ups. The economic benefits associated with instilling confidence was evidenced when an entrepreneur, who was attempting to secure bank financing to start a blanket factory, used a simulation model to show the feasibility of the proposed factory. Based on the processing times and equipment lists supplied by industry experts, the model showed that the output projections in the business planwere well within the capability of the proposed facility. Although unfamiliar with the blanket business, bank officials felt more secure in agreeing to support the venture (Bateman et al. 1997).

Often, simulation can help achieve improved productivity by exposing ways of making better use of existing assets. By looking at a system holistically, long-standing problems such as bottlenecks, redundancies, and inefficiencies that previously went unnoticed start to become more apparent and can be eliminated. “The trick is to find waste, or muda,” advises Shingo, “after all, the most damaging kind of waste is the waste we don’t recognize” (Shingo 1992). Consider the following actual examples where simulation helped uncover and eliminate wasteful practices:

- GE Nuclear Energy was seeking ways to improve productivity without investing large amounts of capital. Through the use of simulation, they were able to increase the output of highly specialized reactor parts by 80 percent. The cycle time required for production of each part was reduced by an average of 50 percent. These results were obtained by running a series of models, each one solving production problems highlighted by the previous model (Bateman et al. 1997).
- A large manufacturing company with stamping plants located throughout the world produced stamped aluminum and brass parts on order according to customer specifications. Each plant had from 20 to 50 stamping presses that were utilized anywhere from 20 to 85 percent. A simulation study was conducted to experiment with possible ways of increasing capacity utilization. As a result of the study, machine utilization improved from an average of 37 to 60 percent (Hancock, Dissen, and Merten 1977).

In each of these examples, significant productivity improvements were realized without the need for making major investments. The improvements came through finding ways to operate more efficiently and utilize existing resources more effectively. These capacity improvement opportunities were brought to light through the use of simulation.

Conclusion

Plastics producers, like other manufacturers, face the challenge of quickly designing and implementing production systems that are capable of meeting growing demands for quality, delivery, affordability, and service. Simulation provides an excellent way to help meet this challenge.

Simulation is a powerful technology that is being used with increasing frequency to improve system performance by providing a way to make better design and management decisions. When used properly, simulation can reduce the risks associated with starting up a new operation or making improvements to existing operations.

Because simulation accounts for interdependencies and variability, it provides insights that cannot be obtained any other way. Where important system decisions are being made of an operational nature, simulation is an invaluable decision making tool. Its usefulness increases as variability and interdependency increase and the importance of the decision becomes greater.

Lastly, simulation actually makes designing systems exciting! Not only can a designer try out new design concepts to see what works best, but the visualization makes it take on a realism that is like watching an actual system in operation. Through simulation, decision makers can play what-if games with a new system or modified process before it actually gets implemented. This engaging process stimulates creative thinking and results in good design decisions. So remember, if at first you don't succeed, you probably should have simulated it.

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