Proceedings of the 1994 Winter Simulation Conference
ed. J. D. Tew, S. Manivannan, D. A. Sadowski, and A. F. Seila

SIMULATION FOR AGILE CONTROL OF AEROSPACE MANUFACTURING

Ray Rolen

McDonnell Douglas Aerospace - East
P.O. Box 516 St. Louis, MO 63166

Richard A. Kilgore

Midwest Modeling Technologies
P.O. Box 6949 St. Louis, MO 63123

ABSTRACT

This paper discusses the use of simulation for both planning and control of aerospace manufacturing through work-instruction level models. The approach uses detailed models, pre-validated alternative process plans and use of continuously updated simulation models which have the capability for providing control instructions when expected performance is not realized. The initialized model can also be used in an off-line mode for further planning.

1 INTRODUCTION

Agility in aerospace manufacturing is a becoming an increasingly critical requirement for the US military industrial base as program quantities decrease, work force characteristics evolve, and affordability objectives continue to challenge the manufacturing environment.

In this new environment, a cluster of specific factors will make lean manufacturing essential. Decreases in production volumes and more aggressive affordability targets will require more effective utilization of capital resources and more flexible product routings and work force assignments. These changes will require efficiency gains through improved management of productivity and less emphasis on traditional capital-intensive improvements. The productivity equation will require agile decision support for intelligent assignment and reassignment of operators and tasks. The objective is more effective resource utilization and shorter product span duration in an environment of frequent and unanticipated process change.

Simulation of aerospace manufacturing systems is one of the tools needed to facilitate agile aerospace manufacturing in this new environment. The proposed simulations must support planning, scheduling, and work-instruction communication at the factory level in a manner which provides more realism than conventional decision support systems. These software tools must support both *decision making* (planning and scheduling) and *execution* (task assignment and electronic work-instruction) functions for timely and agile command and control (Figure 1).

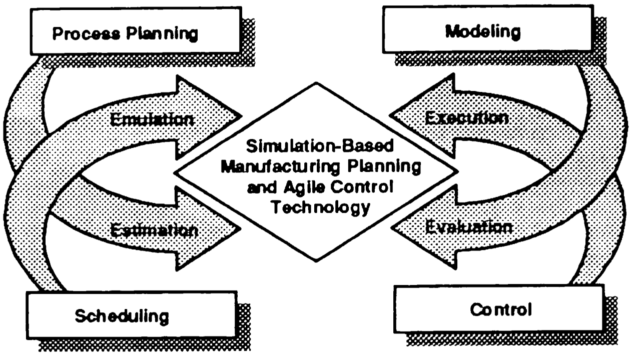

Figure 1. The approach integrates manufacturing planning, scheduling modeling and control around a common simulation-based software environment.

2 AEROSPACE MANUFACTURING

The need for agility in aerospace manufacturing is due to daily changes in the sequence in which fabrication and assembly operations occur in otherwise identical products. A simulation-based approach is designed to facilitate better understanding of the short-term and long-term consequences of daily process flow changes. Unfortunately, agility in aerospace manufacturing is bounded by firmly entrenched "legacy" information systems which require a large amounts of manual data entry. The fidelity and latency of this information makes it inadequate for agile command and control.

During the initial phase of aerospace planning, manpower forecasts are established using rough approximations based on labor standards and learning assumptions. The data is then passed on to the core management in production to begin the process of allocating the personnel of the needed skill classification to the program assembly manager according to the scheduled need dates. The dates are connected to the schedule for the major assembly sections. Personnel assignments and/or reassignments are made based on a number of constraints including company seniority, skill classification, experience levels, personal skill levels, and in some cases the ability to acquire a security clearance. The shop foreman typically has little control over the manpower allocation except for skill category.

It is the shop foreman's responsibility to routinely assess the work progress in the assigned area and allocate the necessary skilled laborers to complete the open work. Likewise, when work is completed, the foreman will reassign personnel to other tasks. With some exceptions, the majority of the work force will report back to the foreman for a new assignment.

In making the work assignments, the foreman must be alert to the scheduled completion date of the assembly. He must also be aware of the changes in skills required to complete an assembly. For example, if he were building a forward fuselage section, initially (during the structural assembly) he would require a preponderance of workers in a "sheet-metal" skill classification. As the structure is completed the skills requirements would transition to electrical and mechanical installations.

The ability to understand and communicate how changes in the production variables can impact the critical path is an essential skill for the foreman. Periodically, work from a previous assembly station is incomplete when it arrives into the next position. Typically, the completed portion of the prior work has already been credited as produced hours in the previous assembly station under a separate job, item, and cost code. The incomplete work that has been "statused" to the next position remains uncredited until it is completed. This cascade effect has negative cost ramifications for the receiving foremen. Not only are they responsible for completing their planned work but now they must complete the status or "out-of-position" work as well.

Agility is also required when demand peaks in a particular assembly shop department. This peak may result in an unplanned need for additional shop workers of certain skill classifications for a short duration. Rather than hiring the needed skills and then laying them off after the critical stage has passed, the shop foreman, superintendent and director may request additional help from another program. If available, temporary loans are made by the requesting department for the duration of critical need.

Low-Rate Aerospace Manufacturing

Lower production rates leave aerospace manufacturers with two choices. The first choice is to increase the number of tasks each worker performs on a given product through cross-training. In this scenario, manpower scheduling must determine the best mix of jobs which keeps each worker fully utilized yet maintains learning through repetition. The second choice is to combine programs such that a sheet metal assembler begins work on Product B after finishing similar, but not identical work on Product A. This approach has a better potential for maintenance of learning opportunities through greater specialization, but still requires advanced manpower and program scheduling to meet affordability targets for manpower utilization.

In either case, aerospace manufacturing is in need of better tools for determining low-level task assignments which best utilize available resources. This tool must be able to aid in short-term decisions regarding worker reassignment and aid in the delivery of these assignments in the form of work-instructions and other training aids which show the current status of work performed, the content of the work to be performed next and the consequences of this work to downstream operations.

A Simulation-Based Approach

In existing systems, a variety of simplifying assumptions are made to allow manufacturing planning and scheduling relationships to be represented mathematically. Historically, however, it is evident that aerospace products are rarely manufactured according to these plans and schedules, except for adherence to major milestones and delivery dates. Simulation is the best tool for representing the actual reality of these processes, and only simulation provides a high-fidelity, non-abstract modeling environment which promotes system understanding in the process of constructing and validating the model. As more emphasis is placed on affordable and agile manufacturing, factory simulation is a common modeling denominator which can aid the planning of the process, the scheduling (and dynamic rescheduling) of process resources, and the delivery of these schedules to process supervisors, foremen and manufacturing personnel.

Presently, aerospace planning and control tools do not address the work-instruction level because convenient predecessor-successor relationships are available only when large sets of tasks are combined. The consequence of this is that short-term decisions are performed at a level where modeling or analysis tools are unavailable to assist foremen in determining the consequences of these decisions. Our approach builds on current development in electronic work-instructions and visual aids to integrate this information as a more valid level of model fidelity and as a central feature of the control function.

3 A SIMULATION-BASED PLANNING AND CONTROL TOOL

Modeling, planning, scheduling and control activities are currently performed by separate functional departments based on separate manufacturing "models" (Centano and Standridge, 1994). A simulation-based approach requires the concurrent development of four integrated products as described below (see also Figure 2):

1. Development of simulation modeling and analysis tools which support modular and reusable models of aerospace processes with a level fidelity and ease-of-use to support integrated planning and scheduling of manual operations and combinations of manual and automated operations at the work-instruction level.

2. Extension of the hierarchical Computer-Aided Process Planning (CAPP) concepts such as those developed in ARPA Project 8881, "Rapid Prototyping of Shop-floor Control Systems for CIM" (Wysk, et al 1992) in construction of a formalized aerospace process planning definition for shop-floor environments which are dominated by manual operations of uncertain duration and a variety of alternative operation sequences.

3. Integration of the process planning definition with shop-floor scheduling heuristics and decision support rules based on real-time shop floor status and schedule evaluation capabilities (Derebail et al, 1994).

4. Integration of the planning and scheduling modes of operation with a unique execution mode of operation for real-time control which incorporates electronic and visual work-instructions and an effective man-machine interface to support efficient, high-quality implementation of dynamic shop floor scheduling decisions.

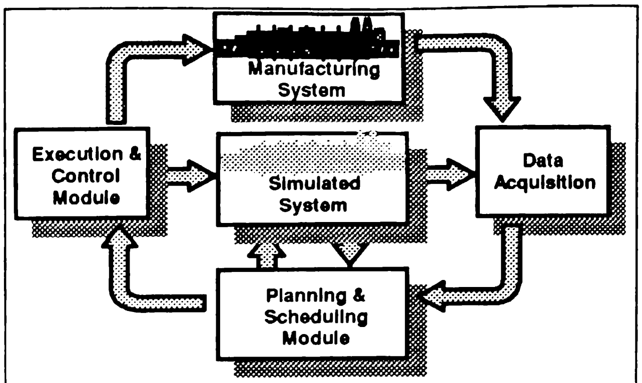

Figure 2 The architecture includes both data acquisition and an execution (control) module.

A primary objective of a simulation-based approach is to address the issue of latency in the command and control of the system in response to new information. The most critical component of the approach described is the ability to execute the simulation in an off-line mode to establish rules and alternative process plans prior to the receipt of new information. This provides timely, pre-validated support to the evaluation and execution mode operation.

The remainder of this section will describe a specific approach in each of the four functional areas followed by a description of the strategy to be employed in the overall integration.

4 SIMULATION SYSTEM REQUIREMENTS

Traditionally, discrete event simulation has been used in aerospace manufacturing as an analysis and planning tool prior to the actual implementation of manufacturing systems. Simulations analyze a proposed manufacturing system design and evaluate proposed improvements. Once the system design has been chosen, the planning simulation is set aside and the non-simulation-based control or scheduling system is created. This approach requires the same system control logic to be developed twice: once for use in the planning simulation, and then again for the control system.

Similarly, when modifications to the aerospace manufacturing system are required, the simulation is typically used to test potential modifications first. Once the impact of the modifications has been verified, the control system is correspondingly modified without reference to a common model. This duplication of effort represents a significant cost in the development and maintenance of agile manufacturing systems. A more attractive alternative is to use the same logic for the simulation and the control, thereby reducing or eliminating this duplication of effort.

A novel approach towards this goal has been developed as part of the RapidCIM Project (ARPA

Project #8881, 1992). In this paradigm, once the system design has been finalized, the simulation that was used for **evaluation** is then used as the basis for the **execution** or control system. While this approach was demonstrated for control of small cells of automated equipment, the theory should be valid for control systems of larger, less-automated aerospace manufacturing systems (Harmonosky and Robohn, 1991).

The enabling technology for design and development of this approach to aerospace manufacturing simulation is motivated by advancements in simulation modeling templates such as those in the commercial Arena simulation system by Systems Modeling Corp. (Pegden et al, 1990). SIMAN modeling segments are graphically developed which can be linked hierarchically to form reusable modeling components. These components are organized in templates which become customized modeling tools for specific industrial and application domains. The flexibility, modularity and reusability of these templates make large-scale industrial application manageable since the modeling components can be custom built for a particular industrial application. Our present MDA Agile Manufacturing Simulation IR&D project (94-22) has initiated the development of these modeling templates in support of aerospace manufacturing processes.

5 AEROSPACE MANUFACTURING PROCESS PLANNING

The challenge of aerospace manufacturing simulation experience comes from the fact that the process flow is not well-defined. Representation of the behavior of the system requires understanding and representation of a great many alternative process plans.

Since aerospace manufacturing is characterized by a large number of alternative process plans, our approach focuses on hierarchical Computer-Aided Process Planning (CAPP) relevant to aerospace manufacturing (Chang and Wysk, 1991). Presently, aerospace manufacturing planning is accomplished through high-level flowchart representations of tasks in ideal sequence. While these high-level precedence diagrams are useful for some planning decisions, in reality, the actual relationships are such that X% of Activity A is necessary before Y% of Activity B can begin.

It is not reasonable to expect that any modeling tool can manage the tremendously large number of possible process sequences that the aerospace manufacturing can follow. Rather, the objective of this simulation-based approach is to pre-load the most likely alternative process paths. Without a scientific method of developing and representing these process plans, it would be impossible to implement simulation-based scheduling on a decentralized, enterprise-wide basis.

As in Computer Integrated Manufacturing systems, the hierarchical nature of aerospace manufacturing makes an "AND/OR" representation attractive since it allows for convenient roll-up of detailed work-instruction process plans into higher level

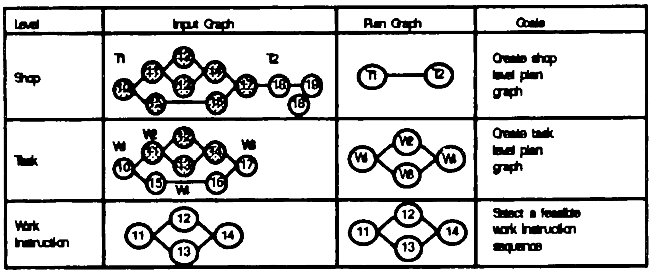

Figure 3 The aerospace process plan will support the evolution of work-instructions into a plan for higher levels shop floor control

task and shop plans (Figure 3). Most importantly, the AND/OR representation is a natural foundation for conversion of the process plan into a modeling representation (Cho et al, 1994; Wu and Leon, 1994).

The availability of formal, detailed alternative process plans will then support the use of the factory simulation planning tool as a factory scheduling and control tool. It also allows convenient storage of additional process plans which evolve during manufacturing operations due to work-arounds and engineering changes.

An important characteristic of the formal process plan is that it provides the detail required to operate any shop-floor control system (SFCS) (see Figure 4). The process plan decomposition must parallel that of the control architecture, and thus ensure that alternatives are provided for decision making at an appropriate level of detail suitable for each level in the architecture.

6 SCHEDULING AND DECISION SUPPORT INTEGRATION

The first step in the scheduling and control extension of the planning model will be the real-time representation of shop-floor status. The decision to model at the work-instruction level is critical to accurate representation of shop floor conditions as work-instructions represent the base level activity that is non-decomposable. Modeling at the work-instruction level will require a significant changes in the information systems used to support aerospace manufacturing.

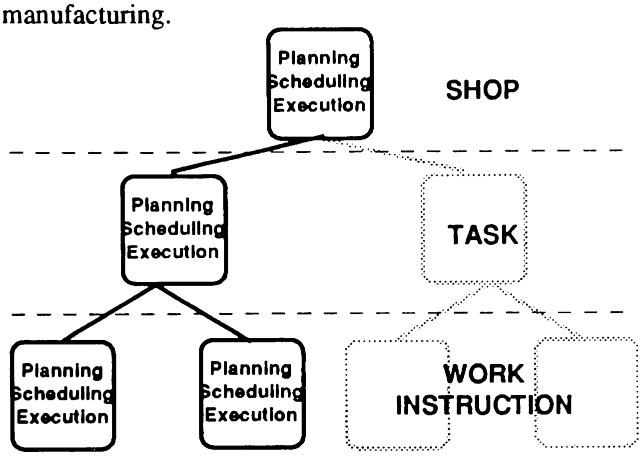

Figure 4 Hierarchical aerospace process planning is supported by the AND/OR formalism.

Once the current factory status and future requirements are determined, scheduling heuristics and operator assignment rules must be developed based on the information provided by experimentation with the simulation model under various alternative future states. Shop floor personnel and methods engineers are required to make the selection of scheduling rules and performance objective functions by evaluating the simulated result of alternative resource assignments and process flows.

A critical requirement is the ability to represent such a large set of dynamic process procedures and rules. Each time the specifics of the process change, the scheduling rules in the simulation model must be rewritten or updated which must be done manually. Although the benefits can be significant, the implementation costs can be quite expensive. The key to the development of this type of distributed scheduling lies in the generation of "robust" schedules (Wu and Wysk, 1989).

7 SHOP FLOOR CONTROL AND EXECUTION

In this approach, the shop floor controller functions are partitioned so as to separate the *decision support* evaluations (planning and scheduling) from the *execution* functions. According to this partitioning, execution is responsible for interacting with the shop floor in order to implement tasks, and decision support is responsible for specifying which tasks will be executed and in which sequence in order to meet the production requirements (Davis and Jones, 1988).

The execution functions of the program would require a distributed control system. In a distributed control system, control is exercised by passing messages and signals between controllers and by performing specific tasks. Figure 5 illustrates the baseline structure of a the shop floor controller. In this

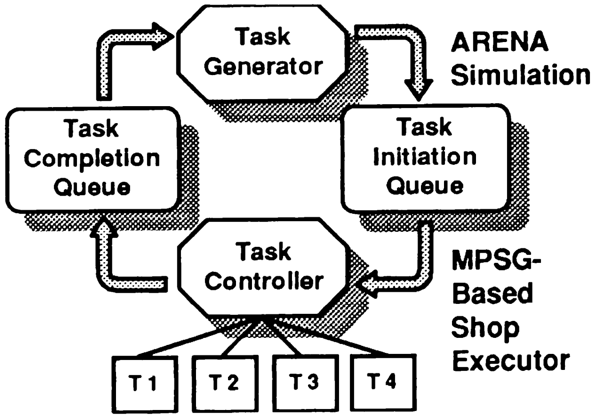

Figure 5. The simulation-based shop floor controller structure sequences tasks.

structure, the ARENA simulation provides decision support (task generation) and the controllers perform the execution functions. The task generator and execution module communicate through a task initiation queue (TIQ) and the task completion queue (TCQ).

Agility is not complete without direct, integrated support for the coordinated release and distribution of work-instructions to shop floor personnel. The result of *execution* is the generation of the task instruction and the presentation of electronic work-instructions to complete the task. Our definition of work-instruction is any kind of message, document or picture that provides information about the task. Work-instructions thus provide answers to questions about what task to do, what is required to do the task, how to do the task and how to determine if the task was done correctly. In the aerospace environment, delivery of work-instructions is a combination of electronic, verbal and written channels and the receiving devices are foremen and operators in addition to machines.

This information will be available not only for the current task, but also for any task upstream or downstream from the current task.

8 SUMMARY

As demonstrated by the recent release of Air Force Acquisition Policy 93M-013, factory simulation is recognized as an enabling technology for the achievement of agile aerospace manufacturing. The approach described here promises to be an efficient and effective method of leveraging the investment in factory simulation to improve four critical manufacturing functions (modeling, planning, scheduling, and work-instruction) in a single integrated environment.

A key feature of our approach is that the rules and procedures of the proposed scheduling system are first previewed by using a simulation of the system to determine how well they perform. The advantage of the approach is that the underlying simulation model provides the most accurate depiction of future production capacity. The shop controller generates start and finish times which become constraints for the workstation level schedulers who, in turn, do their own independent scheduling.

The major function of the simulation model is to evaluate alternate control policies. The simulation model queries current databases and determines the future state of the system by making a pass of deterministic simulation according to a rule or set of rules defined in the rule module. The system performance predicted by each pass of simulation is a measure of closeness to an objective function from the higher level factory control system. Thus, at the end of all passes of the simulation, the best schedule is then applied to the physical manufacturing system.

The execution function is responsible for interfacing with the operators, machinery and other applications which control the system. Execution provides the mechanisms for carrying out the actions specified by the scheduler and manages the actual flow of information and parts between the operators, fixtures and departments.

REFERENCES

Centeno, M. A. and C. R. Standridge, "Databases: Designing and Developing Integrated Simulation Modeling Environments," Proceeding of the 1994 Winter Simulation Conference (forthcoming), Society for Computer Simulation, La Jolla, CA, 1993, pp. 526-534.

Chang, T. C., Wysk, R. A. and Wang, H. P., Computer-Aided Manufacturing, Prentice-Hall, Englewood Cliffs, NJ, 1991.

Cho, H., A. Derebail, T. Hale and R. A. Wysk, "A Formal Approach to Integrating Computer-Aided Process Planning and Shop Floor Control," Transactions of the ASME, Vol. 116, February 1994, pp. 108-115.

Davis, W. and A. Jones, "A Real-Time Production Scheduler for a Stochastic Manufacturing Environment", Inter. Journal of Computer Integrated Manufacturing, Vol. 1, No. 2, 1988, pp. 101-112.

Derebail, A., H. Cho and R. A. Wysk, "Process Plan Representation for Shop Floor Control", to appear in Computer Control of Manufacturing Systems, edited by Joshi, S. B. and Smithe, J. S., Chapman and Hall (in press).

Harmonosky, C. M. and S. F. Robohn, "Real-time Scheduling in Computer Integrated Manufacturing: A Review of Recent Literature," International Journal of Computer Integrated Manufacturing, Vol. 4, No. 6, 1991, pp. 331-340.

Pegden, C. D., R. E. Shannon and R. P Sadowski, Introduction to Simulation Using SIMAN, McGraw-Hill, New York, NY, 1990.

Smith, Jeffery S., A, Derebail, R. Wysk, D. Sturrock, S. Ramaswamy, G. Smith and S. Joshi, "Discrete Event Simulation for Shop Floor Control", Proceeding of the 1994 Winter Simulation Conference (forthcoming), Society for Computer Simulation, La Jolla, CA, 1994.

Wu, S. A. and R. A. Wysk, "An Application of Discrete Event Simulation to On-line Control and Scheduling in Flexible Manufacturing," Inter. Journal of Production Research, Vol. 27, No. 9, 1989.

Wu, S. and Leon, V., "A Search Algorithm for AND/OR Graphs Containing Chance Arcs", Artificial Intelligence (to appear).

Wysk, R. A., S. B. Joshi and C. D. Pegden, Rapid Prototyping of Shop Floor Control Systems for Computer Integrated Manufacturing, ARPA project #8881, 1992.

AUTHOR BIOGRAPHIES

RAY ROLEN is presently the Technical Team Leader for the development of the Automated Concurrent Engineering Synthesis System (ACES) at McDonnell Douglas Aerospace. He has developed commercial electronic systems and processors for 15 years with Sycor Inc., Automation Industries and Northern Telecom. With MDA for the past 12 years, he has been involved in a variety of system engineering disciplines including reliability, maintainability, product support, and manufacturing in direct support of programs and engineering tool development. Mr.

Rolen has a B.S. in Industrial Engineering Technology from the University of North Florida.

RICHARD KILGORE is currently under contract to McDonnell Douglas Corporation as leader of the Process Simulation team of the New Aircraft and Missile Products division of McDonnell Douglas Aerospace - East (MDA-E). He is the Principal Investigator for an MDA-E Internal Research and Development project in Agile Manufacturing Simulation. Dr. Kilgore received his BBA and MBA degrees from Ohio University and his PhD in Management Science from The Pennsylvania State University. Dr. Kilgore has been a consultant to industry in the area of operations research, simulation and scheduling for the past 6 years as a partner in Midwest Modeling Technologies.