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METHODOLOGY FOR SIMULATION APPLICATION TO VIRTUAL MANUFACTURING ENVIRONMENTS

Tracey L. Geller
Raytheon Electronics and
Systems Division
20 Seyon Street, MS 133
Waltham, Massachusetts 02254

Suzanne E. Lammers
Motorola's Satellite
Communications Division
2501 S. Price Road, OSC-T1
Chandler, Arizona 85248

Gerald T. Mackulak
Industrial and Management
Systems Engineering
Arizona State University
Tempe, Arizona 85287

ABSTRACT

Supply chain management, enterprise integration and global optimization are all necessary to compete in today's global market. As new products are developed and partnerships are formed, companies will need to focus on "global optimization" across the entire supply chain, not just a portion. This paper describes the application of discrete event simulation for modeling the entire supply chain, or what has been coined "virtual factories." Using simulation during the design and implementation phases provides the supply chain with valuable insight into upstream and downstream processes to allow them to understand impacts before contracts are settled, schedules are defined or facilities are developed.

There are many benefits to be realized from virtual factory modeling. The first and most obvious is it provides the means and visibility to make decisions at the global level. This includes areas such as:

- optimization of shared resources (e.g., shipping containers);
- schedule alignment (evaluation of strategic inventory); and
- contingency planning.

Secondly, it aids in communication between the suppliers and customers by providing better visibility into all of the business operations, policies and assumptions. Finally, it is the only tool that provides a visual representation of the entire virtual factory. It is the one place where management can see how their products are moving through this virtual factory without traveling from one company to the next.

Implementation experience with the IRIDIUM® low earth orbit satellite communications system is described. This virtual factory simulation model along with focus on lean manufacturing and global optimization is what has driven Motorola and its partners to produce 66 satellites at an unheard of rate of 1 satellite per week.

1 INTRODUCTION

This paper presents the concept of a virtual factory and the benefits of using simulation for supply chain analysis. A methodology is then introduced with the steps for creating, validating and managing large scale simulation models of the entire supply chain. Using Law and Kelton's (1991) steps to a traditional simulation study, Figure 1 shows how these steps are modified to complete a successful virtual factory study (highlighted boxes represent steps that have been added or modified). Each of these unique steps is discussed in detail in this paper (Section number noted by step), while the other steps will follow a traditional modeling project (Law & Kelton 1991).

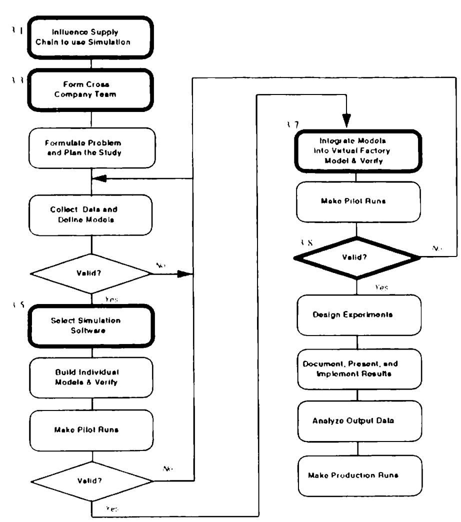

Figure 1: Steps to Virtual Factory Simulation Study

This paper then demonstrates this methodology on the IRIDIUM satellite manufacturing process. The purpose of these models and methodology was to provide management with the means to evaluate lean manufacturing practices and global optimization of the IRIDIUM satellite manufacturing supply chain. Finally, the benefits and results from the IRIDIUM virtual factory analyses are presented, as well as the challenges encountered along the way.

1.1 Virtual Factory Concept

A virtual factory is one in which the product production cannot be identified within any four walls of one factory. The virtual factory is composed of components from the entire supply chain: from raw material suppliers through various levels of manufacturing and ultimately to the final consumer. In 1990, Savage proposed this concept as the enterprise of the 21st century. This notion of an integrated enterprise has become increasingly more important for maintaining a competitive advantage. Individual companies no longer have the breadth of knowledge and capability to understand all aspects of the supply chain. Therefore, strategic alliances that share knowledge and resources have an advantage in this global market (Shunk 1992).

Although companies have formed partnerships and have focused on integrating the supply chain, most have only implemented "transaction systems" like inventory control, order processing and shop floor management. While these systems help management execute production, they do not provide the necessary information to plan, predict and make decisions. Using integrated decision support tools to analyze the virtual factory provides many benefits (Turner 1993). These include:

1. better operational decisions and lower cost;
2. better communication; and
3. better visibility into all of the business operations.

Similarly, discrete event simulation has been used to model individual pieces of the supply chain, but rarely used as a decision support tool for the *entire* supply chain. Many would argue that run time, accuracy and/or manpower required to perform the modeling and analyses are too costly to make such a venture worthwhile. This paper will use the IRIDIUM Virtual Factory simulation model as a prime example of how easy and beneficial virtual factory modeling can be during the design stage of a program.

1.2 The IRIDIUM Virtual Factory

The IRIDIUM system will provide personal communications worldwide, to anyone, anywhere, anytime. The IRIDIUM system is a worldwide, digital, satellite-based, cellular, personal communication network. Its primary intent is to provide commercial and rural service through either hand-held mobile or transportable user units, employing low profile antennas, to millions of individual users throughout the world. The system includes a constellation of 66 small satellites in low-Earth orbit (LEO) (Swan & Zukoski 1994).

To meet the aggressive goal of 17 launches in 18 months, Motorola and its partners had to design and ultimately produce satellites at an unheard of rate of 1 satellite per week, radically changing the satellite industry. Traditionally satellites were produced at a rate of one satellite every 6 months to a year.

Motorola had developed the concept and design of the IRIDIUM system and the satellite's communication panel. However, Motorola's expertise was in the communications industry not the space industry; therefore, we teamed up with other best in class companies to form the IRIDIUM Virtual Factory (Figure 2).

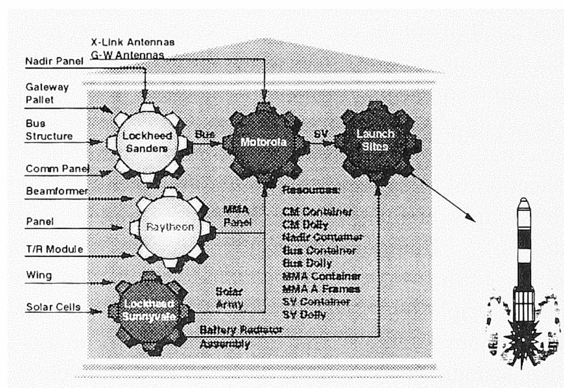

Figure 2: IRIDIUM Virtual Factory

2 BENEFITS OF VIRTUAL FACTORY SIMULATION

In order to understand the benefits of virtual factory simulation, we must first explore the differences between traditional modeling and virtual factory modeling (see Table 1). These differences allow us to achieve greater results and benefits from a virtual factory simulation.

Table 1: Comparison of Traditional and Virtual Factory Modeling

	Traditional Simulation Studies	**Virtual Factory Simulation Studies**
Goals	Internal to single company	Internal & External
Model Builder(s)	Individual(s) at location	Team members build sections (different partners) of the virtual factory
Trust	Internal trust between divisions, management and engineers	Both Internal and External trust needs to be developed
When Important	Facility/product change, expansion, capacity problems, etc.	New partnership formations and as partnerships evolve

2.1 Better Operational Decisions and Lower Costs - Goals of Global Optimization

Although these are generalizations, traditionally simulation models are internally focused as are the metrics (e.g., increasing throughput of a line, decreasing inventory in the factory or improving yield of a station). In the virtual factory simulation analysis, the goals are focused on the entire supply chain (e.g., optimizing shared resources and aligning schedules). These goals can only be achieved through a virtual factory analysis since individual models cannot accurately predict what is happening at other partner sites without knowledge of their operations. Because of this knowledge, management is able to make better operational decisions and lower overall costs. The following sections emphasize this point with examples of global optimization.

2.1.1 Optimizing Shared Resources

The first example is optimization of shared resources. Recycling of resources between suppliers, manufacturers, distributors and customers is becoming increasingly prevalent as we become more environmentally conscious. Examples of these resources include transportation containers, tooling, storage facilities and transition or temporary parts removed at the next stage in the supply chain.

What we have found is that when each partner makes a prediction using their individual models, they tend to be conservative. The accumulated effect of the partners' conservative estimates results in a non-optimal and greatly over-estimated amount of resources. Virtual factory simulation provides the means to accurately predict the required amount for the entire chain; hence, influencing partners to re-evaluate their estimates and to make a better purchase decision, ultimately lowering program costs.

2.1.2 Optimizing Schedules Through Schedule Alignment

Another benefit to global optimization through simulation is alignment of partner production and delivery schedules. Normally, when a supplier and customer develop a contract for a new product line, the delivery dates are contracted before all of the process details are understood. Therefore, in most cases the contracted dates are not aligned and the partners either have more than enough or not enough time to make their product. Unfortunately at this point in time, since they have little or no knowledge of up or downstream processes, they do whatever it takes to meet those contracted delivery dates without thinking about the global effect.

Consider the following situation (Figure 3a and 4b). Contracts for a program were negotiated and delivery dates settled prior to any process details. During the analysis, one partner (factory A) finds they have excess time to make their product and still meet scheduled deliveries. However, they have limited storage space for finished goods; so the analysis indicates to slow production down to meet deliveries and optimized storage of finished goods. On the other hand, the second company (factory B) which receives the product is barely meeting its delivery dates due to processing constraints. Therefore, the individual analysis is focused on increasing capacity (possibly by buying more equipment). With the virtual factory simulation, it quickly becomes obvious that if factory A ships early to factory B the problems of both would be solved. In addition, the entire cycle time of the product from end-to-end could be decreased translating to a shorter time-to-market. This is a win-win situation!

Local Optimization

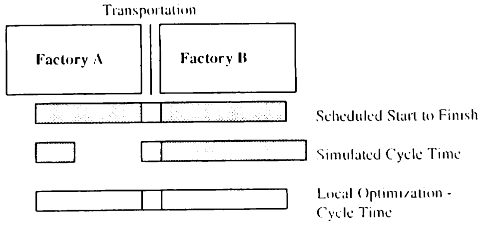

Figure 3a: Before Global Optimization

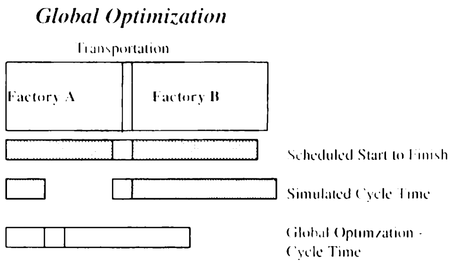

Figure 3b: After Global Optimization

Although this simple example seems intuitively obvious, many companies miss opportunities such as this because of the lack of knowledge and lack of communication that are inherent in building virtual factory simulations.

2.2 Better Communication and Visibility - Team, Influence and Trust

One of the intangible benefits of virtual factory simulations is the increased communication and visibility. Although simulation is useful at any point in a program, using it as a tool during design of a virtual factory has added benefits. Like any modeling project during the design phase, concurrent engineering has many advantages. However, for virtual factory simulations performed during design there are two additional advantages:

1. influencing supplier strategies; and
2. strengthening communication prior to production.

The *process* of building integrated virtual factory models provides each partner with visibility into the end-to-end manufacturing cycle. This increased visibility during model development and model reviews initiates the communication between partners earlier during the design phase. Questions about policies, inventories and shipping/receiving between customer and supplier are all brought out during the model development and review. The virtual factory simulation team provides the means to analyze the factory from each partner's point of view.

Finally, trust is developed during this phase and that trust will remain in place during implementation. Having communication and trust developed early will ease the transition to production.

3 CRITICAL STEPS TO COMPLETING A SUCCESSFUL VIRTUAL FACTORY SIMULATION MODELS

The following sections explain the critical steps for virtual factory modeling, outside of Law and Kelton's traditional simulation study (Figure 1).

3.1 Getting Simulation Accepted Across the Supply Chain

Every virtual factory simulation project must begin with the influence and acceptance of simulation across the supply chain. Although simulation is a widely used tool, many companies still do not see the value, especially during the design phase of a new product with little or no process history. In order for the virtual factory simulation project to be a success each partner must "buy in" to simulation early. This is essential since each partner will be responsible for developing and analyzing their individual simulation models. In addition, partner involvement with problem definition, data collection and integration is *critical* to the success of the project.

In order to influence the supply chain on the use of simulation, the company leading this effort should give presentations to upper management at each partner site to obtain their support for the project. This presentation should be made to key personnel who can allocate resources to the virtual factory simulation team. The presentation should include a high-level review on the concept of discrete-event simulation followed by its application to the program and anticipated benefits foreseen.

3.2 IRIDIUM Acceptance of Simulation

The use of simulation, though necessary, was not automatic. Most of the IRIDIUM partners were used to working on government contracts, not industrial partnerships. We had to overcome the barriers created by our different business cultures and management attitudes had to be altered. Since simulation was not "required" in the contracts, we needed to convince management that it was in their best interest to perform duties above and beyond contractual requirements. We achieved this by taking high-level process data from *their* site and performing simplified analyses to highlight the potential of this tool. These results, along with a high-level review simulation and our anticipated benefits, were presented to all partners.

This process of influencing new partners became much easier once results were obtained from the original end-to-end model. Managers quickly realized that simulation could be used as a real-time analysis tool, and it was widely accepted by the partners. In fact, the IRIDIUM virtual factory has inspired the industrial partners to use this tool in other areas of their businesses. Partners are now developing virtual factory models with their suppliers. Models are being created for virtual factories, outside of IRIDIUM, with products such as aircraft and printed wire assemblies.

3.3 Building the Virtual Factory Team

Once the supply chain has been successfully influenced to use simulation and before any analysis can be completed, a simulation team should be formed with representation of all major partners and suppliers. This is important since both business cultures, policies and processes from each partner will be integrated in the virtual factory model. Without this balanced team, decisions can become one-sided in favor of the partners represented on the simulation team. Figure 4 shows the modeling team formation and communication lines.

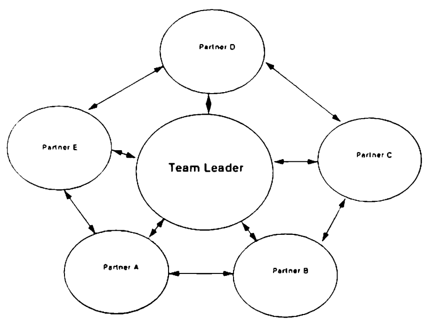

Figure 4: Simulation Team

The purpose of this team is to share modeling knowledge, define metrics, perform analysis and report to management on a monthly basis. During this monthly review, users of the simulation analysis (both input and output) should be present to review all assumptions and results. This monthly review will also facilitate communication between the key personnel from each partner.

The team should consist of an individual from each partner whose responsibilities include:

- developing and analyzing the simulation model of their facility;
- communicating results to the team leader; and
- assisting with the virtual factory problem definition, modeling and analysis as it relates to their factory.

One person should lead the team and be the focal point for the virtual factory analysis. This person's responsibilities should include leading team meetings, ensuring common documentation and standards, and most importantly he/she is responsible for integrating the models and analyzing the virtual factory.

3.4 IRIDIUM Simulation Team

No one person knew all the processes and tooling required to build a satellite. So, a cross-company team was formed to create the virtual factory simulation model. First a team leader was selected by Motorola to develop this core competency across the supply chain. Team members from each company were chosen for their knowledge of the manufacturing processes and experience with simulation.

Today the simulation team meets monthly to report results and discuss modeling techniques and process information. Members of the simulation team have attended classes and conferences together to assist in model building and analysis. When the IRIDIUM partners meet for technical exchanges, the model is presented by the simulation team to verify process information and provide the analysis results. At this time, requests for additional analysis, and model modifications can also be discussed. The presentation of this information is used to assist managers with their business decisions and information is shared with the understanding that it will be used to better the IRIDIUM program, not used as a weapon against a partner.

3.5 Software

Once the team is formed, the first step is the selection of the software for the project. Since analysis needs to be performed at the integrated level, it is important that all partners either use identical or compatible software. We strongly suggest using the same software whenever possible. Using the same software will enhance the knowledge sharing and model reuse between partners. In addition, we have found that software that allows one to easily import and export detailed models into an end-to-end model has many advantages. First, it is an excellent presentation and management tool (assuming graphics are available). The end-to-end model gives one visual representation of the virtual factory from start to end. Secondly, it allows one to quickly integrate and build models without having to characterize and continually rebuild the virtual factory model. Even if the team decides to use a black-box method for the end-to-end model (discussed in Section 3.7.2), it is still important to have the ability to build a visual representation of the virtual factory with the detailed individual factories. This visual representation will probably be the only place where management can actually view the entire virtual factory floor - an extremely powerful communication tool.

Before the team can begin to evaluate different packages and languages on the market, we suggest developing a list of criteria. It is important that *all* partner criterion is captured. For example, one partner may require AGV logic while that is irrelevant to another. Compiling this list of requirements with the entire team and then using that during the evaluation of software will ensure that the software meets the individual needs as well as that of the virtual factory.

The next step is the actual evaluation of all available software products. Each team member should rank these products against the requirements, and should unanimously agree on a simulation language or package. Having this agreement will initiate team synergy.

3.6 IRIDIUM Software

After performing an extensive software review with the existing simulation team, we selected AT&T Istel's Witness. We now have the capability to import each individual partner model as a sub-model into the virtual factory model or black box the partners' detailed models for high-level analysis. One of the newer capabilities of Witness that has been instrumental in our virtual factory model is its ability to create modules. We use this feature by importing the individual factory models as modules. During the virtual factory simulation runs, we have the ability to "zoom" into one of these modules to look at the details of any one factory. This has been extremely effective for management reviews and presentations.

3.7 Building the Virtual Factory Model

3.7.1 Individual Models

Before the team can begin to build the end-to-end virtual factory model, the individual models need to be developed, validated and verified. This can be done in two ways:

1. each partner builds their individual model and then brings it to the team for review;
2. the company assists with the model development of each of its suppliers.

We recommend the latter since it has three main advantages. First, the "two heads are better than one" theory, having more than one person work on the model tends to produce a simplified and higher quality model (e.g., fewer errors). Secondly, and more importantly, the team does not rely on a single individual to understand the model. Either the supplier or the customer could present the supplier model and data with the same knowledge and expertise. This has a profound effect on upper management when one understand the supplier's processes, strengths and weaknesses. Understanding their capability allows one to influence decisions at the supplier level that can benefit both the supplier and the entire virtual factory. However, this knowledge should *never* be used against the supplier. Trust is critical in this process. If one wants to continue to have the capability of virtual factory analysis, one must *influence* not *dictate* changes to the supplier/partner.

Finally, if the suppliers and their companies do not see the benefits of simulation, this joint development provides the perfect opportunity to get their involvement and to highlight the potential savings (e.g., costs, cycle time and inventory) *they* can gain by using the results of this tool. Although this joint development may be more time consuming, the benefits of first hand knowledge of the supplier's processes and the ability to influence their decision is well worth the time.

3.7.2 Virtual Factory Model

Once the individual models have all been developed, validated and verified, the team can begin to integrate the models. Depending on the objectives of the virtual factory analysis, the level of detail can vary between projects. For example, if the objective is to have a communication tool or precise accuracy, then one should include the details of all factories. However, if precise accuracy is not required, and run time is a factor, the team may want to consider black-box modeling, where each partner's facility is characterized and represented as one time delay with no further detail (Robinson 1994).

3.7.3 The IRIDIUM Virtual Factory

Although the factories have not all been built and no product has been produced, Motorola and the IRIDIUM partners are producing estimated manufacturing reports today. We can predict our cycle times, pulse rates and bottlenecks across the entire supply chain before production begins.

Using discrete event computer simulation tools to model the dynamics of the entire supply chain, Motorola has been able to understand impacts of design decisions to both the upstream and downstream processes. This dynamic model includes all of the partners' factories, transportation methods, and launch sites. We have used the black-box approach as well as a detailed model depending on the purpose of the analysis. When analyzing container requirements we use a black-box approach where each factory is represented as a single machine. However, if we analyze the impacts of contingency/recovery planning where parts need to be reworked at upstream processes, then we utilize the detailed models.

3.8 Validating the Virtual Factory Model

Once the virtual factory model has been developed, it too needs to be verified and validated. This process is critical in the success of virtual factory modeling and should be done with the entire simulation team. In addition, a formal walkthrough should take place with key users from each of the partners involved with the virtual factory.

One major issue is coordinating different levels of model sophistication and validating the results. This is often a problem in integrated models, where one model has a better resolution and validation to the existing system than another. We are still tackling this problem, especially during a design project where there is no existing system from which to validate the individual models. Section 3.9 explains how the IRIDIUM program has developed a "quick-fix" answer to this problem. However, more analysis and research are needed to develop a quantitative approach for integrating and validating models of this complexity.

3.9 IRIDIUM Validations

The IRIDIUM virtual factory model has varying degrees of model complexity and validation. Since we have no existing system against which to validate, we developed our own means of validation. Although structured walk-throughs are essential in the validation, they do not provide us or management with an estimate on how accurate our predictions are. Therefore, in order to determine how valid the end-to-end model is, we capture the number of processes that fall into the following categories according to cycle times, yields, rework, and machine downtime and repair:

1. historical;
2. tested (small sample size);
3. engineering estimates;
4. budgeted.

For example, out of 10 processes how many of the process cycle times are based on historical data? How many are based on tested data? How many are simply budgeted? Finally, we ask the modeler and users to estimate a subjective confidence level they have about their individual models (e.g., 80% confident in the results). All of this information is then presented along with the results to allow management the visibility into how the data was derived and hopefully some validation on the results. We are still determining how and if it is possible to combine all of the information into one top-level confidence about the end-to-end results.

3.10 Conclusions About Steps to Virtual Factory Modeling

Once the model has been developed, verified and validated, the analysis and experimentation proceed like traditional simulation studies (see Law & Kelton 1991). The key point to keep in mind during these steps is to maintain open communication and involvement of ALL major partners modeled in the virtual factory.

4 IRIDIUM RESULTS

The results that the IRIDIUM program has achieved from virtual factory analysis are astounding, and the potential has still not yet fully been realized. We have achieved both tangible (cost savings) and intangible results (increased communication) which are presented below.

4.1 Resource and Capacity Optimization

Using simulation for both individual factory and virtual factory analysis along with focusing on global optimization, we have begun to optimize our shared resources. Table 2 illustrates the cost savings to date on four shared resources.

Table 2: Savings on Shared Resources

Resource	*Improvement*	*Cost Savings*
Antenna A-Frames	50% reduction	
Antenna Shipping Containers	60% reduction	
	Antenna Total:	*Over $400K*
Satellite Dolly	60% reduction	
Satellite Shipping Containers	17% reduction	
	Satellite Total:	*Approx. $1.7M*

Simulation has also simplified the overwhelming task of analyzing and coordinating the container and dolly (transport fixture) routings between domestic and international partner sites. With this tool and linear programming, we can now use the results during our negotiations with the transport carriers to determine the optimal shipping policies to international launch sites. For example, if we change a shipping assumption (hold containers at launch sites longer), how does that impact our container requirements and cost versus the cost of a charter aircraft.

4.2 Re-aligning Schedules Before Production

Another area of potential cost savings is the alignment of production and delivery schedules. The virtual factory simulation model and analysis highlighted "schedule-necks." "Schedule-necks" is a term we coined meaning where parts are not flowing through the system because of schedules. In some cases a part would sit in finished goods waiting to be shipped, while at other facilities the major production piece would sit idle waiting for the scheduled delivery of those same sub-components. Figure 5 shows the inventory over time at the integration point before simulation re-alignment. In this example, we have up to 5 part Es while part Gs are being used as soon as they arrive.

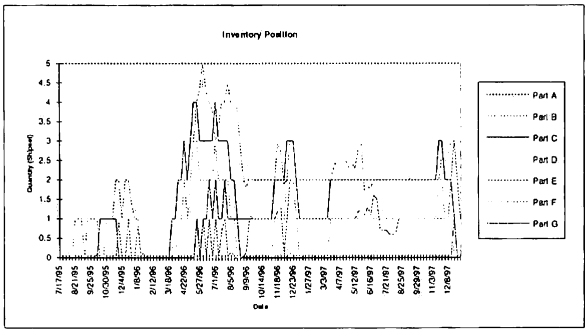

Figure 5: Inventory Before Alignment

We used simulation to predict when these parts would actually be pulled into the integration process. We are currently in the process of re-negotiating schedules prior to production. This is an issue in itself due to contracts and payment milestones; however, this information gives contract personnel a better understanding of the implications of not re-negotiating (e.g., the costs associated with storage, product life-time and insurance).

5 CONCLUSIONS

Although the tangible results are impressive and have save thousands of dollars on the IRIDIUM program, the intangible benefits are probably the most beneficial to this program and also the most difficult to quantify.

As stated early, communication, visibility and trust are the real benefits of a virtual factory analysis (of which simulation is one tool). Without these three things, it would be impossible to achieve the results we have. In addition, the communication and trust that have followed has made the IRIDIUM program one of the most sought after programs at each partner site. The attitudes are positive and the work environment is innovative.

We have presented our findings on how to successful develop and analyze virtual factories of new partnerships. The benefits are endless if the respect for each partner is developed and the focus is on influencing changes rather than dictating.

REFERENCES

Law, A. M. and W. D. Kelton. 1991. *Simulation Modeling & Analysis*. 2d ed. New York: McGraw-Hill.

Robinson, Stewart. 1994. Simulation Projects: Building the Right Conceptual Model. *Industrial Engineering*: 26: 34-36.

Savage, C. 1990. *Fifth Generation Management*. Boston: Digital Press.

Shunk, D. 1992. *Integrated Process Design and Development*. Homewood, Illinois: Business One Irwin

Swan, P. & J. Zukoski. 1994. Manufacturing Technologies, the "key" to a 66 Small Satellite System. Presented at the 1994 *International Aeronautical Congress*.

Turner, J.R. 1993. Integrated Supply Chain Management: What's Wrong with This Picture? *Industrial Engineering* 25: 52-55.

AUTHOR BIOGRAPHIES

TRACEY GELLER is a Process Engineer at Raytheon Electronics and Systems Division, where she is responsible for all chemical related processes, as well as performing factory simulations of the main mission antenna. She received her B.S. in Chemical Engineering from Worcester Polytechnic Institute and her M.S. in Engineering Management from Northeastern University.

SUZANNE LAMMERS is a Manufacturing Engineer with Motorola Satellite Communications, where she is responsible for the simulation of the entire IRIDIUM supply chain and detailed launch schedules. She received her B.S. in Industrial Engineering from Columbia University and a B.A. in Management Engineering from Claremont McKenna College. She is currently pursing an M.S. in Industrial Engineering at Arizona State University.

GERALD MACKULAK is an Associate Professor of Engineering in the Department of Industrial and Management Systems Engineering at Arizona State University where he is also Director of the Systems Simulation Laboratory (SSL), a laboratory within the CIM Systems Research Center (CIMSYRC). Dr. Mackulak received all his degrees from Purdue University in the area of Industrial Engineering and has held prior positions with U.S. Steel (Industrial Engineer), Burroughs Corporation (Management Information Systems Analyst), and Pritsker and Associates (Senior Simulation Analyst).