Systems Thinking for Manufacturing: Distributed, Multi-Disciplinary Simulations for Graduate Education

Dr. Heidi Hahn
Philip Kunsberg
Los Alamos National Laboratory*

This project summary first discusses the methodology employed, "distributed interactive simulation," then describes the architecture and some of the features of the project, and finally examines potential applications in graduate education.

Distributed Interactive Simulation

A "distributed" simulation is one composed of different modules that are resident on different computers. The top-level model consists of a number of integrated sub-models which exchange data. The sub-models are part of a functional whole; they are linked to each other by input and output parameters. A variable output by one sub-model is the input to one or more of the other sub-models, and vice-versa. Each sub-model depicts a separate facet of a complex system. This approach borrows conceptually from object-oriented programming, where each component is independent and "encapsulated" from the others, while exchanging data through a prescribed interface.

A distributed simulation may be limited to real-time interactions, such that all sub-models must be up and running at the same time in order for the top-level model to function properly, or the sub-models may be capable of running asynchronously. In the latter case, several users or "players" participating in the simulation can run their sub-models at different times and in different places, while data are integrated and results presented by a central server computer linked to each of the sub-models. This architecture permits participation via the Internet as well as via a Local Area Network (LAN).

One benefit of sub-dividing the top-level model into components is that it allows the depiction of different aspects or perspectives of the total system, each corresponding to a particular human role in the system. For example, in a business simulation, one sub-model might represent the perspective of the Chief Executive Officer while another represents the perspective of the Plant Manager. Each player receives only that information appropriate to his or her role, and similarly

* This paper draws upon work done jointly by the University of New Mexico (UNM) and the Los Alamos National Laboratory (LANL), under sponsorship of the US Advanced Research Project Agency. Prof. John Wood, Director of Manufacturing Engineering, led the UNM team, which included Prof. H. V. Ravinder, Prof. Joel Beer, and others. (See: http://www-mep.unm.edu/Paper97_TRP1221.html, for references, acknowledgments and additional details.) The LANL team, in addition to the authors, included Mr. Andy Andrews. The contributions of all participants are gratefully acknowledged.

exercises controls appropriate to that role. This provides realistic human involvement in the simulation, and moreover, it allows individual players to experiment with different roles, given them a better understanding of the "other person's" point of view and of the overall dynamics of the system.

The simulation can be "interactive" in two ways. First, it can allow the user to input variables or to change variables while the simulation is running, to view the results of these changes, and to continuously modify a control strategy in an effort to achieve identified goals. For example, in a business simulation, the goals might be to maximize profit, or to maximize return on investment, or to achieve market dominance, etc. The scenario for the simulation might prescribe goals for all players, or it may allow players to select their own goals and then measure their performance in terms of their declared goals. Second, the simulation can allow human-to-human interaction between the players, in addition to human-to-machine interactions. For example, the players may be grouped into teams, each representing a different company competing in a particular industry. The teams may communicate within themselves to form a business strategy, or they may communicate between teams, to conduct business negotiations, such as for the purchase of a factory or raw materials. The communication can take the form of face-to-face meetings or electronic message traffic, such as e-mail.

Distributed Interactive Simulation allows exploration of the full complexity of a human organization. The relationships and dynamics associated with multiple levels of human decision-making and with the different goals and perspectives of the various members of the organization can be realistically depicted in the model. While mechanistic components, such as an automated production process, may be optimized by computed algorithms, or by experimentation and inductive methods, the total simulation involving multiple human players is inherently unpredictable. As in "real life," an understanding and anticipation of the behavior of other players becomes a critical element of success. Ideally, the simulation provides both analytical and intuitive knowledge of a system which is far too complex and unpredictable to allow adequate description in a deterministic model.

Until recently, the use of distributed interactive simulations has been largely confined to military organizations because the resources required were prohibitive to other users. However, developments in personal computer technology have made this technique increasingly accessible. In particular, the developments in server technology, simulation software, object-oriented programming, and "visual" development environments, provide the tools to create distributed interactive simulations at relatively low cost, in terms of both time and money.

The UNM / LANL Project in Manufacturing

The University of New Mexico, Department of Mechanical Engineering, and the Los Alamos National Laboratory are collaborating on a project of this type. The goal of this project is to use distributed interactive simulation to depict a manufacturing industry, from the worldwide scale of multiple, international competitors, down to the individual factory, the individual production line, and, at the highest resolution, the individual production machine showing the dynamics of physical processes. The players in this simulation include: (1) an all-powerful "Moderator" who controls historical and macroeconimic events, such as wars and interest rates; (2) a Government Official, who controls national economic variables, such as taxes and tariffs; (3) a Chief Executive Officer, who heads an individual company that owns one or more factories in domestic or overseas locations; (4) a Factory Manager responsible for an individual plant; and (5) a Machine Operator, who controls the "sputtering process" in a vacuum chamber, which is a critical phase in production. The simulation can accommodate several competing companies, each of which would have, for example, a CEO, a Factory Manager, and a Machine Operator, working as a team.

For the research and development phase of this project, a sample manufacturing process was chosen for construction of detailed models. The end-product in this example is an advanced fuel cell envisioned to replace the batteries in cellular telephones. A start-up company in Los Alamos, New Mexico, which is developing this technology, provided technical data and other information necessary to construct a detailed and realistic model, called the "Battery Factory." *

This scenario was chosen because it has elements typical of the electronics industry, allows the use of real data, such as actual raw material prices, and promises to hold the interest of students more than an abstract, "generic" factory model. It also allows students to explore the simulation's potential for problem-solving in a real-life context. For example, students can model and assess the productivity and cost impact of purchasing automation equipment to substitute for hand operations.

The key element of the fuel cell is an electrode configured on a plastic membrane. The fabrication of the electrode is done by lamination of several layers of conducting metals on the plastic membrane by means of a "sputtering" process. Sputtering takes place in a vacuum chamber where an ion beam vaporizes a piece of solid metal atom-by-atom and deposits a thin film of the metal on the plastic surface. A stencil is used to give the metal film a desired configuration. This process is frequently used in the manufacture of solid state electrical components.

The vacuum chamber operations are depicted in greater detail in a separate sub-model, which can run on a separate platform controlled by a different individual (the "Machine Operator"). The Vacuum Chamber Model examines the physical processes taking place inside the chamber, such as heat exchange, rate of vaporization, current fluctuations, etc. The Vacuum Chamber Model requires continued vigilance by the Operator to reduce the occurrence of several possible

* Both information and expert advice for this model were freely provided by Robert Hockaday, President, Energy Related Devices, Los Alamos, New Mexico. His contribution was an important asset for this project.

failures in the machine operation, including loss of vacuum, "meltdown" of the material being processed, and a mis-feed of the material spooling into the vacuum chamber.

The player who assumes the role of Factory Manager makes decisions that affect both the production rate and the cost efficiency of the Factory. Specifically, the Factory Manager decides when to order raw materials and what inventory levels to maintain; the Manager determines the number of workers assigned to various phases of the manufacturing process, as well as the operating hours per day, when defect rates need to be counteracted, etc. He or she can control the training period for new workers, trading-off increased labor costs for improved worker efficiency. The basic goal is to optimize production in terms of greatest weekly output and lowest average cost per item, given the Company's current business objectives.

The Factory Manager may receive operating instructions or production goals from the Company's Chief Executive Officer. The CEO may shift the emphasis toward higher production rate or lower cost depending upon current and foreseen market conditions. The CEO's decision context is influenced by the regulatory framework set by the Government Official, including tax rates and tariffs imposed on imported materials. In addition, by actions of the Moderator, global economic conditions may change in the course of the simulation and directly affect both the CEO's and the Factory Manager's respective decision framework. The prices of raw materials may change, or the cost of labor, or the mandatory surcharge for overtime pay. The Factory Manager must interact dynamically with the simulation in the context of changing conditions, unpredictable events, and direct intervention by the CEO.

Applications in Education

We have only begun to explore the full potential of this type of interactive simulation as a tool for education. The emphasis on human interactions and relationships (instead of deterministic algorithms), joined with the reach of the Internet, opens up possibilities for new concepts in collaborative learning that are not limited by time or place. As an example, the UNM / LANL project provides multiple opportunities for learning about manufacturing processes, for improving business management, and for focused problem-solving in the manufacturing industry, as follows:

The simulation focuses on **the human dimension** of a manufacturing enterprise. While mechanical processes are included, they are placed in the context of human intervention at all levels. This provides a more complete and realistic setting for understanding business dynamics.

The model explores the full depth and breadth of the system in which a manufacturing enterprises operates, from the physical-process level, to assembly-line, to single-facility management, to company management, to a global, international perspective. Each level can be represented by a different "player" in a distributed simulation. This framework encourages **multi-dimensional, "systems thinking."**

The model encourages exploration of **business objectives**, instead of prescribing a set of rules for "winning" the game. Criteria for winning, such as Return on Investment, Cumulative Profit, or Market Dominance, can be set by consensus among the players, or, alternatively, individual players can choose their own goals and evaluate their success in terms of their declared objectives. They can also explore the industry-wide consequences under various scenarios where companies, either with identical or different start-up capabilities, have chosen different business objectives.

The model provides experience in dealing with **information overload**, time-constrained decision making, and inundation by complexity. The interactions of human and mechanical processes at multiple levels is too complex for a complete analytic understanding. Thus, the simulation develops the ability of students or business managers to acquire intuitive understanding of a complex system, to selectively attend to information and events on a priority basis, and to make timely decisions in a situation with constrained opportunities for analysis.

The simulation lends itself to **multi-disciplinary participation**: the Factory Manager might be a student in manufacturing engineering; the Chief Executive Officer from the business school; the Government Official from the political science department, etc. The interaction of these different perspectives should provide a rich learning environment. The use of the simulation should be accompanied by extensive de-briefing of participants to explore the interaction of different and perhaps conflicting approaches, perspectives, and goals.

The simulation teaches **team-building and teamwork** within an enterprise by requiring cooperative interactions between the Chief Executive Officer and the Factory Manager, for example. At the same time, the simulation reveals the dynamics of conflicting goals and perspectives within a team, and the problems associated with limited communication.

The important problems associated with information access are depicted in the simulation. The communication links and information access of each player depend upon that individual's role and situation in the enterprise. The degree of communication within a team also depends on personal initiative in sending messages. A scenario can also include face-to-face meetings as appropriate, or strategy and planning sessions within a team. These activities can build **communication skills** for the business environment.

The **case study method**, using a prototype manufacturing process for an innovative electronics product, presents a real-life scenario on a manageable scale. Students can discover inefficiencies in the prototype and explore re-design alternatives.

The simulation can also be used as an **assessment tool** to measure students' abilities and knowledge associated with the use of modeling as a method of analysis. While these measures may not correlate directly with real-world business management skills, they do represent an increasingly important set of analytical skills that will be required in the business environment.

The model affords a variety of opportunities for **learning to build simulations**. Several relatively easy "add-on" or "plug-in" modules are suggested by the scenario. Students can acquire skills in computer simulation and analysis by building and testing these modules.