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Edwin A. Kjeldgaard, Dean A. Jones, George F. List, Mark A. Turnquist

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Planning and Scheduling for Agile Manufacturers: The Pantex Process Model

Edwin A. Kjeldgaard
Transportation Systems Analysis Department
Sandia National Laboratories
Albuquerque, NM 87185-0718

Dean A. Jones
Parallax, Inc.
Albuquerque, NM 87112

George F. List
Rensselaer Polytechnic Institute
Troy, NY 12180

Mark A. Turnquist
Cornell University
Ithaca, NY 14853

Abstract

Effective use of resources that are shared among multiple products or processes is critical for agile manufacturing. This paper describes the development and implementation of a computerized model to support production planning in a complex manufacturing system at the Pantex Plant, a US Department of Energy facility. The model integrates two different production processes (nuclear weapon disposal and stockpile evaluation) that use common facilities and personnel at the plant. The two production processes are characteristic of flow-shop and job-shop operations. The model reflects the interactions of scheduling constraints, material flow constraints, and the availability of required technicians and facilities. Operational results show significant productivity increases from use of the model.

Contents

Figures

Executive Summary

Introduction

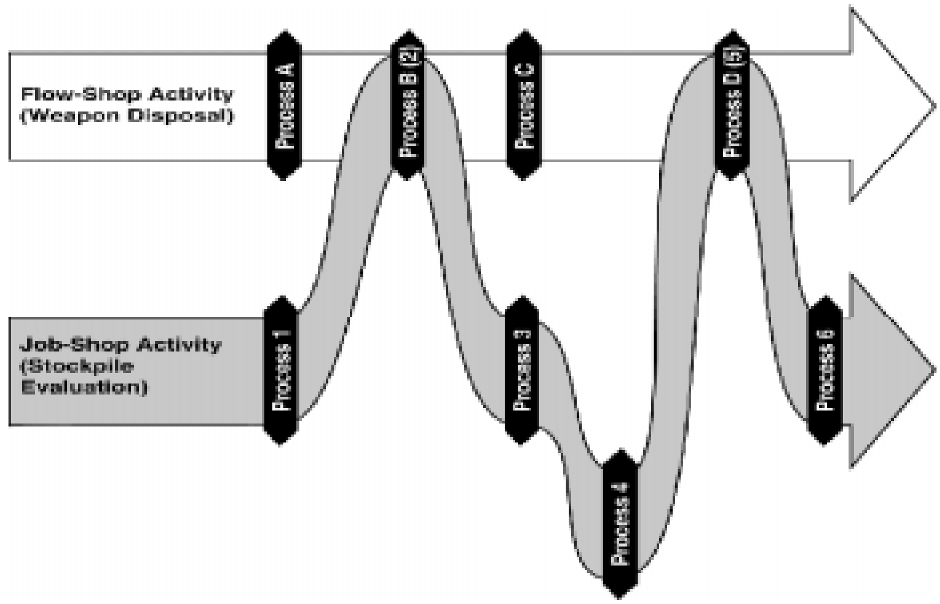
Sandia National Laboratories has developed and implemented a computerized model to support the planning and scheduling activities at Pantex, a US Department of Energy (DOE) production plant in Amarillo, Texas. The Pantex Process Model (PPM) incorporates modern management science techniques to optimize production planning and scheduling in the complicated production system at Pantex. The plant simultaneously supports two major DOE programs—nuclear weapon disposal and stockpile evaluation—which share its resources (facilities, technicians, and equipment).

The PPM, a major advancement in manufacturing optimization tools, has the ability to

- **integrate** two fundamentally different types of production processes that use common facilities and personnel,
- **optimize** total production output,
- **allocate** technicians efficiently, and
- **expedite** recovery planning and evaluation of options if production is disrupted.

These capabilities make the PPM particularly well suited to support *agile* manufacturing, which must be able to revise production plans quickly in response to changing customer needs.

Traditional manufacturing is generally set up as one or the other of two different production environments: a *flow shop* **or** a *job shop*. A flow shop is a Henry Ford-like production line in which a large number of individual production units follow the same sequence of operations. In a job shop, a small number of individual units are made, and the sequence of operations is different for each unit.



The Pantex Process Model integrates two different types of production activities.

The mathematical formulations required for modeling the two activities are quite different. Computerized tools had been developed to support the separate scheduling of flow-shop and of job-shop activities, but the requisite computational tools were not available to support, in a user-responsive manner, the demanding calculations required to solve scheduling problems for **both** activities commingled in an agile production environment.

In active collaboration with the Production Planning and Scheduling Department at Pantex, Sandia designed the PPM to solve concurrent flow- and job-shop planning and scheduling problems, thus optimizing the total output from an agile manufacturing facility such as Pantex.

Complexity of the Planning/Scheduling Problem

Production planning and scheduling for Pantex is a challenging problem. The objective is to maximize total production output, given the resource constraints of the plant. Pantex production activities are primarily manual operations associated with the assembly/disassembly and evaluation of nuclear weapons. Processing a specific weapon system requires facilities with appropriate capabilities and technicians with appropriate certifications.

The production planning/scheduling problem for these activities includes the following elements:

Concurrent flow of two different production processes. Pantex production operations comprise two fundamentally different processes—weapon disposal and stockpile evaluation—that share common facilities and personnel. Weapon disposal activities resemble a typical production line (flow shop). Stockpile evaluation activities, on the other hand, resemble a typical job shop; they require unique sequences of operations on individual units, and each unit has its own scheduling constraints (earliest available start time, latest allowable completion time). Operations networks for the evaluation activities are substantially more complex than those for disposal.

Constraints on resource allocation. The problem of allocating available resources (technicians and facilities) is compounded by extremely demanding, complex rules for safety and security.

Technician allocation considerations include the following:

- ***Certification constraints***. Before technicians can perform a particular operation, they must receive extensive training and be certified to perform that operation. Each technician holds up to five certifications. Allocating some three hundred technicians and one hundred unique certifications presents a daunting problem in itself. Added to the challenge is the fact that these certifications must be used or they are lost, as determined by another complex set of rules.
- ***The "two person" rule***. Most operations require that at least two technicians, both holding the same certification, be present during the operation.
- ***Radiation dose constraints***. Strict guidelines must be followed to ensure that technicians receive radiation doses as low as reasonably attainable per a specific period of time. If they reach the maximum dose level, they are unavailable for production activities for a specified period of time, regardless of their certification status.

Facility allocation is likewise complicated by complex rules for safety and security. Currently, there are 29 unique types of facilities considered by the model. Each is governed by a set of rules, including limits on fissile and explosive materials, as well as by environmental and physical requirements.

Storage constraints. An additional factor that complicates production planning and scheduling at Pantex is the plant's limited storage capacity. Currently, the PPM tracks upwards of 55 parts of interest from each weapon unit relative to storage capacity. Because of tight storage (or staging) constraints, the arrival, staging, and shipment of weapons, as well as the storage, staging, and shipment of parts, must be closely monitored and controlled to support a production plan and schedule. The Pantex storage facilities, like the production facilities, are governed by complex rules for safety and security.

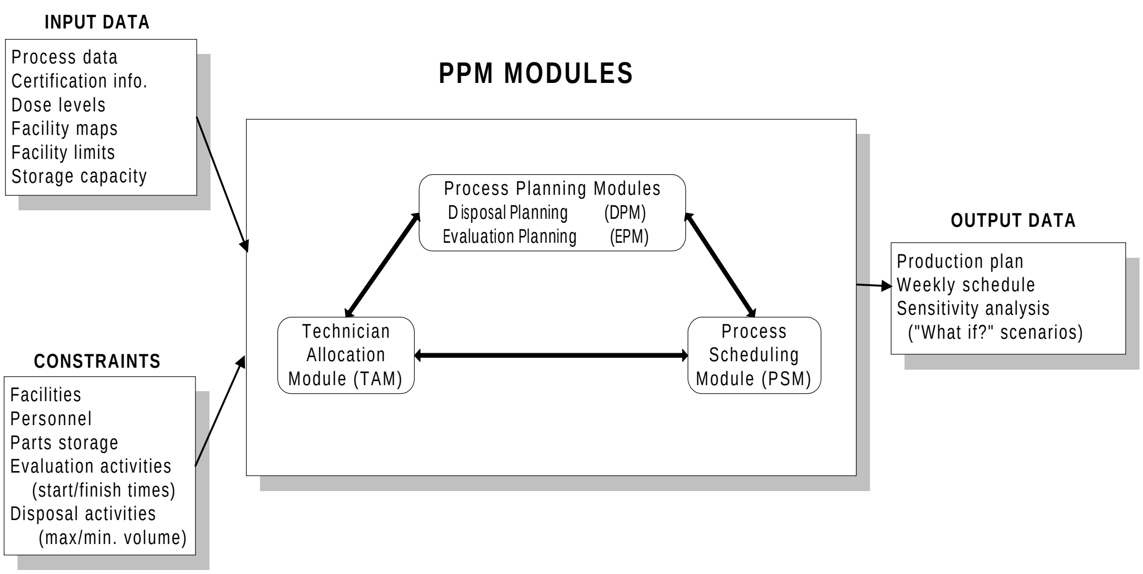
The Solution Procedure

An effective solution procedure was developed that allows near-optimal solutions to be computed in a matter of minutes on a PC-based system running under MS Windows. The procedure uses commercial software (a database management system, optimization software) and custom code, which is written in Visual Basic.

The model involves a very large mixed-integer programming formulation (in excess of one million variables). The keys to the computational success are an effective decomposition of the overall problem and development of efficient solution procedures for the resulting subproblems.

Structure of the Model

The PPM is modular in design. This modular design facilitates modification of the model to meet new or changing requirements. It also allows substitution of other components, such as alternate optimization software.



Structure of the Pantex Process Model (PPM)

How the Model Works

The figure above shows the modular structure of the PPM, which includes process planning modules for disposal and evaluations, a technician allocation module, and a process scheduling module. The process scheduling module translates information from the process planning modules (monthly production volumes and activities) and from the technician allocation module (technician certifications, radiation dose levels) into a workable schedule. This schedule assigns particular operations and individual technicians to specific facilities. The following paragraphs describe how each module in the PPM functions, and how the modules are interconnected.

The Disposal Planning Module (DPM). The DPM is a large-scale linear programming model that seeks to maximize the total number of units **(weapons) disposed** over a one-year planning period, subject to constraints on

- availability of facilities,
- technician availability,
- availability of space for storage/staging of both incoming units and outgoing parts/subassemblies, and
- mandated program requirements for specific weapon systems.

The DPM output is an optimal disposal plan, on a month-by-month basis, for a one-year planning period. Because the DPM is a linear programming model, the solution also yields valuable sensitivity analysis information. For example: "How much could total throughput be increased if additional hours of facility type X were made available?" The binding constraints in the DPM solution identify the choke points in the process and enable the user at Pantex to determine whether the number of disposals is being limited by the availability of facilities, technicians, or storage/staging areas.

The user interface for the DPM enables the staff in the Production Planning and Scheduling Department at Pantex to focus on providing input data in a form they are already familiar with. Output is as graphical as possible in order to facilitate understanding and communication among all sections of the Pantex operation. The user-responsive interface also allows the Pantex planners to

- change selected inputs quickly and rerun the model,
- respond effectively to "what if" questions from DOE, and
- change the disposal plan to reflect the influences of unanticipated disruptions in the production process.

The Evaluation Planning Module (EPM). The EPM creates a plan for conducting a set of pre-specified **stockpile evaluation** activities over the course of a one-year planning period. Typically, each activity involves an earliest possible start time, a due date for completion, and a specified set of operations that must be performed in a particular order. Each operation requires a certain type of facility and technicians with specific certifications. The evaluation activities share the overall pool of facilities and technicians with the disposal activities.

The solution to this problem is based on techniques for multi-project, constrained-resource project scheduling. The output of the EPM is a proposed plan, on a week-by-week basis, for conducting the required evaluation activities, and a determination of what resources (facilities and technicians) must be allocated to those activities each week.

The essential idea embedded in the solution procedure for the EPM is to “slide” the evaluation activities into their available “time windows” in order to stay within the resource constraints (facility availability, technician availability) and maintain the required sequence of operations for each activity. For situations of realistic size, this is a very complicated problem. Therefore, the useable solution methods are heuristics (approximating algorithms).

The DPM and EPM are closely connected because they are used to plan activities that compete for a common set of resources (facilities and technicians). These two modules interact directly to ensure that the available facility-hours of each facility type are allocated efficiently between disposals and evaluations. For technicians, the interaction is more complex because both the DPM and the EPM are seeking available technician-hours for particular certifications, and individual technicians often hold multiple certifications. Thus, the interaction between the DPM and EPM for technicians requires a third module, the Technician Allocation Module.

The Technician Allocation Module (TAM). The TAM determines allocations of technician-hours in each month of the one-year planning period to meet demands arising from the DPM and EPM for technician-hours of various certifications. The model takes the form of a network optimization for each month, with linking constraints across the months of the year to prevent overexposure of any individual technician to radiation. In the network structure of the model, the “supplies” (available hours for a specific technician with given certifications) are allocated to meet the “demands” (required technician-hours, by certification, within a given month). A “pseudo-source” is included to identify any infeasibilities that must be resolved by iteration with the DPM and EPM. The resulting network problem can be solved very efficiently using specialized algorithms.

In a typical application, the DPM and EPM are run first, using “infinite” technician resources, to generate a desired level of technician-hours in each certification. Then the TAM is run to determine how many hours in each certification can be supported by existing technicians. These values are then input back to the DPM and EPM for analysis with certification AND facility constraints. The TAM is run one final time to bring the analysis to closure—a complete, consistent plan.

The Process Scheduling Module (PSM). When consistent results (involving disposals, evaluations, and technician allocations) are achieved, the PSM is invoked to translate those results into actual assignments of specific technicians and facilities to specific tasks over a specific time period (typically one week to one month). At that point, detailed requirements and special regulations such as limits on fissile materials are taken into account to ensure the feasibility of the planned activities. If infeasibilities are uncovered, it may be necessary to return to the planning modules to revise the overall plan.

Results in Application

The potential productivity increases achieved from use of the PPM may be substantial. Using the PPM, the Production Planning and Scheduling Department at Pantex has already realized significant improvement in the following areas:

- **total production output –** The PPM allows Pantex to achieve *near optimal* production output, as opposed to settling for the first *workable* plan and schedule.
- **response time for planning and scheduling –** Use of the PPM cuts the response time from weeks to hours, while increasing confidence in the answers achieved, for planning and scheduling challenges such as rescheduling production activities after a disruption or replying to “what-if” questions.
- **allocation of technicians –** The optimal allocation of technicians requires juggling thousands of variables, which is an impossible task to do well without computer support. The PPM assigns technicians optimally; it also provides guidance on future requirements for technician training.
- **allocation of facilities –** The PPM assigns specific facilities for specific tasks in an optimal manner, taking maintenance activities into account.
- **identification of potential choke points –** For production planning and risk management purposes, it is important to understand which processes control production output. The PPM identifies such choke points. It also provides valuable sensitivity analysis information that enables the users to determine whether production output at any particular point in time is being limited by facility availability, technician availability, or the availability of storage/staging areas.

Future Direction

This report provides a snapshot of the Pantex Process Model as of September 1996, when the application (PPM Version 2.0) was delivered to the Production Planning and Scheduling Department at Pantex. Future work will focus on the future needs of Pantex by enhancing the analytic capabilities of the model and exploring new solution strategies.

Introduction

Manufacturers today face increasing pressure to be *agile*—that is, to be able to produce a variety of products in varying volumes with short lead times, and to be able to revise production plans quickly in response to changing customer needs. Nagel and Bhargava (1994) define agile manufacturing as “the ability to thrive and prosper in a competitive environment of continuous improvement and unanticipated change, to respond quickly to rapidly changing markets driven by customer-based valuing of products and services.”

Although this definition is aimed primarily at private-sector, for-profit companies, it also applies to many manufacturing operations conducted today for the US government, particularly the DOE. The Pantex Plant in Amarillo is a classic example of a DOE facility under increasing pressure to be agile. The plant is responsible for conducting two fundamentally different types of production processes concurrently. And their product is a highly specialized one: nuclear weapons. The production planning and scheduling problems Pantex faces are therefore even more formidable than the problems faced by most private-sector manufacturers.

As manufacturing environments in both the private and government sector become increasingly complex, production planners must wrestle with the dilemma of demands that compete for shared production resources (e.g., facilities, technicians, equipment, tooling). Production planning and task scheduling have become all the more difficult.

Effective production planning tools to allocate and schedule shared resources are required in an agile manufacturing environment. Therefore, Sandia National Laboratories, in active collaboration with the Production Planning and Scheduling Department at Pantex, developed and implemented a computerized model to optimize the plant’s production planning and scheduling. The so-called Pantex Process Model (PPM) is a major advancement in manufacturing optimization tools, in that it has the ability to

- **integrate** the planning and scheduling of two fundamentally different types of production processes that use common facilities and personnel,
- **optimize** total production output,
- **allocate** production technicians efficiently, and
- **expedite** recovery planning and evaluation of options if production is disrupted.

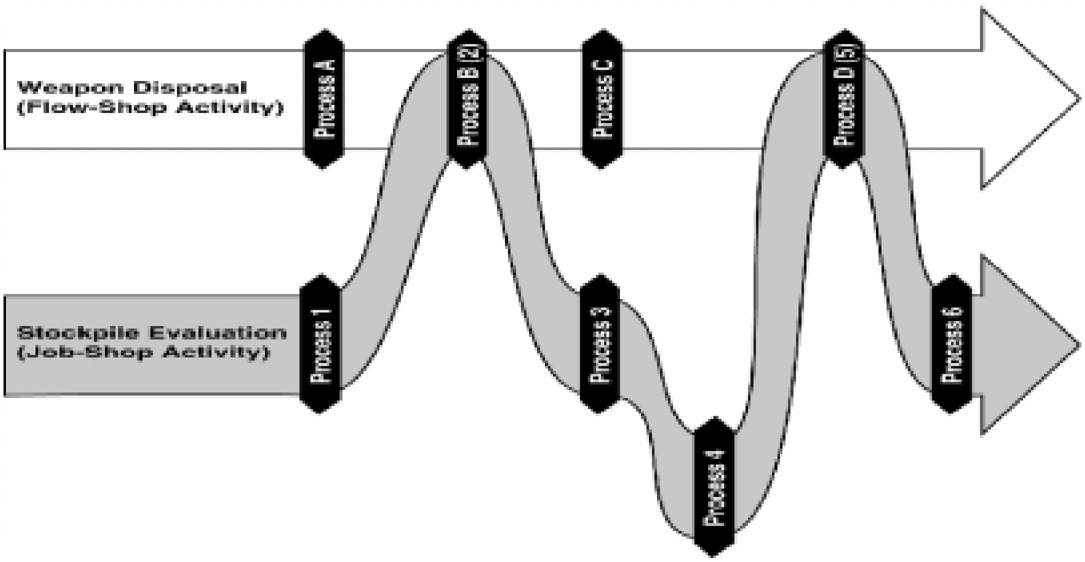


Figure 1. The Pantex Process Model (PPM) enables users to optimize the total throughput in a manufacturing environment where flow-shop and job-shop activities are commingled.

Simultaneous planning of so-called *flow-shop* and *job-shop* production processes that use common resources is a key characteristic of the model (see Figure 1). Pantex is engaged in a mixture of production tasks that compete for common production facilities, personnel, and storage areas. **Disposal** tasks involve many similar units that are processed through the same sequence of steps. In manufacturing terms, the disposal process is a **flow shop**, a traditional Henry Ford-like production line in which many individual units follow the same specified sequence of operations. The focus of production planning is on overall throughput, line balancing, bottleneck identification, etc.

Evaluation tasks, on the other hand, involve only a single unit, which is partially disassembled, tested, and then reassembled; each evaluation task involves a relatively unique sequence of steps. In manufacturing terms, the evaluation process is a **job shop**. Individual units are “made” to order, with varying sequences of operations and varying start and stop times for each operation. Morton and Pentico (1993) provide a thorough description of the differences in approaching production planning and scheduling for flow shops and for job shops.

The mathematical formulations for modeling flow-shop production flow and job-shop production flow are quite different. Although computerized tools exist to support the scheduling of each type of flow, the requisite computational tools were not yet available to support the demanding calculations required to schedule **both activities commingled** in an agile manufacturing environment. To meet this need, Sandia designed the PPM—a mathematical model that enables users to solve concurrent flow- and job-shop planning and scheduling problems, thus providing a computed solution that is likely to be much closer to optimal than a hand-developed solution, where finding any workable plan is a time-consuming challenge.

Morton and Pentico (1993, p. 297) define a flow shop as one in which “each job is processed by a series of machines in exactly the same order.” Hence the dismantlement process at Pantex is a flow-shop operation in that multiple jobs (individual weapons of the same type) are processed by a series of machines (operations that require a specific type of facility plus one or more technicians with specific certifications) in exactly the same order.

The process is a classic *compound flow shop*, in that there is more than one machine (operation) available at most steps in the series. The complexity of the dismantlement process far exceeds that of a flow shop defined in the scheduling literature, however. At Pantex, multiple streams of jobs (different weapon systems) compete for the same set of resources (facilities, technicians). And these different job streams may require particular types of facilities in a different order, even though each job within a stream is processed identically.

Because the dismantlement process is more complex than the standard flow-shop process, the dismantlement planning problem addressed by the PPM is different than the conventional flow-shop problem in the scheduling literature (see, for example, Morton and Pentico, 1993; Lawler et al., 1993; Hall, 1997). The conventional problem is one of determining the start time for each job on each machine in order to optimize an objective, the standard objective being to **minimize makespan, the total time** from initiation of the first job on the first machine until completion of the last job on the last machine. The fundamental problem addressed by the PPM is to provide a plan for allocating limited resources (facility-hours and technician-hours) to the various streams of jobs (different weapon systems) in order to **maximize the total number of weapons dismantled** over a one-year planning horizon. The resource allocations are done for a set of very coarse time periods (months), and the model produces answers of the form “140 hours of time in facility *xyz* should be allocated to operation *j* for weapon system *s* next month.” This solution is quite different from the conventional solution of determining the exact time that operation *j* for weapon *serial number 123456* should begin in a particular facility.

The evaluation planning problem addressed by the PPM is much closer to that of conventional job-shop planning, although the problem is complicated by the fact that multiple resources must be present simultaneously in order for a specific task to be performed. By the standards in the literature on scheduling theory, evaluation planning at Pantex is a very large problem, with several hundred jobs, more than a thousand tasks, several dozen types of facility, and more than a hundred technician types (certifications). The size and complicated nature of the problem dictate that we use heuristics to find good, but not necessarily optimal, solutions.

The PPM has been designed to integrate two types of processes— one fundamentally a flow shop and the other fundamentally a job shop—that compete for shared resources. Our objective, however, is to provide guidance on **planning the allocation of resources** to these various activities, not to determine precise schedules for individual tasks, specific facilities, and particular technicians.

Problem Definition

The problem is to maximize total throughput (production) at Pantex, given limited resources and required milestones for certain operations. Production activities are mostly manual operations associated with the assembly/disassembly and evaluation of nuclear weapons. Processing a specific weapon requires facilities with appropriate capabilities and technicians with appropriate certifications. The production area comprises 29 unique types of facilities. Total throughput is in the thousands, and production technicians number about 300.

The problem of production planning and scheduling is extremely complex. It includes the following elements:

Concurrent flow of two fundamentally different production processes. Pantex production operations comprise two fundamentally different processes that share common facilities and personnel. Some processes are flow-shop activities—the disassembly of many similar units that require processing through the same sequence of steps. **Disposal** (disassembly) requires performance of a sequence of operations, which are defined as a network flow diagram in Figure 2. At any given time, several different types of weapon systems are being disassembled at Pantex, and each type is at a different stage in its sequence of disposal operations.

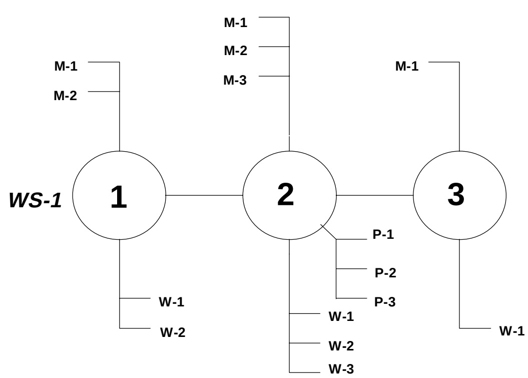


Figure 2. Example flow diagram of* disposal operations *used by the PPM for weapon system WS-1. The three nodes (numbered circles) indicate specific disposal operations or processes, where* W-1 = *waste stream 1,* M-1 = *input material 1, and* P-1 = *part 1.

Other processes are job-shop activities—the evaluation of a single weapon (unit) that must be partially disassembled, tested, and then reassembled in a relatively unique series of steps, as shown in Figure 3. Each unit typically has scheduling constraints (i.e., earliest available start times and latest allowable completion times). ***Evaluation*** tasks are significantly more complex than disposal tasks, and often involve situations where facilities are being "used" by partially disassembled units, even though no technicians are involved. In addition, each task has precedence constraints (for example, task 5 can't be started until task 4 is completed).

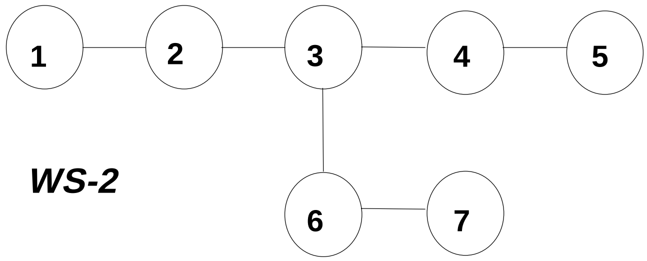


Figure 3. Example flow diagram of evaluation operations used by the PPM for weapon system WS-2. The seven nodes (numbered circles) indicate specific evaluation operations or processes. Unlike the disposal sequence, the number and type of evaluation operations are different for each weapon, within and across weapon systems. Like the disposal sequence, however, evaluation operations include waste streams, input materials, and parts, although these are omitted from the figure for the sake of clarity.

Constraints on resource allocation. The problem of allocating available resources (technicians and facilities) is compounded by extremely demanding, complex rules for safety and security. Technician allocation considerations include the following:

- *Certification constraints*. Before technicians can perform a particular operation, they must receive extensive training and be certified to perform that operation. Each technician holds up to five of the required certifications. Allocating some three hundred technicians and one hundred unique certifications presents a daunting problem. Added to the challenge is the fact that these certifications must be used or they are lost, as determined by another set of complex rules.
- *The "two person" rule*. Most operations require that at least two technicians, both holding the same certification, be present during the operation.
- *Radiation dose constraints*. Strict guidelines must be followed to ensure that technicians receive radiation doses as low as reasonably attainable. If they reach the maximum dose level, they are unavailable for production activities for a specified period of time, regardless of their certification status.

Facility allocation is likewise complicated by complex rules for safety and security. Currently, there are 29 unique types of facilities considered by the model. Each is governed by a set of rules, including limits on fissile and explosive materials, as well as by environmental and physical requirements. Furthermore, a hierarchy exists among these facilities, so that an operation that is normally performed in a facility of type A can also be performed in a facility of type B, but the converse is not necessarily true.

Storage constraints. An additional factor that complicates production planning and scheduling at Pantex is the plant's limited storage capacity. Storage facilities are used both to stage incoming weapons (to be evaluated or disposed of) and to store parts removed from the weapons (either temporarily or permanently). Currently, the PPM tracks 55 parts of interest from each weapon unit relative to storage capacity. Because of tight storage (or staging) constraints, the arrival, staging, and shipment of weapons, as well as the storage, staging, and shipment of parts, must be closely monitored and controlled to support a production plan and schedule. Pantex storage facilities, like its production facilities, are governed by complex rules for safety and security.

Background

Between 1984 and 1989, some members of the PPM design team participated in the Production Risk Evaluation Program (PREP), a large-scale analysis of the US nuclear weapon production complex (Kjeldgaard et al., 1997). This analysis focused on the vulnerability of the production complex to significant disruptions. The experience and knowledge they gained from that activity led to the effort to apply similar modeling techniques to the nuclear weapon dismantlement program at Pantex.

The original concept for the PPM was born in the fall of 1991 in response to DOE’s having placed nuclear weapon dismantlement on a directive schedule. (That is, the formal schedule for dismantlement over a multi-year period—agreed upon at the top levels of government—had become the primary driving force behind production planning at Pantex.) The results from the PREP effort included capabilities for analyzing dismantlement process flows and the total throughput of various weapon systems. These capabilities led to the **first major transformation** of the model, from vulnerability analysis to dismantlement planning. At that point, the primary customer was DOE in support of its dismantlement program planning activity.

The **second major transformation** of the model occurred in the fall of 1993, when the Pantex Production Planning and Scheduling Department committed to making the PPM its primary tool in upgrading its planning and scheduling infrastructure. That commitment greatly expanded the scope and complexity of the model, in that it was to include the planning and scheduling of all production (disposal, evaluation, and rebuilds) at the plant.

NOTE: The terms ***dismantlement*** and ***disposal*** are synonyms in the context of this report. For clarity and consistency with the client’s terminology, however, we hereinafter use only the term *disposal*. Hence, the report discusses two Pantex production processes: *disposal* and *evaluation* of nuclear weapons in the US stockpile.

Implementation and Impact of the Pantex Process Model

Sandia adopted an effective strategy for solving the complex Pantex problem of production planning and scheduling: ***agile development*** of the Pantex Process Model. Agile development refers to the ongoing, creative collaboration between the Sandia PPM development team and the Pantex customer. This arrangement has been encouraged in order to meet the challenge of creating a useful, practical tool that would have a measurable impact on the way Pantex does business. After delivering the initial application (PPM Version 1.0), and its successor (PPM Version 2.0), the development team has continued to work with the customer through full implementation to ensure that the project goal is met.

Software

To meet the needs of Pantex users in terms of ease of use and functionality, Sandia designed the PPM as a Microsoft Windows application. The system integrates custom code, written in Visual Basic, with commercial software to produce a user-friendly environment. As shown in Figure 4, custom code has been used to implement specialized analysis routines, as well as input and output structures. The commercial software integrated into the application includes Microsoft Access, LINGO optimization software, Crystal Reports, and Microsoft Project.

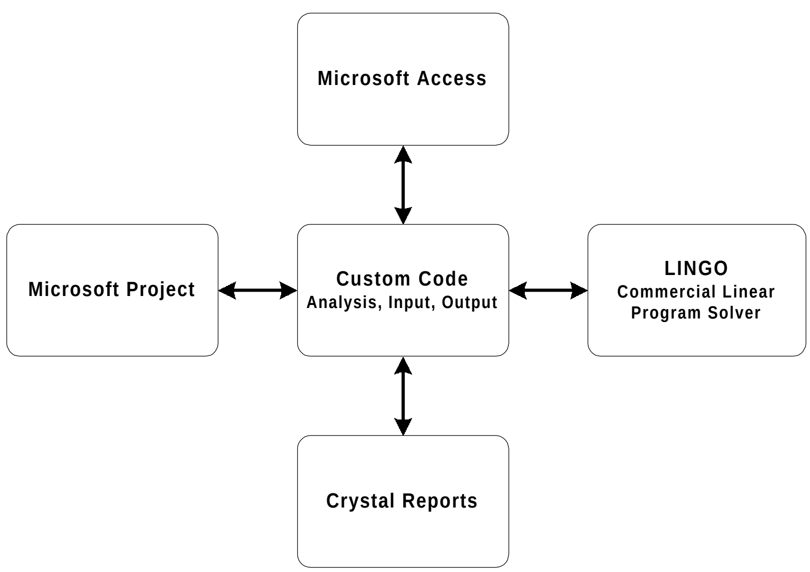


Figure 4. Custom code written in Visual Basic integrates the commercial software in the PPM system.

User Interface Design

The interface designed for the PPM employs a host of menus and toolbars to assist the user in navigating various aspects of the model. The actions taken by the user are tracked so that menu choices and toolbar buttons are active only at the appropriate times (context sensitive). This design simplifies the running of the PPM significantly because it allows users to actively limit the features requiring their attention.

As with most detailed analysis models, extensive quantities of data are required for accurate results. The interface and underlying data structures were designed to assist users in managing this data and selecting necessary analysis parameters. Terms familiar to the customer were used throughout the interface to assist in the interpretation of model results. This results in an overall model that is very responsive to user needs. This user-responsive interface also allows the customer to change selected inputs quickly and rerun the model, in order to:

- respond effectively to “what if” questions from DOE, and
- change the production plan to reflect the influence of unanticipated disruptions in the production process.

The two figures that follow show representative views from the PPM. Figure 5 is a typical input form, which shows the level of detail incorporated into the model. In this view, a particular production technician’s availability is being adjusted. This technician has a number of active certifications (shown on the left side of the figure) along with daily availability (in hours) for this particular month (shown on the right). Note the menu and toolbar structure at the top of the figure. Figure 6 is a representative graphical output form—a final production plan. Additional examples of PPM graphical output are presented in the next chapter.

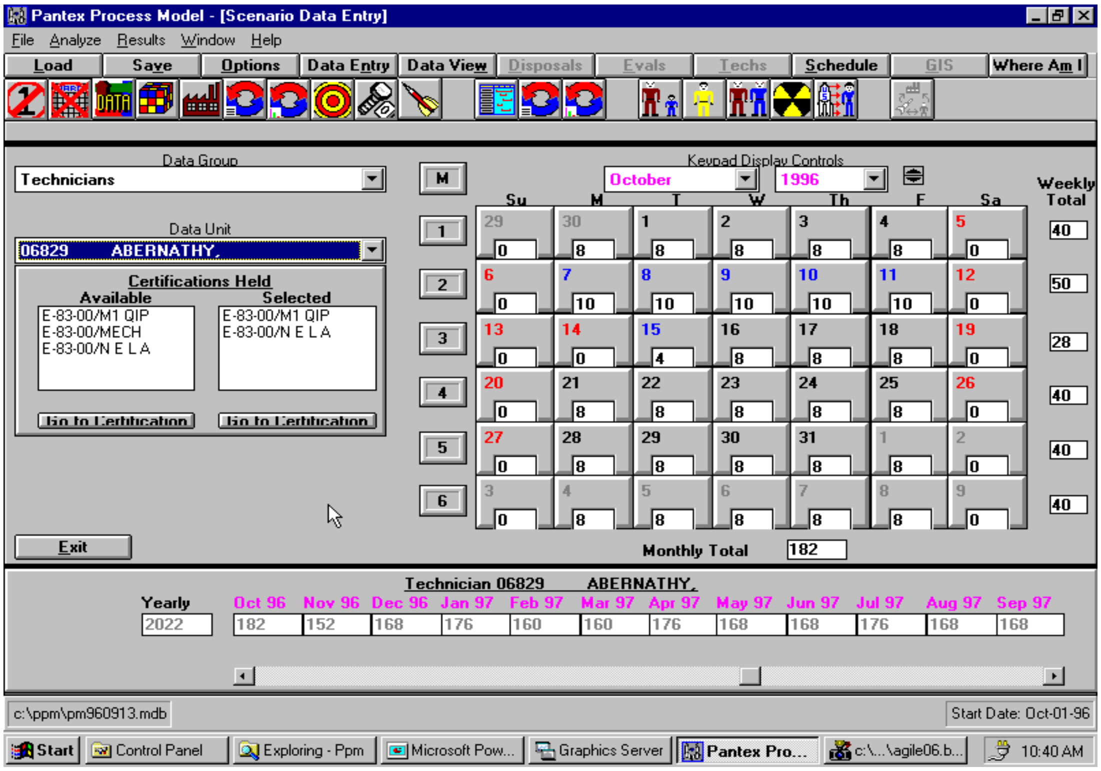


Figure 5. Example of a PPM data entry screen

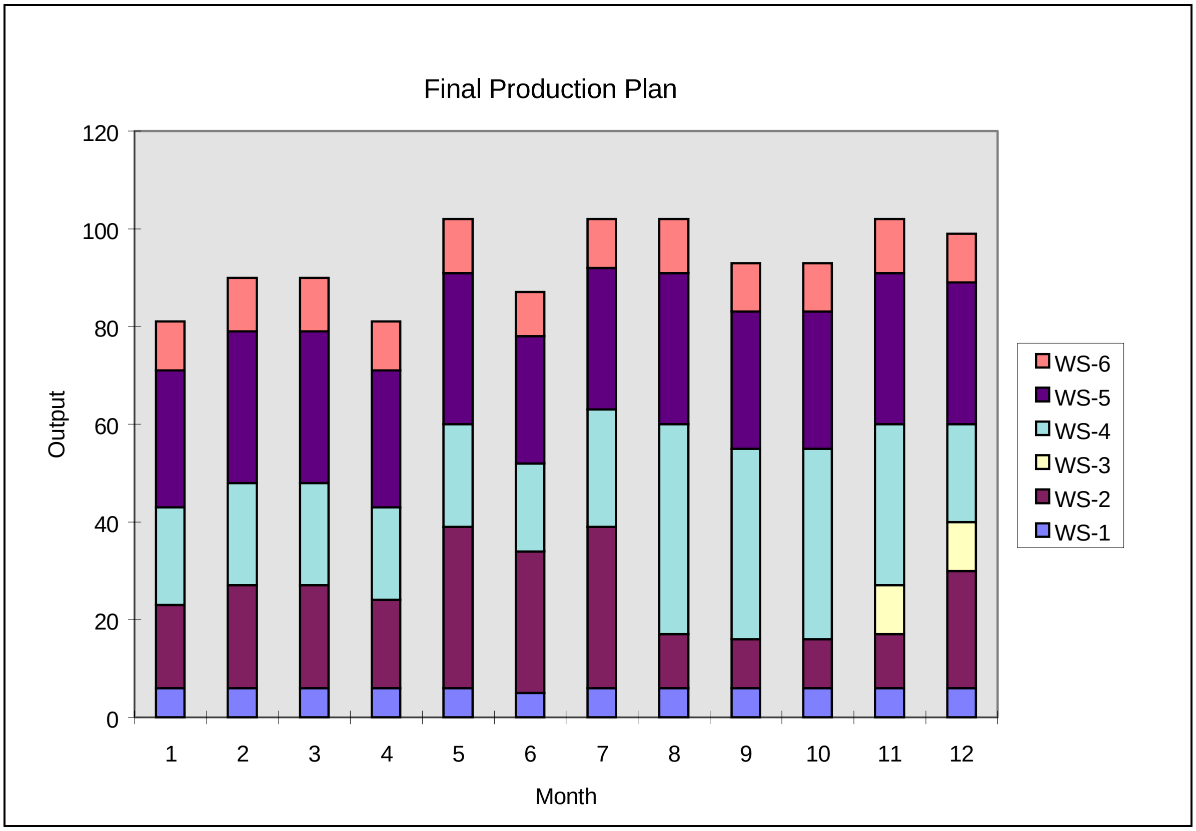


Figure 6. Example of PPM graphical output, showing the production plan for optimal throughput (output), by month, of six types of weapon systems (WS-1 through WS-6) over a 12-month planning horizon.

Improvements Realized by Pantex

The potential productivity increases achieved from use of the PPM could be substantial. Using the PPM, the Production Planning and Scheduling Department at Pantex has already realized significant improvement in the following areas:

- **total production output –** The PPM allows Pantex to achieve *near optimal* production throughput, as opposed to settling for the first *workable* plan and schedule.
- **response time for planning and scheduling –** Use of the PPM cuts the response time from weeks to hours, while increasing confidence in the answers achieved, for planning and scheduling challenges such as rescheduling production activities after a disruption or replying to "what-if" questions.
- **allocation of technicians –** The optimal allocation of technicians requires juggling thousands of variables, which is an impossible task to do well without computer support. The PPM assigns technicians optimally; it also provides guidance on future requirements for technician training.

- **allocation of facilities –** The PPM assigns specific facilities for specific tasks in an optimal manner, taking maintenance activities into account.
- **identification of potential choke points –** For production planning and risk management purposes, it is important to understand which processes control production output. The PPM identifies such choke points and presents valuable sensitivity analysis information that enables the users to determine whether production output is being limited by facility availability, technician availability, or storage/staging availability.

Development of the PPM Model

Problem Formulation

In this section, we develop the mathematical formulation of the production planning problem. The overall production planning problem can be formulated as a large-scale mixed integer programming problem in which the objective is to maximize overall plant productivity (numbers of weapons disposed and evaluation jobs accomplished) over a one-year planning horizon. The constraints include resource availability limits (facilities, technicians, and storage) and schedules for inbound and outbound shipments of weapons. We explain thoroughly the construction of the constraints on technician use and allocation, but give only a brief summary of the constraints on facility and storage use, and weapon shipment schedules.

For the disposal activities, the basic time unit is one month. The actual disposal output in each month, V_{st} , is defined in terms of the units of weapons system *s* processed through particular operations in time unit *t*, since the operations are weapon-specific. Each operation requires a facility and technicians with the correct certification. The model focuses on the **flow** of units through the system, and the consumption of resources is measured in facility-hours and technician-hours.

If we let *s(i)* be the weapon system to which operation *i* belongs, we can write the consumption of technician-hours by disposals for a particular certification *c*, in month *t*, as follows:

$$\sum_{i \in I_c} u_i z_i V_{s(i)t} \qquad (1)$$

where I_c is the set of operations, *i*, for which certification *c* is required; u_i is the number of machine hours required to perform operation *i*; and z_i is the number of technicians required for operation *i*.

Technician-hours are also consumed by evaluation activities, so to form the full constraint for the resource represented by technicians with a specific certification, we need to add to the quantity in (1) the amount consumed by the evaluations. In contrast to the disposal activities, where many units flow through the same sequence of operations, the evaluation of a specific weapon unit requires a set of tasks that may be unique, so it is important to track the individual units through the specific tasks that are performed on it. For example, a lab test involves partial disassembly of the weapon, assembly of a test bed, conduct of the test, disassembly of the test bed, and rebuild of the weapon. These steps must be done in sequence, and within each step, more detailed tasks exist, some of which may be performed in parallel. "Due dates" are common for the intermediate tasks (e.g., for completion of the test bed), and meeting these dates has high priority. Also, tasks have priorities, and lower-priority tasks are "fit in" around the higher-priority ones on a resource-available basis.

These evaluation activities share technicians and facilities with disposals, but the required level of detail in terms of timing is much finer than for disposals. Individual tasks must be tracked, and these tasks require anywhere from a few hours to several weeks. Consequently, short time periods, *t'*, are defined, and these are "rolled up" to gain resource utilizations that mesh with the disposal activities. We will use *t* to denote months in the planning horizon (*t* = 1, 2,..., 12), and *t'* to represent the smaller periods used for tracking evaluation activities, and define $\beta(t')$ to be the length of period *t'* (e.g., hours) and *T(t)* to be the set of periods, *t'*, contained in month *t*. Then, a set of constraint equations can be written to ensure that sufficient technician resources (with a specific certification) are available to support all planned activities (disposals and evaluations) in each month.

$$\sum_{j} \sum_{l=t'}^{t'+d_j-1} g_{jk} v_{jl} = \Gamma_{kt'} \qquad \forall \quad k, t' \tag{2}$$

$$\sum_{i \in I_c} u_i z_i V_{s(i)t} + \sum_{t' \in T(t)} \Gamma_{k_c t'} \beta(t') - \sum_{e} x_{ect} - D_{ct} = 0 \qquad \forall \quad c, t \tag{3}$$

where d_j is the duration of task *j*; g_{jk} is the number of units of resource *k* required for task *j* (e.g., number of technicians); $\Gamma_{kt'}$ is the total units of resource *k* required during period *t'*; v_{jl} is equal to 1 if task *j* ends in period *l*, and 0 otherwise; x_{ect} is the technician-hours of employee *e* allocated to using certification *c* in month *t*; and D_{ct} is the excess technician-hours of certification *c* used in month *t*.

Constraint (2) is used to define the amount of resource *k* used in period *t'*. Constraint (3) then ensures that sufficient technician-hours of time (from technicians with the correct certifications) are allocated to support both disposal and evaluation activities. In (3), k_c is used to designate the resource index which corresponds to certification *c*. The variable D_{ct} for "excess technician- hours" in (3) helps remove the possibility that the PPM can terminate with "no feasible solution," leaving the users at Pantex wondering why that happened. These variables are added to the objective function as penalty terms, so the solution will not normally include them, but if a problem setup is created for the PPM that really is infeasible, the output values of D_{ct} help show why.

For the evaluation tasks, we must ensure that each one ends in some period, and include constraints to ensure that precedence relationships among the tasks are observed, as shown in constraints (4) and (5). Constraint (4) ensures that each task is scheduled to end in one (and only one) period. The limits on the summation, e_j and τ_j, in (5) are determined prior to the optimization, based on due dates and precedence relations among the tasks.

$$\sum_{t'=e_j}^{\tau_j} v_{jt'} = 1 \quad \forall \quad j \tag{4}$$

$$\sum_{t'=e_j}^{\tau_j} (t' - d_j) v_{jt'} - \sum_{t'=e_j}^{\tau_j} t' v_{lt'} \geq 0 \quad \forall \quad j, l \in P_j \tag{5}$$

where e_j is earliest time at which task j can end, based on the earliest possible start time for the evaluation activity of which j is a part, and the precedence relationships among the tasks; τ_j is the latest time for completion of task j, based on required due dates and precedence relationships among the tasks; and P_j is the set of all tasks that immediately precede task j.

Technician-hours (reflected by the x_{ect} variables) are allocated based on the availability of individual technicians, maximum allowable radiation exposure, and crew-size requirements for specific operations. If S_{et} is the hours available for technician e in month t, one set of constraints is:

$$\sum_{c \in C_{et}} x_{ect} \leq S_{et} \quad \forall \quad e, t \tag{6}$$

where C_{et} is the collection of certifications held by technician t.

The radiation exposure constraints, which ensure that no technician is allocated to tasks in such a way as to violate the acceptable exposure level, are written as follows:

$$\sum_{t} \sum_{i} r_i x_{ec(i)t} \leq U \quad \forall \quad e \tag{7}$$

where $c(i)$ is the certification required for operation i, r_i is the average radiation exposure for operation i, and U is the maximum radiation exposure allowed over a year.

The crew size requirements imply, for example, that if a particular operation requires two technicians, and a total of 180 technician-hours in a given month, we want to allocate two technicians for 90 hours each, not one technician for 160 hours and a second for 20 hours. To make sure that the total allocation of technician-hours is spread across sufficient technicians to allow staffing of the operations, we limit each of the individual allocation terms, as follows:

$$x_{ect} - \sum_{i \in I_c} u_i V_{s(i)t} \leq 0 \quad \forall \quad e, c, t \tag{8}$$

The consumption of facility resources (facility-hours) is represented similarly to the consumption of technician-hours, but with greater detail in some respects and less in others. The overall set of constraints is as follows:

$$\sum_{i \in Y_f} d_i W_{ift} \le F_{ft} + E_{ft} \qquad \forall \quad f, t \tag{9}$$

$$V_{st} = \sum_{f} W_{ift} \qquad \forall \quad t, i \in I_s, s \tag{10}$$

where W_{ift} is the number of units processed through operation i in a facility of type f during month t; Y_f is the set of operations, i, that can be performed in a facility of type f; d_i is the facility-hours required to perform operation I; F_{ft} is the facility-hours of facility type f available in month t; and E_{ft} is the excess facility-hours of type f consumed in month t.

Note that the variable definitions refer to facilities of a particular **type**, since there may be several individual facilities that are identical, and the PPM is only concerned with consumption of facility-hours in a facility of that type, without identifying exactly which facility is involved. The E_{ft} terms are similar to the D_{ct} values in the technician constraints, and must also be added to the objective function as penalty terms on overuse of facility-hours.

In constraint (10), the throughput of system s in any month t is connected to the variables that account for the number of units processed through operation i using facility f during month t (W_{ift}). If we denote I_s as the set of operations required for dismantling system s, and sum over the facility types, f, we count the total units processed through operation i in month t. By having a "copy" of constraint (10) for each i in I_s, we ensure that all required operations are performed on each unit disposed.

There is a hierarchy in facility types, and each operation i will have a minimum required facility, but can also be assigned to any higher-capability facility. Thus, in general, for each i there will be several f values that are feasible assignments. Normally, we will want the solution to assign each operation (as much as possible) to the lowest available facility in the hierarchy. This is accomplished by adding to the objective function a set of usage penalties for assigning an operation to a higher-than-necessary facility type. Such assignments are then feasible, and will be done as necessary to use available facility-hours most effectively, but will be penalized in the objective function.

There may also be bounds on volume throughput. These produce constraint set (11):

$$V_{\min_{st}} \le V_{st} \le V_{\max_{st}} \qquad \forall \quad s, t \tag{11}$$

where $V_{\min_{st}}$ is the minimum required volume of system s in month t and $V_{\max_{st}}$ is the maximum allowable volume for system s in month t.

In addition to representing the operations necessary for disposal, the PPM also tracks inventory balances and inbound/outbound shipment schedules. This integration of storage management within the PPM ensures that the disposal plan developed is internally consistent with the inbound and outbound shipment plans and the on-site storage constraints and logistics.

For units of system *s*, stored on-site awaiting disposal, an inventory balance equation can be written as follows:

$$Q_{st} = Q_{s,t-1} + A_{st} - V_{st} + \alpha_1 Z_s \qquad \forall \quad s,t \tag{12}$$

where Q_{st} is the units of system *s* in storage at the end of month *t*; A_{st} is the units of system *s* that arrive during month *t*; Z_s is the additional units of system *s* that would have to be in inventory (or scheduled to arrive across the planning horizon) to support the disposal plan; and α_1 is 1 for month 1 in the planning horizon and 0 otherwise.

The values of A_{st} are assumed to be specified exogenously. The use of the Z_s variables in equation (12) allows the PPM to find a "solution" to any set of input data, even if the inbound shipment schedule is too small to support the level of system disposal demanded by the minimum values, $V_{\min_{st}}$, specified in (11). On output, if one of the Z_s variables is nonzero, it means there is a shortfall in the number of units of system *s* available (either from initial inventory or the inbound arrival schedule) to support the disposal schedule that the model has developed.

An analogous set of constraints is defined to maintain the inventory balance for parts stored on-site after disposal:

$$R_{pt} = R_{p,t-1} + \left(\sum_s \sum_{i \in I_s} n_{ip} V_{st}\right) - G_{pt} + \alpha_1 L_p \qquad \forall \quad p,t \tag{13}$$

where R_{pt} is the units of part *p* in storage at the end of month *t*; n_{ip}, the units (pieces, kg, etc.) of part *p* removed (from weapon system *s*) in operation *I*; G_{pt} is the units of part *p* that are shipped off-site during month *t*; L_p is the number of "pseudo-parts" of part *p* shipped in month *t* to meet shipment requirements; and α_1 is 1 for month 1 in the planning horizon and 0 otherwise.

The values of G_{pt} are assumed to be exogenous input to the model. The L_p variables act for parts the same way the Z_s variables act for incoming systems, to indicate the shortfall in parts generation (e.g., due to a lower-than-needed disposal schedule) to support the planned parts shipments in the input data set.

The on-site storage representation also connects the numbers of weapons and parts stored to the amount of space consumed for various configurations of the available storage facilities.

If we index the configurations by *j*, then we can create two variables: ξ_{sj} , which is 1 if system *s* is to be stored in configuration *j* and 0 otherwise; and η_{pj}, which is 1 if part *p* is to be stored in configuration *j* and 0 otherwise.

The requirement for space in configuration *j* in month *t* is then represented by the following set of equations:

$$\sum_s \xi_{sj} (\frac{1}{cs_{sj}}) Q_{st} + \sum_p \eta_{pj} (\frac{1}{cs_{pj}}) R_{pt} = M_{jt} \qquad \forall \quad m,t \tag{14}$$

where cs_{sj} is the capacity of a magazine in configuration *j* for systems of type *s*; cp_{pj} is the capacity of a magazine in configuration *j* for parts of type *p*; and M_{jt} is the number of magazines that must be in configuration *j* during month *t* (i.e., sufficient to handle the inventory at the end of month *t*).

Finally, the configurations are limited by the actual physical facilities available. If we let J_m represent the set of configurations possible for a magazine type, *m*, then these constraints can be written as follows:

$$\sum_{j \in J_m} M_{jt} \le N_{mt} + B_{mt} \qquad \forall \quad m,t \tag{15}$$

where: N_{mt} is the number of magazines of type *m* available in month *t* and B_{mt} is the "pseudo storage capacity" variable reflecting a shortfall in storage capacity of type *m* in month *t*. The B_{mt} variables are introduced to represent possible storage capacity shortages, without having the model report "no feasible solution." The values of N_{mt} are input as data, and can be varied from month to month to reflect special considerations such as repairs.

The overall PPM objective function includes terms to represent the throughput (being maximized), as well as terms to reflect the added "penalty terms" for the excess technician hours, excess facility hours, pseudo-disposals and pseudo-shipments, and storage facility shortages that have been added to the model to prevent conditions of "no feasible solution" from the model, as well as the facility usage penalties. The resulting objective function is:

$$\begin{aligned} \max \sum_t \sum_s \lambda_s V_{st} - \gamma \sum_t \sum_c D_{ct} - \delta \sum_t \sum_f E_{ft} - \pi \sum_s Z_s \\ - \nu \sum_p L_p - \omega \sum_m \sum_t B_{mt} - \sum_i \sum_c \mu_{if} \sum_t W_{ift} \end{aligned} \tag{16}$$

This objective maximizes the system's (weighted) throughput, where the λ_s values reflect the possibility of different importance (weights) being placed on disposal of different systems. The second through sixth terms are penalty terms, with multipliers that must be set large enough to ensure that the model will not violate one of those constraints to increase throughput. Consequently, the sums from these five terms should normally be zero; otherwise, we actually have an infeasible solution.

The last term in (16) is the usage penalty for performing operations in higher-than-necessary facility types. The value of the multiplier μ_{if} is the per-unit penalty for performing operation *i* in facility type *f*. For the minimum required facility for operation *i*, this value is zero. For facility types of higher capability, μ_{if} should be positive, with larger values associated with facilities of greater capability. However, on the whole, the μ_{if} values should be small, relative to the system weight coefficients in the first term of (16). In practice, the μ_{if} values are determined automatically within the model, based on the other input data.

The overall problem (**P**) is then:

Maximize (16)

Subject to: (2) – (15).

The Solution

To solve problem **P** in a manageable fashion, a modular structure is employed, as shown in Figure 7. This modularity facilitates modification of the model to meet new or changing requirements. It also allows substitution of other components, such as alternate optimization software.

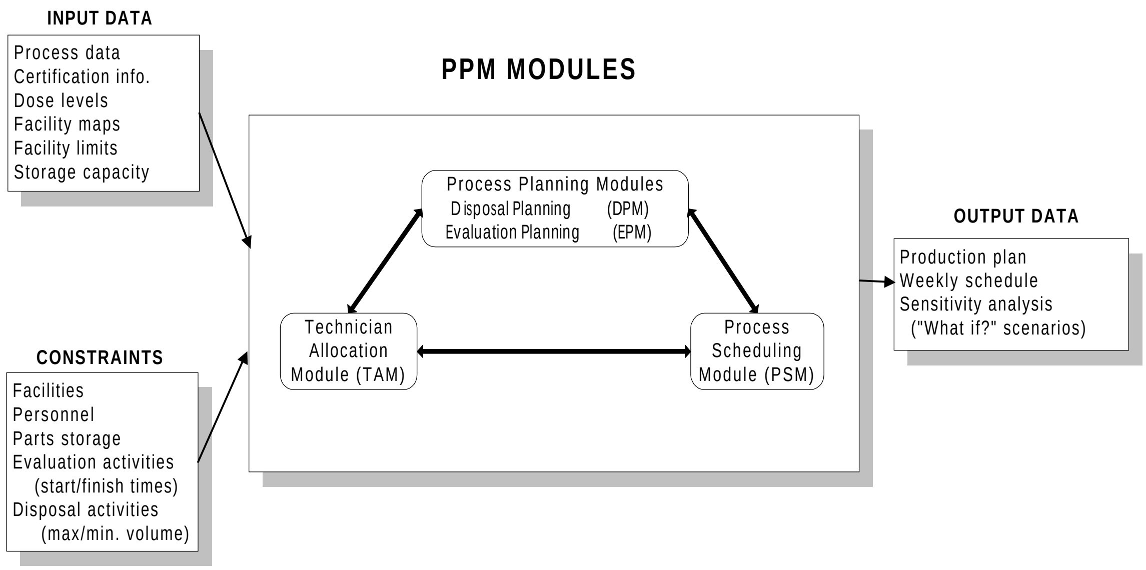


Figure 7. Structure of the Pantex Process Model

The PPM has modules for planning disposal (DPM) and evaluation (EPM) activities, as well as a technician allocation module (TAM) and a process scheduling module (PSM). The following paragraphs describe how each of these modules functions, and how they are interconnected.

The Disposal Planning Module (DPM). The DPM is a large-scale linear programming model that seeks to maximize the total number of units (**weapons) disposed** over a one-year planning period, subject to constraints on facility availability, technician availability, available space for storage/staging of both incoming units and outgoing parts/subassemblies, and mandated program requirements for specific weapon systems. Its output is an optimal disposal plan, on a monthly basis, for a one-year planning period. Because the DPM is a linear programming model, the solution also yields valuable sensitivity analysis information, such as shadow prices that indicate how much the total throughput could be increased if additional hours of a given resource were made available. The binding constraints in the DPM solution identify the choke points in the process, and allow the users at Pantex to determine whether the number of disposals is being limited by facility availability, technician availability, or storage/staging availability.

The Evaluation Planning Module (EPM). The EPM creates a plan for conducting a set of pre-specified **stockpile evaluation** activities over the course of a one-year planning period. Typically, each of these activities involves an earliest possible start time, a due date for completion, and a specified set of operations that must be performed in a particular order. Each operation requires a certain facility type, and technicians with particular certifications. The overall facility pool and set of available technicians are shared with the disposal activities. The solution to this problem is based on techniques for multi-project, resource-constrained project scheduling (see, for example, Bell and Han, 1991). The output of the EPM is a proposed plan, on a week-by-week basis, for conducting the required evaluation activities, and a specification of what resources must be allocated to those activities in each week.

The essential idea embedded in the solution procedure for the EPM is to level the resource demands subject to the time window constraints on the tasks and the precedence requirements. In general, for situations of realistic size, this is a very complicated problem, so a heuristic is employed.

It is clear that the DPM and EPM are closely connected, because they are used to plan activities that compete for a common set of resources (facilities and technicians). For facilities, the modules interact directly to ensure that the available facility-hours of each facility type are efficiently allocated between disposals and evaluations. For technicians, the interaction is more complex, because both the DPM and the EPM are seeking available technician-hours for particular certifications, and individual technicians often hold multiple certifications. Thus, in this design of the PPM, the interaction between the planning modules for technicians requires a third module.

The Technician Allocation Module (TAM). The TAM determines allocations of technician-hours in each month of the one-year planning period to demands for technician-hours of various certifications, arising from the DPM and EPM. The model takes the form of a network optimization for each month, with linking constraints across the months of the year to prevent overexposure of any individual technician to radiation. In the network structure of the model, the “supplies” (available hours for a specific technician with given certifications) are allocated to meet the “demands” (required technician-hours, by certification, within a given month). A “pseudo-source” is included to identify any infeasibilities which must be resolved by iteration with the DPM and EPM. The resulting network problem can be solved very efficiently, using specialized algorithms (see, for example, Bertsekas, 1991).

In a typical application, the DPM and EPM are run first, using “infinite” technician resources, to generate a desired level of technician-hours in each certification. Then the TAM is run to determine how many hours in each certification are actually supportable by existing technicians. These values are then fed back to the DPM and EPM, resulting in new plans. The iteration among the DPM, EPM, and TAM continues until consistent results are achieved.

The Process Scheduling Module (PSM). When a consistent plan (involving disposals, evaluations, and technician allocations) has been developed, the PSM is invoked to check for scheduleability: that a given plan can be converted into actual assignments of specific technicians and facilities to specific tasks over a specific time period—typically, one week to one month (Icmeli and Rom, 1997). This is the point when detailed requirements and special regulations are taken into account to ensure the feasibility of the planned activities. If infeasibilities are uncovered, it is necessary to return to the planning modules and revise the overall plan.

Illustrative Example

Because there are sensitivities about the specifics of problems pertaining to the Pantex plant, the example we present depicts a **hypothetical** production planning problem involving disposal and evaluation programs. Parameters of the problem are as follows:

- The production planning period is *1 year*.
- The production goal for disposal is *1000 weapons* per year, across *6 different weapon systems.*
- The production goal for evaluation is *250 weapons* per year.
- *Eighty-five* facilities are required to support the production tasks (70 facilities for disposal, 15 for evaluations). These facilities comprise 26 different types of bays, cells, etc. A number of these facilities are shared, such as those used for taking x-rays.

- *Two hundred technicians* with specific certifications are required to support the production tasks. At least 2 technicians, both holding the same certification, are required for any given task.

The initial production solution focuses on capacity planning, seeking to determine what level of output is possible if the facility resources (operations and storage) are the only constraint. In this case, the upper limits on production are set to high values while the minimums are set to expected demand. The problem involves 6 weapon systems, 4–5 operations per weapon system (25 total), 1–5 facility options for each operation, and 8 certifications. The overall math programming problem involves about 2300 rows and 3600 variables for the 12-month planning period.

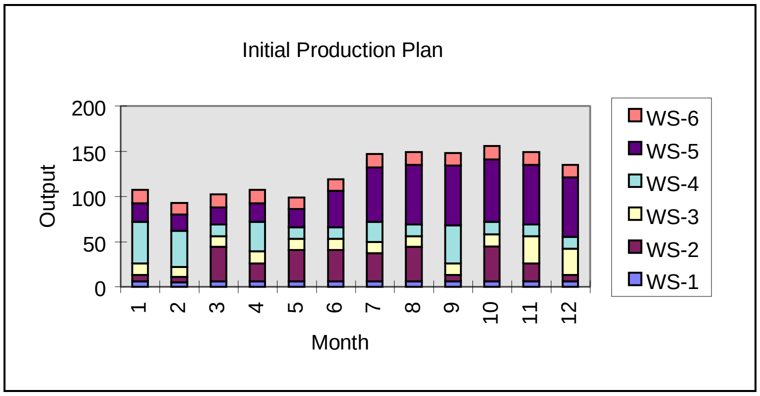


Figure 8. Initial Production Solution

This results in a total potential output of 1,510 completions (disposal or evaluation), 50% in excess of the target value. Figure 8 shows this is a completion rate of 90–160 weapons per month. Weapon system WS-5 predominates and the quantities of WS-2 and WS-4 vary from month to month.

If the current requirements can absorb this level of output, or if alternate schedules can be negotiated, this initial production solution suggests where to focus training efforts to create qualified technicians sufficient to support this level of output.

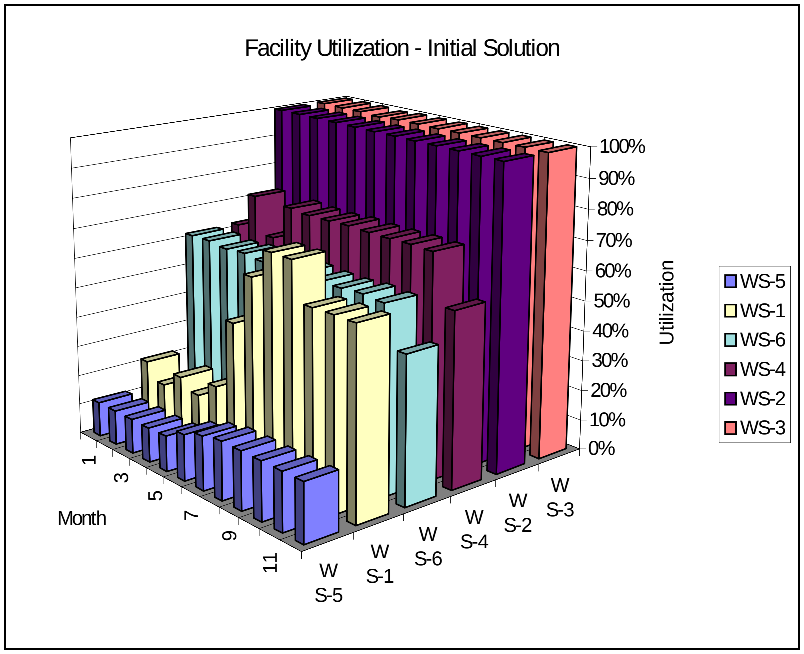


Figure 9. Facility Utilization - Initial Solution

The analysis also tells us whether the right balance of facility capacity exists. As Figure 9 shows, a poor balance currently exists. Facilities for systems WS-2 and WS-3 are in full use for this facility-driven solution. Those two types of facility are the bottlenecks to greater output. The remaining four facility types are only partly utilized, so they could be either reconfigured for other uses or converted into WS-2 or WS-3 facilities. Either strategy would produce a more balanced production situation and better deploy the facility resources.

The evaluation plan calls for 250 weapons to be tested. Unlike the preceding production analysis, however, no potential schedule expansion warrants consideration of greater output. The question is whether the 250 weapon evaluations planned can be accommodated by the facilities available. The facility-utilization problem involves 368 jobs (all with earliest allowable start times and latest allowable finish times), 1000 tasks, and 42 resources (11 facilities, 31 certifications). A job is a major subpiece of an evaluation; jobs are subdivided into tasks, some of which must be performed sequentially, while some are performed in parallel. The plan is developed across 252 days, which constitutes one work year. Resource demands exceed supply on 233 occasions, so the timing of tasks and jobs needs to be adjusted.

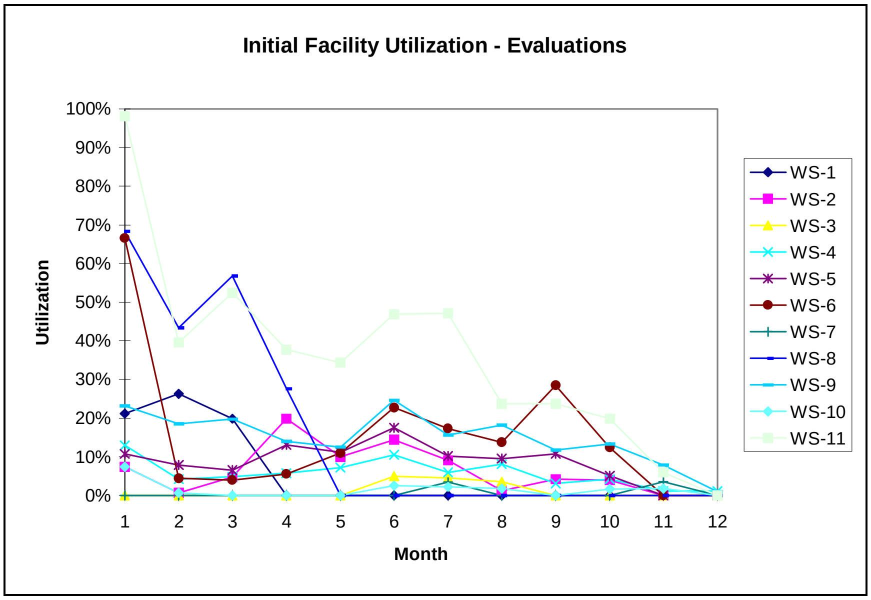


Figure 10. Initial Facility Utilization - Evaluations

The model suggests that the evaluation plan can be achieved. Figure 10 shows that facility utilization rates stay below 65% except for WS-11. Also, the evaluation plan seems to be front-loaded, with more activity occurring in the beginning of the year. Although more output might be achieved if the facility utilization rate were higher, there are earliest allowable start times on most jobs, as well as latest allowable finish times on certain tasks within those jobs. Therefore, a level resource requirement is not an automatic—or even an achievable—outcome. Moreover, many of these facilities are set aside for evaluation use and are not easily diverted to other activities. The main message in Figure 10 is that redeployment of some of these facilities might be a healthy change, which could potentially provide more output.

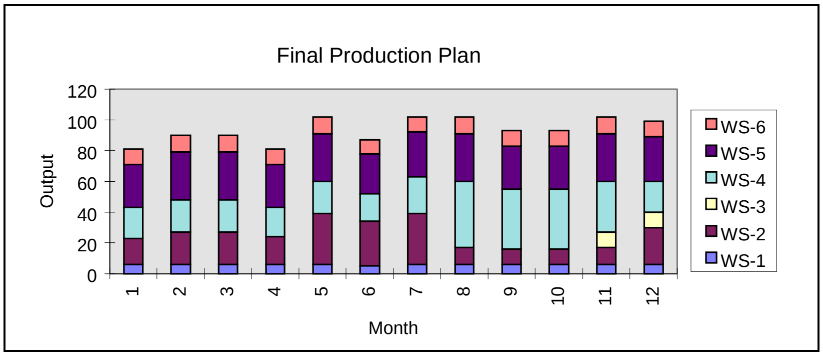


Figure 11. Final Production Plan

When the availability of technicians is taken into account, the total potential output drops to 939 weapons disposed of—just shy of the target of 1000 for the year. The output rate ranges between 80 and 100 weapons per month, as shown in Figure 11. There is less output of every weapon system, especially the WS-5. In fact, only the outputs of WS-2 and WS-4 exceed minimum requirements. This drop in output reflects the fact that few technicians have the certifications required for work on any weapon system but the WS-2 and the WS-4.

Figure 12 provides information about what training is required to rectify this situation. Technicians who hold certifications C-5 through C-8 are needed; some of these needs can be satisfied by retraining technicians who hold C-3 certifications, which are in surplus.

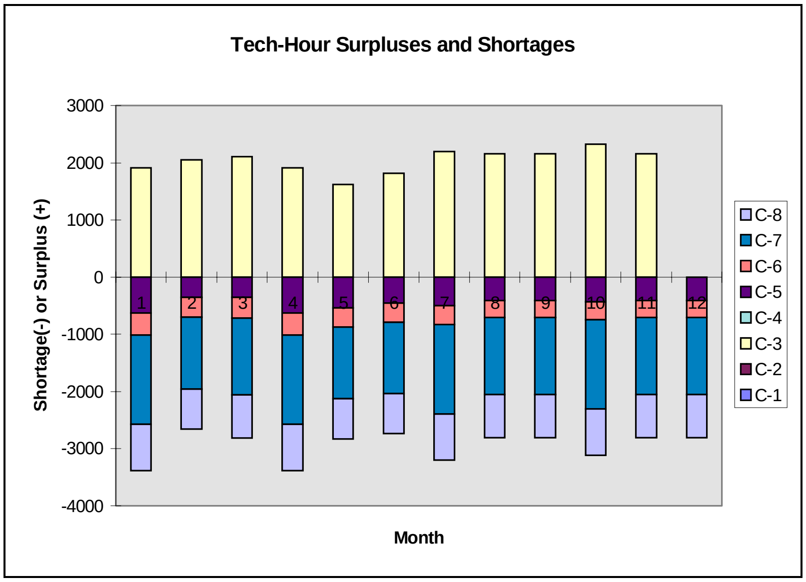


Figure 12. Technician-hour Surpluses and Shortages for Disposals

The technician allocation analysis (the results of which are not included here) indicates that sufficient technicians are available to receive the required training. The technician allocation problem involves slightly more than 140 tech-nicians, who hold slightly more than 230 certifications total, in response to demands for 40 certifications. Short-ages are identified for 19 of these certifications.

If the training does not take place, or if not enough technicians are trained, then the "final" production plan (see Figure 11) must be revised with lower minimums for WS-3 and WS-4 until a feasible solution is achieved. Note that as the production plan is revised, the output of other weapons disposed of may increase, thereby absorbing some of the technicians perceived to be available for training in the current situation.

The labor situation for the evaluation activities is more hopeful, as Figure 13 shows. Only a few shortages exist. None are significant in magnitude. During the early months of the year, certification C-1 is in short supply. In later months, there is a shortage of certification C-5. But at no time are the technician-hour shortfalls for evaluations as significant as they are for disposals.

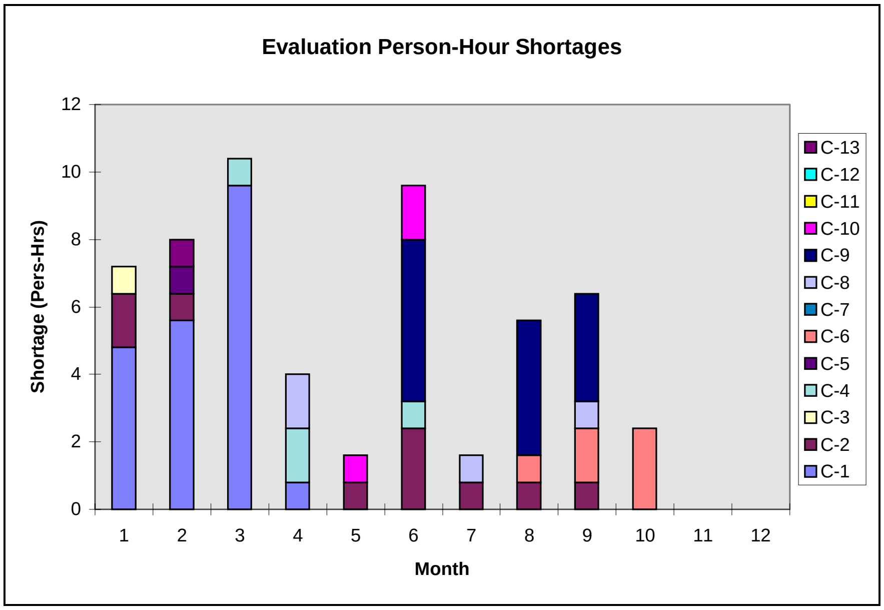


Figure 13. Technician-hour Shortages for Evaluations

This example illustrates how the PPM has been used to optimize throughput, assign specific facilities for tasks in an optimal manner, assign technicians optimally, and identify future requirements for technician training.

This new manufacturing optimization tool also presents valuable sensitivity analysis information that enables Pantex to determine readily whether current production output is being constrained by facility availability, technician availability, or storage/staging availability. Armed with this information, Pantex can respond quickly to change—using the model to reschedule production after a disruption or revise production plans rapidly in response to changing plant demands.

Future Direction of the PPM Technology

Future work will focus on (1) continuing to meet the analytical needs of the Pantex customer and (2) exploring new solution strategies.

(1) Plans for enhancing PPM **analytic capabilities** include development of both a technician training scheduler and a real-time scheduler:

- *Technician Training Scheduler*. This enhancement will provide management with the ability to more effectively determine which production technicians should receive what skills in support of future plant needs. Our example problem illustrates the value of re-deploying resources but stops short of suggesting how such decisions should be made. Such assignment problems are difficult, especially in cases where the training time frames are long, the skill requirements are complex and time varying, and training resources are limited. Such is the case at Pantex.

- *Real-Time Scheduler*. This enhancement will function in real time, tied to production data from the shop floor, and be capable of suggesting workflow strategies that maximize both efficiency and effectiveness at the plant level. Using the PPM as a predictive tool in places like Pantex where safety is of great concern is not simply a matter of maximizing plant utilization, but of achieving a balance among a number of competing objectives—only one of which is maximizing plant output.

(2) In PPM Version 2.0, a solution strategy using decomposition and heuristics allows implementation on a PC. Plans are under way to attempt to solve the integrated mathematical formulation of the very large-scale mixed integer programming problem using Sandia’s massively parallel processor computer in collaboration with Sandia’s computer science organization. The benchmark solution will then be used to guide the exploration of new **solution strategies** and heuristics for the subproblems. Improved solution strategies would result in even more rapid, efficient, and accurate PC-based solutions to problems of production planning and scheduling in an agile manufacturing environment.

Conclusion

A critical need for radically improved production planning and scheduling was identified at the Pantex Plant. An innovative solution to the problem of production planning and scheduling was developed and implemented using advanced management science techniques. The mathematical model developed in active collaboration with Pantex users resulted in a significant improvement in the plant's business practices. Pantex has achieved greater throughput, more optimal resource allocation, and greater responsiveness to its primary customer, the US Department of Energy.

The Pantex Process Model advances the state of the art in science tools for operations research/management. Its formulation is a large, complex mixed-integer programming problem combining flow-shop (disposal) and job-shop (evaluation) activities that use resources in common. A solution strategy using decomposition and heuristics allows implementation on a PC. PPM advances have opened several new avenues for research and application.

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Distribution

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School of Civil & Environmental Engineering
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Hollister Hall
Ithaca, NY 14853

5 Dean Jones
Parallax, Inc.
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