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April 1996

# An Interactive Simulation of a Manufacturing Enterprise: Preliminary Observations

The Advanced Research Projects Agency has sponsored a partnership between the Los Alamos National Laboratory and the University of New Mexico to develop a dynamic systems model of a manufacturing process. The main goals are to design a computer model that can be used in graduate education of students in business and engineering, and that can also serve as a analytical and planning tool for managers in the US manufacturing sector. A central feature is the use of interactive simulation, where key decision-makers each control dynamically linked sub-models. The promotes a better understanding of the human dimension of complex systems and allows exploration of both teaming and competitive scenarios. At the time of this writing, we are somewhere near the midway point of this project, but we have already drawn some important lessons, at least from our perspective, about the utility and the proper sphere for system dynamics modeling.

First, the reality to be depicted is infinitely more complex than any model we can design. It is always possible to point out something that has been left out. If we decide to model individual fabrication machines on the factory floor, at a time scale of minutes or even seconds, we could be faulted for omitting details about the mechanical systems internal to the machines. If we attempt to model the stress factors affecting the labor force, such as overtime hours, rest breaks, etc., we could be faulted for ignoring a host of other factors, such as lighting conditions, noise level, or morale programs. Of course all cognitive processes are inherently selective, but the process of building a computer model compels the author to attend in detail to this selectivity and presumably to adopt a reasoned approach to carrying it out. So, in this project, we must ask ourselves, what are the essentials of the manufacturing process, or more precisely, what aspects of the process do we want to monitor and to understand? Once an initial selection is made, there is an ever-present danger that some factor or relationship that has been disregarded or unobserved is really driving the system. The only cure for this is vigilence and empirical validation.

Second, we have learned that an exact correlation with data derived from some real-life situation is less important than might be assumed, at least in the context of our project and goals, so long as the relationships depicted in the model are authentic. In fact, in keeping with the broad educational objectives of this project, we have settled on a "generic" model of the manufacturing process. Instead of a model that depicts the production of automobiles, or shoes, or computer chips, we have tried to extract the common processes of all manufacturing operations. The model portrays ordering and processing of raw materials, machine operations, quality control, labor assignments, and waste management, without reference to any particular product.

Inevitably, we have made assumptions about the mathematical relationships between these processes that may or may not reflect the actual operations of any particular industry. The justification for this approach is twofold: first, it would be a relatively easy matter (although limiting) to adjust the numeric input of the model to correspond to specific data; moreover, much of the insight to be gained from the model is independent of a correlation with real data. For example, the model demonstrates the difficulty of maintaining adequate but not exessive inventories of raw materials when lead-times for ordering are different and when the manufacturing tempo is variable. The model teaches the importance of adjusting throughput at each stage of the manufacturing process to keep the process smoothe and efficient, without bottlenecks and backlogs. These dynamic relationships could be observed by someone working on the factory floor, but with the computer model, where seconds can represent hours, or weeks, or years, the lesson is quicker and the impact is more pronounced.

Third, there is much to be gained from the process of constructing the model. It compels you to ask precise questions about the system you seek to represent and to uncover hidden or murky relationships. For example, in our manufacturing model, we sought to depict the long-term consequences of investment in research and development. Accordingly, we gave the "Chief Executive Officer" running the model an option to invest any amount in R&D at any point in the course of the simulation. For the sake of simplicity, we limited the possible beneficial outcomes to (1) an improvement in product quality, with a resultant increase in consumer demand for the product, or (2) an improvement in manufacturing technology, with a resulting decrease in the cost of production. We assumed that the greater the investment in R&D, the more likely a positive outcome, but that a positive outcome should not be guaranteed. Further, we assumed that there should always be some possibility of a "dead end," where, unknown to the business manager, additional investment will be fruitless. The built-in "Montecarlo" function of the software, based on random-number generation, enabled us to create probabilisitc events and relationships.

This sector of the model prompted an extended exchange between the UNM and LANL teams working on the project. For example, we debated to what degree the positive outcomes of R&D should be exclusive of one another, in order to represent a dedicated and directed research effort that foregoes other opportunities; or whether incremental gains in R&D, short of a pre-determined threshold for "success," should carry over into a new fiscal period; or what indicators should be associated with reaching a "dead-end." Similarly, in constructing other parts of the model, we were led to inquire about the effects of overall market saturation on the normal relationship between price and demand, and the effects of historical market dominance in allocating market share between competitors. In the context of our "generic" model, these relationships were defined simply by choosing plausible hypotheses. But if the model is adapted to a specific industry, or if a different model is built for specific, descriptive purposes, questions of this type will stimulate an empirical learning process. The builder of the model will discover gaps in its structure and will be prompted in a focused manner to gather information about the system of concern. There is a cross-fertilization between the model and the system depicted by it, where each elucidates the other. This learning process is associated with building the model. It is absent when someone simply runs a pre-packaged simulation.

Fourth, there are serveral distinct types of learning that can be acquired from working with a system dynamics model. One is the purely analytical understanding that comes from working out mathematical relationships and examining the data output of the model. For example, if all cost factors remain stable, it may be possible to work out the optimal solution for producing a given output from a systems model of a factory production line. With some effort and attention to detail, the sequence for ordering raw materials, the allocation of available labor, the operating hours, etc., can be set to yield the lowest possible price per unit. However, if the person running the simulation is given only limited time to make decisions, and especially if the cost factors are not stable, it quickly becomes impossible to calculate the optimal solution. The "player" must then rely to some degree on estimation and intuition. These skills are augmented by experience in running the model and by knowledge of its details. Eventually, the player can acquire a "feel" for the system which enables him or her to make good, although probably not optimal decisions with very little opportunity for calculation and analysis.

At another level, precise calculation may be literally impossible. This is true when probabilistic functions are used in the model. In the example of the R&D Sector described above, there is no way of knowing for certain whether an investment in R&D will pay off. However, it is possible to roughly assess the probability of a profitable outcome, based on the information available, and to decide on a prudent course of action. The player's potential to accurately estimate probabilities can be made little or great by design of the model, depending on what data readouts or text messages are provided as indicators in the course of the simulation. This feature develops an ability to control the system which might be called "Hedging Your Bets." For best results in the long run, some action is required; the better your understanding of the system, the better your chances of making a good decision, but there is no guarantee of success.

Finally, there is an element in our model which can be referred to as "Dumb Luck." This is a deliberate feature intended to simulate real life, where dumb luck often has decisive importance. The model may generate an unpredictable event, such as a big change in interest rates or a contraction of customer demand, which throws off previous planning and critically affects success. Such events are kept within the bounds of plausibility but they are made virtually unpredictable. However, with substantial experience in running the system, knowledge is acquired about the nature and liklihood of these intruding events. A player can acquire skill in developing a long-term strategy to absorb these shocks.

## Interactive Simulation

In a model that describes a human system, or a human-machine system, it is useful and extremely interesting to allow for human interactions directly in the simulation. By this we mean a setting for multiple players who interact not only by means of linked computer models but who also interact person-to-person as part of the simulation. After all, the human-to-human relationships and dependencies are the least likely to be accurately reduced to a mathematical formula that can be input into the computer model. Furthermore, these relationships are often the key to success, however "success" may be defined. For example, experts in business management and consulting are in broad agreement today that employee morale and effective communication between managers and staff are critical to profitability; they may well be the decisive factors in a competitive environment. Negotiation and deal-making skills are critical in almost any human organization.

For these reasons, we are developing a model of the manufacturing process that will consist of four connected sub-models. Each sub-model will represent a different perspective and a different set of inputs or influences on the overall system. Specifically, there will be four "players" who will simultaneously run the simulation: (1) a Chief Executive Officer, who will make decisions on capital investment and marketing strategy; (2) a Factory Manager, who will manage the production process; (3) a Government Official, who will make regulatory decisions, such as imposing a tax on disposal of untreated toxic waste; and (4) a Moderator, who will control macro-economic factors, such as interest rates and exchange rates for foreign currency. The Moderator will also have power to trigger major world events and market perturbations, such as wars, earthquakes, and export quotas.

The decisions of each player will be data inputs into the sub-models of other players. For example, decisions by the Factory Manger will generate a weekly production volume and an associated production cost per unit. These data will be input into the Chief Executive's sub-model where they will influence the CEO's decisions on the selling price of the product, or whether the company needs additional production capacity, and if so, in what region, etc. If the CEO needs to borrow money for capital investment, his or her decision will be influenced by interest rates set by the Moderator; if consideration is given to investment in a foreign region, currency exchange rates set by the Moderator will be a factor. Similarly, at the factory level, the Factory Manager will order raw materials, assign labor details to the different phases of the production process, and regulate the tempo of production. In addition, the Factory Manager will be able to adjust recycling efficiency (within a range) for units that do not pass quality control, and will be able to decide whether or not to treat toxic waste before sending it out for disposal. The latter decisions will be heavily influenced by regulatory factors set by the Government Official.

The players will be permitted to interact appropriately during the course of the simulation. For example, the CEO and the Factory Manager will meet periodically (in simulation time) so that the CEO can issue instructions and discuss long-term business strategy with the Factory Manager. Perhaps, in addition, the CEO will be allowed to meet with the Government Official to complain about interest rates, or the Factory Manager and the Government Official will meet to discuss limits on on-site storage of toxic waste. These human-to-human interactions will take place during a pause in the simulation, which will resume upon a signal from the Moderator. If an agreement is reached in these negotiations, the substance of the agreement will be input by the Moderator in the next round of the simulation. While the Moderator will regulate the pace of the simulation and the time for meetings, and will issue "news bulletins" (perhaps by e-mail) to inform the players of important economic events, the Moderator as a rule will remain aloof and will not entertain any discussions with the players.

Further, the simulation could be run as a competition between separate teams, each consisting of one CEO and one Factory Manager. Thus the price set by one CEO will show up in the sub-model of the other CEO as the "Competitor's Price," where it will absorb an appropriate part of the customer demand in the market. Two such teams might be given the same start-up capital and compete head to head in terms of cumulative profit. Or the teams might be given different start-up assets. In that case, their relative success would be a topic for discussion and debate. The players would collectively decide at the outset whether the criterion for "winning" should be overall profit, return on investment, world-wide production capacity, market dominance, or more plausibly, some combination of all of these outputs.

In the setting of university education, this type of interactive simulation will lend itself to a cross-disciplinary exercise. For example, a business student might take the role of CEO; an engineering student might be the Factory Manager; a student from the Political Science Department could serve as Government Official; while the presiding professor will presumably want to be the Moderator. The learning process will derive both from understanding the complex relationships and dependencies depicted in the computer model, and from the content of the human-to-human interactions. Students will hopefully gain insight into the multi-dimensional human involvement in a complex system, where conflicting and overlapping goals converge, as well as the internal dynamics of the manufacturing process. The human-to-human interactions might assist in the development of interpersonal skills for the business environment, or at least give students an appreciation of the other person's perspective. The same considerations would apply if the model were used as a planning or training tool for an ongoing business operation.