Computer Aided Analysis, Planning, and Control of Space Systems Operations

D. L. Erickson
Senior Information Scientist, Information Systems, McDonnell Douglas Astronautics, Company — West

R. E. Smith
Senior Information Scientist, Information Systems, McDonnell Douglas Astronautics, Company — West

E. J. De Caroli
Senior Information Scientist, Information Systems, McDonnell Douglas Astronautics, Company — West

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ABSTRACT

The complexity and operational dynamics of modern space systems has dictated a need for computerized tools to assist in the analysis, planning, and control of space system operations. Three computer programs (ACTNET, TLGEN, and WICK 9) which have been applied successfully to these problems are discussed in this paper.

ACTNET is a second generation discrete-event simulation system designed for the functional analysis of complex processes. It is applicable to systems which may be modeled as networks of activities that are constrained by precedence, logical conditions, and limited resources. ACTNET has been employed within the Nuclear Stage, Space Station, and Space Shuttle programs by MDAC-West.

TLGEN is a computer program currently under development by MDAC-West for generating operational mission timelines. In its batch mode of operation, it is used for planning on-orbit operations. In its interactive (on-line) mode, it can support real-time control of on-orbit operations by mission control/ground system personnel. TLGEN is designed for scheduling detailed sequences of events subject to event duration time, execution time, priority, resource usage, and environmental constraints (ephemeris).

Little theoretical progress on developing an optimal task scheduling method for processes with tasks constrained by precedence and multiple resources has been made. This is due primarily to the difficulty of the general scheduling problem. With the advent of low cost timesharing, a promising approach to this problem is incorporating man-in-the-loop as decision maker. WICK 9 is the latest version of an interactive scheduling system developed by MDAC-West. The application of WICK 9 to scheduling experiments within a ten year space station experimental program is presented.

STATEMENT OF THE PROBLEM

The operation of modern space systems is characterized by complex interactions between numerous subsystems, system operators, and environmental elements (physical, political, and social). Therefore, development of effective space systems requires careful consideration of constrained system dynamics, along with its natural operational dynamics. The inherent dimensionality, nonlinearity, and stochastic characteristics associated with such problems has motivated the development computer aided analysis, planning, and control tools.

A system may be thought of as an operator which transforms inputs into outputs. That is

\[ S = [\langle X, Y \rangle] \]

where \( S \) represents a system, \([\ ]\) is a set of elements, \( \langle \rangle \) represents an ordered pair of elements, \( X \) is an input vector (collection of inputs), and \( Y \) is an output vector (collection of outputs).

The analysis problem involves finding \( Y \), given that \( X \) and \( S \) are known or assumed. That is, analysis has as its goal the determination of a system's performance dynamics (measurement of outputs) as a function of inputs impressed on the system and the system's design.

Analysis and design are often used synonymously. The distinction should be made clear. In contrast to analysis, the design (synthesis) problem involves finding \( S \), given that \( X \) and \( Y \) are known or assumed. Thus, design has as its goal, finding a system which will transform required inputs into desired outputs.

Due to the relative difficulty of the design process, an iterative analysis approach is often used. That is, the form of the system under design is assumed and analysis applied. If the resulting outputs \( Y \) are not sufficiently similar to the desired outputs \( \hat{Y} \) (design requirements), the assumed design is modified and again analyzed. This process continues until \( Y \) is within specified limits of \( \hat{Y} \).

The planning problem consists of developing a course of action which will carry a system or process from some initial condition to some desired final condition (plan objectives). It is complicated by the fact that it requires the participation and coordination of many varied disciplines and organizations. It must consider and contend with uncertainty (planning involves predicting/forecasting future events), time constraints, task ordering requirements (precedence), and limited resources.
Little theoretical progress has been made toward solving the general planning problem. This situation is due primarily to the difficulty of the problem, and to a lesser degree, on lack of attention. Problem dimensionality (size, complexity), varied and complex performance indices, and decision making within a multidimensional constraint environment have all contributed to impeding progress. A promising avenue toward developing useful and practical planning tools appears to lie in the combination of man (as the decision maker) with the timesharing computer (for assessment of the implications of decisions). The advent of powerful, low cost computer timesharing has satisfied the necessary condition for cost-effective real-time planning.

The control problem deals with guiding performance (operation) of a system by manipulating system variables. To be effective, a control system must apply corrective action in a timely manner. In this sense, all control can be thought of as real-time control, where real-time is defined in terms of the time constants (dynamic response time) of the system under consideration. The problem is complicated by the highly constrained environment in which control must be applied. First, controls must be applied in real-time. In many systems this is the overriding constraint. Second, there are fewer degrees-of-freedom open to the controller for guiding system performance. System parameters and structure are generally fixed and, therefore, unavailable for control purposes (these system elements may be manipulated in analysis and planning). Third, control schemes must be computationally efficient since they have a high frequency of use. Finally, effective control methods require a comprehensive understanding of the operational dynamics of the system under control and an unambiguous performance index against which to measure system performance.

Considerable theoretical progress has been made in the area of optimal feedback control for a large class of system problems. Techniques of multilevel control have extended optimal control to selected large scale system problems. For the most part, however, optimal control of most real-world systems is not feasible using current techniques. Again, a promising avenue of research appears to be the incorporation of man as the real-time decision maker.

Characteristics and representative applications of the following three computerized analysis, planning, and control tools are presented in the remainder of this paper.

A. ACTNET is a second generation functional simulation system which has been successfully applied to large scale space system problems. It is primarily an analysis tool but may be employed for planning in selected situations.

B. TLGEN is a timeline generation system currently under development. In its batch mode, it is used for planning on-orbit operations. In its interactive (on-line) mode it can support real-time control of on-orbit operations.

C. WICK 9 is an interactive (on-line) task scheduling system used for real-time planning. It has been extensively applied to scheduling on-orbit experiments within the Space Station Program (NASA).

ACTNET CAPABILITIES AND APPLICATIONS

Modern space systems are characterized by complex interactions between numerous subsystems, people, organizations, and environmental elements. The inherent nonlinearities and stochastics of such systems have prevented realistic modeling and analysis of their operational dynamics by means of traditional analytic techniques. In many such cases, a functional model coupled with a computer simulation has proven to be an effective analysis technique. ACTNET is a discrete event simulation system designed for the analysis of processes which may be modeled as networks of activities.

ACTNET Design Objectives

In an activity network, processes are modeled as sequences of activities constrained by precedence (order), resource availability, and logical conditions. From an organizational point of view, each activity represents a unique step in an overall process to attain some desired objective. Functionally, an activity can be thought of as a mechanism which performs a specific task and in the process requires a finite amount of time and a transformation of resources (creates, consumes, or uses a resource or resources).

The specific nature of an activity depends on the modeler's objective. At one extreme, it may represent the entire process being analyzed and at the other extreme, detailed operations of system components. In all cases, an activity is the elementary subprocess of the model. Detailed processes within an activity are (by definition) irrelevant to the analyst and, therefore, need not be specified. Thus, in a functional analysis approach, attention is focused on the function being performed, rather than the physics necessary to perform it. This feature provides functional simulation its inherent power and flexibility. If analysis of intra-activity operations is of interest to the analyst, further model decomposition is necessary.

The primary ACTNET design goal, producing a useful general-purpose activity network simulation system, dictated the following design requirements: (1) ACTNET will be user oriented in its application, (2) process modeling with ACTNET will be conceptually simple and intuitive, (3) ACTNET will be sufficiently general to handle the majority of processes representable by activity networks, (4) ACTNET will be computationally efficient and employ state-of-the-art programming techniques (pointers, dynamics memory management, etc.), and (5) ACTNET will be compatible with all third generation computing hardware (written in FORTRAN IV).

To attain these design objectives and to simplify ACTNET design, the following assumptions were made: (1) activities may not be interrupted, (2) resource requirements are absolute, (3) resources may not be reserved in advance, (4) resources are independent, (5) resources are assigned to activities on a first come first served (FIFO) basis, and (6) network configuration is time/state invariant.
ACTNET Features and Capabilities

A diagram of the macrostructure of the ACTNET model is given in Figure 1. As indicated, the ACTNET model encompasses three major domains: the activity network, its local environment, and the controller.

The activity network is a model of the process to be analyzed. It incorporates all information relevant to the operation of that process. The activity network, in addition to specifying precedence, provides for constraint of process behavior by both resources and logical conditions. Resources are quantifiable entities which may be created, consumed, or occupied by an activity.

Logical conditions are constraints which reflect status. They control behavior independently of the number of activities affected. Logical conditions constrain by defining binary (yes, no) states in the system.

Since ACTNET networks incorporate these two types of constraints, it is possible (and often desirable) to formulate activity networks which have no networking connection between them (decouple precedence constraints). Such networks interact only through exchange of resources or changes in logical conditions, or both.

Only five network elements are required to construct ACTNET models; an activity and four logical nodes. The simplicity of network elements coupled with the flexibility provided by resource and logical constraints, make modeling and analysis of realistic large scale systems feasible and relatively easy.

The context in which an activity network must function is its environment. The dichotomy between network model and environment must be drawn by the modeler to suit his analysis goals. The local environment incorporates only those elements which directly influence, or are directly influenced by, the activity network. Initial resource levels, initial system status, and system resource and logical constraints are specified in the local environment.

The controller is an on-line decision maker. It manages the environment-network interface through resolution of resource and logical conflicts. The controller also makes all decisions relative to probabilistic outcomes, such as probabilistic activity time duration, probabilistic resource requirements, and path selection at probabilistic branching points. The controller thus records and executes the operating policies established by the modeler or specified by internal ACTNET decision rules.

The ACTNET program is designed on a modular basis. A master subroutine controls the simulation by stepping it through five major modules: data input, data verification, execution, inter-replication initialization, and data output.

The input module reads and processes data cards. The input editor within the module arranges groups of data into sets for convenient processing within the execution module. The ACTNET input editor allows the user considerable flexibility in sequencing and modifying input data by means of a vector overlay capability.

The data verification module tests the legality and consistency of input data. Comprehensive error diagnostics are available within the module to pinpoint and diagnose input errors.

Simulation of the activity network model is performed within the execution module. This module also accumulates all pertinent statistical data.

The reinitialization module resets all initial conditions and replication parameters and returns control to the execution module for another replication run (Monte Carlo simulations).

The output module generates all reports. Both standard and optional reports are available. Standard reports are produced after every run. Optional reports may be selected by the user and may be output in either a tabular or plotted format. This module returns control to the input module when all reporting has been completed.

Significant capabilities of the ACTNET system are as follows:

A. ACTNET may be effectively applied by nonprogrammers.
   1. ACTNET conventions are simple and easy to learn.
   2. ACTNET modeling is intuitive (networks of activities).

B. ACTNET is capable of analyzing realistic systems.
   1. ACTNET is usable in the analysis of processes constrained by precedence, resource limitations, and logical conditions.
   2. ACTNET can analyze asynchronous systems (systems incorporating feedback loops).
   3. ACTNET can analyze systems incorporating stochastics (random phenomena).
   4. ACTNET can analyze large scale systems (multiactivity, multivariate, multilevel systems).

C. ACTNET is computationally efficient.
   1. ACTNET is written in Fortran IV.
   2. ACTNET employs state-of-the-art techniques (pointers, dynamic memory management, etc.).

Representative ACTNET Applications

ACTNET has been applied successfully to a variety of large scale space system problems. Areas of application include: analysis of operational dynamics, system sizing, resource utilization and delay
analysis, activity sequencing and timeline analysis, and sensitivity analysis (sensitivity to resource availability, activity sequencing, resource allocation strategies, random phenomena, etc.).

Several specific applications of ACTNET to Space Station operations are presented in the remainder of this section.

The schedules for delivery of a complete set of manufacturing end items to the launch site for a single logistics launch are presented in Figure 2. These data were generated by means of a reverse-time network, with initial condition set at logistics vehicle lift-off; they are based on 50 replications.

Each horizontal line on Figure 2 gives the minimum time, mode time, and maximum time for delivery of a particular manufacturing end item. Items delivered to the launch site prior to their minimum delivery time will impact the launch time with probability \( P(\cdot) = 0.0 \). Items delivered subsequent to their maximum delivery time will impact the launch time with probability \( P(\cdot) = 1.0 \). Items delivered within their delivery timespans will impact the launch time with probability \( 0 < P(\cdot) < 1.0 \).

The optimal end item delivery time will most likely lie between the minimum and mode delivery times, depending on the relative cost of early delivery versus the cost of launch time delay. Delivery prior to the minimum delivery time will introduce unnecessary costs associated with early manufacture, and storage and maintenance at the launch site. Delivery subsequent to the mode time of each distribution will have a large probability of impacting launch time.

When a number of consecutive logistics launches are considered, the timely delivery of manufacturing end items becomes increasingly significant since any launch delays may be reflected down the entire chain of launches in the queue. Simulation data of end item delivery times for multiple consecutive logistics launches show an increasing spread between minimum and maximum desired delivery times for launches further down in the launch queue. These data reflect the increased uncertainty associated with future launch time predictions as upstream time horizons increase.

Analyses of logistics launch operations indicate that launch preparation time is highly sensitive to variations in the availability of launch pad and launch personnel. Figure 3 displays logistics launch preparation time for three consecutive logistics launches as a function of the availability of launch pads and spacecraft logistics module (SLM) personnel. In these analyses, only launch pad and SLM personnel availability was constraining; all other ground support equipment, facilities, and manpower were held constant at a level that induced no launch time delays. As launch pads are added, an equal number of supporting ancillary facilities and equipment is made available. When only one pad is available, launch preparation times are essentially unaffected by changes in the number of SLM personnel available. Thus, provision of additional SLM personnel over the threshold level does not result in a significant reduction in launch preparation time when only a single launch pad is available.

When multiple launch pads are available, SLM personnel availability has significant impacts on launch times for all three consecutive launches. Also, launch preparation times for multiple logistics launches are highly sensitive to launch pad availability. For example, the addition of a second launch pad reduces launch preparation times for the second and third launch in the sequence; addition of a third pad lowers launch preparation time for the third launch only. These logistic launch sensitivity data aid schedule and cost tradeoff analyses.

An analysis of crewman/crew skill utilization for a twelve man space station is presented in Figure 4. On-orbit operations included both duties associated with housekeeping and performance of a selected experimental program. The simulation assumed three shifts per day with four crewmen per shift. These data represent results of a simulation of 360 hours of on-orbit operations.

Figure 4 results suggest that the biomedical/behavioral experimentation duties should be more equally balanced between the medical doctor and his assistant. The duties now distributed among the film specialist, mechanical-optical-electrical specialist, man/system integration specialist, and sensor electronics specialist can more efficiently be handled by a single crewman with general knowledge and skills in those areas. This crewman would probably have overlapping duty shifts or be on call during all shifts.

These data further suggest that the space station is overstaffed for the present experimental program. This condition will be partially remedied when the two final functional program elements are defined and incorporated. Also, the earth resources experiments and sensors planned for the first 6 months on-orbit are insufficient in scope to effectively utilize a full-time earth resources/meteorology scientist. The two astronaut/physicists available are highly utilized, and the astronomical and space physics experiments are being completed at the desired rate.

A number of bottlenecks with respect to experiment completion were uncovered during on-orbit operations analyses. Figure 5 presents the major experiment delay-inducing elements of the space station facilities and crew. By far the greatest experiment bottleneck was the insufficient availability of the medical assistant skill. This imbalance in crew skill mix was the primary factor in completing medical/behavioral experiments at only 35 percent of the planned rate.

The use of only one airlock in the space physics experiments impacted the desired experiment completion rate and reduced the usefulness of the astronaut/physicists. With two airlocks available, significant delays were induced, as shown in Figure 5, but they did not appreciably reduce the desired experiment completion rate. The remaining delay-inducing items had little effect on experiment completion rates.

The impact of environmental stochasticities (cloud cover, ephemeris conditions, radiation levels, etc.) on crew skill utilization and experiment completion rates is shown in Figure 6. The constraints imposed by the space station's environment have pronounced
effects on the astronomical, space physics, and earth resources studies. In the case of earth resources, the utilization of the earth resources/meteorology scientist is reduced by approximately 30 percent, while the completion rate of photographic and infrared earth resources studies is reduced by nearly 80 percent. Environmental influences on the other experimental program elements are minor.

The ACTNET approach has been found to be useful in the analysis of space system problems. More generally, the ACTNET methodology affords the system scientist an effective tool for the analysis of complex, nonlinear, stochastic systems.

TLGEN CAPABILITIES AND APPLICATIONS

In generating and maintaining operational timelines for modern space systems, considerable effort must be expended in task scheduling and schedule/resource conflict resolution. TLGEN, a computer program under development by MDAC-West, computes much of the tedious work associated with this effort. In its batch mode, TLGEN assists the space system designer and operations analyst in planning on-orbit operations. In its interactive mode (on-line), it may be used by mission control personnel for timeline maintenance and real-time control of on-orbit operations.

TLGEN Design Objectives

Design requirements placed on TLGEN development assured system generality, i.e., applicability to a variety of vehicles and missions. It is recognized that an operational mission timeline generator must become vehicle/mission specific in order to be an effective operational tool. With careful design, the dependence of the timeline generator on specific vehicle/mission requirements can be restricted to areas of I/O, event and resource definitions, and priority/scheduling algorithms. Accordingly, the TLGEN system allows the user to select (from a library) or specify: (1) event scheduling algorithms/rules, (2) event priority algorithms, (3) remote tracking station selection rules, (4) event interdependence rules (prerequisite and postrequisite requirements), and (5) I/O characteristics and formats.

With this flexibility, the user may tailor TLGEN capabilities to his specific timeline requirements and efficiently integrate TLGEN into his operational environment.

The scheduling modules of the system, which perform task/event scheduling and conflict resolution, are designed to be universally applicable. These modules are augmented by a library of priority and event scheduling algorithms. Standard data input and reporting modules along with a program control module complete the basic TLGEN system. Modular design allows easy modification and expansion of TLGEN’s basic capabilities.

The computer program schedules events utilizing, as a minimum, the following four event scheduling algorithms. The user may specify which algorithm is to be applied to each event.

A. The event shall be scheduled for execution immediately, or at a specific time increment, after (n) executions of a prerequisite event.

B. The event shall be scheduled at a specified time increment subsequent to the vehicle attaining a specified space/ground track position.

C. The event shall be scheduled when a specified resource increases or decreases to a given limit value.

D. The event shall be scheduled at a specified time and at successive times separated by a constant increment of time.

An event end time may be defined by a given time duration or as a prerequisite, position, or resource associated event. The user may augment this library of algorithms with specific algorithms of his own.

TLGEN is capable of accepting ephemeris data and, if required, to convert these data to the Keplerian coordinate system. Additionally, TLGEN scheduling may be constrained by event execution, and environment status flags, e.g., day/night cycle.

The TLGEN system incorporates two modes of operation: batch and interactive. In the batch mode, mission timelines are created in an unattended run (the user submits input data). In the interactive mode, the user has the option of real-time participation (control and decision making) in the development of the operational timeline using a CRT/keyboard terminal. Thus, TLGEN is applicable to both space mission planning and control.

TLGEN Capabilities

The TLGEN system is capable of scheduling detailed sequences of events/functions based upon time of execution, event duration, event priority, resource utilization, and status of event required environment. It provides automatic as well as user directed conflict resolution. In addition to mission timelines, TLGEN provides output data on resource utilization and availability, e.g., power, vehicle consumables, crew, and equipment.

TLGEN’s modular design allows for the additon and/or modification of its structure to interface with the specific requirements of a variety of space programs. This modularity also allows easy adaptation to meet changes or modifications to vehicle subsystem design, orbit definition, and operational concepts during the operational phase.

TLGEN has the capability to record interim data on tape or disk to ensure a restart capability without the necessity of regenerating the input data.

A functional diagram of TLGEN’s off-line mode of operation is presented in Figure 7. In this mode all scheduling is done without user intervention. The program surveys the Remote Tracking
Station (RTS) acquisition list and automatically selects those RTS contacts required to support the mission (based on user specified rules). The user may specify the action to be followed if an event or resource conflict is still unresolved following the application of the specified conflict resolution algorithms. If a conflict resolution option is unspecified the program will take a check point of the data base, halt operation, and output an appropriate error message. If specified the conflict will be resolved and scheduling will proceed.

Figure 8 presents a functional diagram for TLGEN’s interactive (on-line) mode of operation. In this mode, the user may guide timeline generation in real-time. The user may also select specific display (CRT) formats from a predefined library of formats.

In its interactive mode, the TLGEN system is capable of updating all timeline data covering the mission subsequent to and including the current timeline period/span being processed. It requires as input a timeline data tape covering the mission in question, the resource status corresponding to the to-be-run timeline period, and the data base corresponding to the timeline being analyzed.

Additionally, TLGEN is capable of resolving event scheduling conflicts based upon priority algorithms selected by the operator prior to the computer run or through real-time keyboard input. In the event of an irresolvable conflict, the computer program requests operator/user intervention to resolve the conflict. An irresolvable conflict shall be defined as a situation in which the difference between the conflicting priorities is less than a given quantity. This quantity shall be input by the operator.

The system is capable of generating and maintaining real-time on-line summary lists or plots and a timeline plot for a given period of time. This timeline period or time span shall be input by the user. The user may specify which list or plot shall be displayed on the CRT such as (1) vehicle resource usage profile, (2) timeline plot, or (3) RTS contact summary list.

The computer program generates a resource status report indicating the status of all vehicle resources at the end of the timeline period or time span. These data are used for initialization of the following span to be processed.

Representative TLGEN Applications

The TLGEN system is presently under development and is scheduled to be available as an operational tool by July 1971. The TLGEN program modules are being tested at the program module level using test data which are representative of a manned space station mission. The test case mission is derived from MDAC-West Space Station study flight plans.

A portion of the TLGEN system test plan calls for the generation of a mission timeline using realistic data supplied by MDAC-West Skylab Flight Mechanics department. A timeline covering the first 24 hours of the Skylab mission will be generated.

TLGEN output is comprised of the following reports: (1) Chronological Events List (which is not a conflict free schedule); (2) Timeline Report (a conflict free schedule); (3) two resource utilization reports; one based upon the Chronological Events List and one based upon the Timeline Report; (4) Scheduling Conflicts Summary which provides data on each of the scheduling conflicts encountered in the generation of the timeline from the Chronological Events List. These output reports have not been designed to date. No specific applications are discussed herein since realistic examples were not available at the time of publication.

WICK 9 CAPABILITIES AND APPLICATIONS

An extensive on-orbit experiment program has been defined by NASA as part of the Earth Orbiting Space Station project. The relatively high cost of providing experimental facilities in earth orbit dictated the requirement for careful selection and scheduling of experiments. The scheduling problem is complicated by the multiple Space Station constraints of volume, power, data handling capacity, logistics delivery and resupply capabilities, and manpower/skills necessary to conduct experimentation. This problem is further compounded by the additional program constraints of funding and experimental hardware development timelags. WICK 9 is an interactive computer program designed to assist the operations analyst develop a feasible and efficient experiment program.

WICK 9 Design Objectives

The overriding WICK 9 design requirement was to provide a means to rapidly formulate and evaluate numerous candidate space station experiment schedules. The complexity of the scheduling problem (multi-task, multi-constraints) dictated the need for a computerized tool. On the other hand, interaction of the operations analyst was desirable since many of the criteria for making scheduling decisions and evaluating alternative schedules were subjective. Accordingly, WICK 9 employs a timesharing computer to perform scheduling and to summarize implication of schedules while allowing the analyst to make real-time scheduling decisions. The timesharing computer also provided the required rapid turnaround for both modeling and analysis.

The nature of the scheduling problem necessitated participation of both analysts and management personnel. Therefore, to be an effective tool, WICK 9 was designed to be usable by nonprogrammers. All direct interaction between the user and WICK 9 is via questions and answers in English. Additionally, WICK 9 inputs and outputs are highly simplified to facilitate modeling and reporting of results.

WICK 9 Capabilities

The on-line, man-in-the-loop approach of WICK 9 provides several distinct advantages over a batch approach. First, the man with the problem may directly participate in the scheduling process. No translation of input data or output results by a programmer is needed. In this manner the experience and subjective judgement of the expert may be incorporated directly within the schedule. This process has proven in practice to greatly reduce the number of trivial solutions often obtained and analyzed using a batch process.
Using WICK 9, the impact on the schedule of resource availability, task sequencing, task priority, program constraints, and scheduling decisions may be observed in real-time. This real-time feedback allows rapid convergence to feasible solutions. Further, by observing real-time schedule development, critical factors are quickly illuminated and a sensitivity map with respect to these factors rapidly developed. The insight provided by this technique illuminates paths to follow toward developing an optimal schedule.

Figure 9 presents a functional diagram of the WICK 9 program. The user defines characteristics (priority, time duration, resource requirements, etc.) for all tasks to be scheduled. System, mission, and program constraints on the schedule are also defined. The degree to which the schedule is to be constrained is at the option of the user. In the early phases of schedule design, constraints may be relaxed in order to arrive at a broad brush schedule consistent with first order program requirements. This provides a baseline from which more detailed analyses may be launched. Second order tuning of the schedule now may be performed by selectively applying additional constraints.

WICK 9 incorporates three modes of operation: automatic, semi-automatic, and manual (see Figure 9). In the automatic mode of operation, the program attempts to schedule each task within the specified constraints. If insufficient resources are available, the task is not scheduled in the current time period, but deferred to a future period. Upon scheduling a task, the required resources are reserved for the total task duration. The program proceeds through each unscheduled task for each scheduling period and presents a resulting schedule for user approval. At this point, the user may manipulate the schedule to meet special operational conditions. Although resource constraints are removed during this operation, violations to present resource limits are indicated. A final schedule along with its associated resource usages, baseline definitions, special input conditions, and funding requirements is then produced in final documentation form.

During the semi-automatic mode of operation the program functions much the same as in automatic. The major difference is in the degree of user participation. At each opportunity for a task to be scheduled, the task duration is displayed on the schedule timeline for user approval. If the user disapproves, the task is put back into the unscheduled group for possible scheduling at a later period. In this way, the user interacts with the computer to construct a schedule on a task-by-task basis. The user, as in the automatic mode, has the ability to manipulate the schedule before final results are printed.

The manual mode is an open loop mode of operation. Each task is presented to the user for assignment on the timeline. Resource constraints are not imposed. A final schedule is presented along with its implications. If approved, the program proceeds to report preparation and output. If disapproved, modification may be made or WICK 9 recycled.

**WICK 9 Application**

Scheduling a representative ten year space station experiment program using WICK 9 is discussed in this section. The experiment program consists of forty unique experiments and is constrained by five space station resources (volume, manpower, logistics resupply, electrical power, and data handling capacity) as well as program funding. The schedule extends over ten years with the basic scheduling period being one-quarter of a year.

The best feasible experiment flight schedule satisfying the constraints of this case is shown in Figure 10. Time (in quarters) is displayed along the horizontal and unique experiments by code name are listed on the vertical. An X represents a period in which an experiment is active (on-orbit). Notice that several low priority experiments could not be scheduled on the ten year timeline due to insufficient resources. This flight schedule report, like all others to be presented in this section, is an exact reproduction of the report generated at the timeshare terminal.

Figures 11 and 12 present volume and manpower requirements imposed by this schedule. The manpower usage curve is nearly flat since manpower was constrained to be equal to or less than 8.0. In the present case, manpower and electrical power were the two space station constraints which most impacted the schedule. Similar resource usage reports may be generated for all other constraining resources.

Experimental funding requirements by year for this schedule is shown in Figure 13. Notice that funding leads the actual performance of experimentation by several years since the primary experiment funding requirements are associated with development of the experimental hardware and software. In most cases, experimental program funding (both the total amount and its time profile) is an important constraint on experiment selection and scheduling.

Since their inception, the WICK series of programs have been used to schedule and analyze over 100 different space station experiment programs. Experience has indicated that by using WICK 9 manpower investment in Scheduling has been reduced by a factor of better than 50. Additionally, the quality and detail of these schedules has been significantly increased.

**CONCLUSIONS**

The operational dynamics of modern space systems has dictated the need for computerized tools to assist in the analysis, planning, and control of space system operation.

ACTNET is a discrete event simulation system which has been widely applied to the analysis of complex, nonlinear, stochastic systems. Applications to space systems include: analysis of operational dynamics, system sizing, resource utilization and delay analyses, task sequencing and timelining, and sensitivity analyses. ACTNET’s outstanding features include its computational efficiency, its generality and analysis power, and its ease of application.

TLGEN is a timeline generating system capable of scheduling detailed sequences of tasks constrained by precedence, timing requirements, logical conditions, and limited resources. TLGEN computerizes much of the tedious work associated with task
scheduling and schedule conflict resolution. In its batch mode of operation, TLGEN assists the designer and operations analyst in planning on-orbit operations. In its interactive mode (on-line), TLGEN is designed for use by mission control personnel in timeline maintenance and real-time control of on-orbit operations. TLGEN's design modularity allows easy modification of its basic capabilities to tailor TLGEN to the specific timeline requirements and operational environment of the USER.

WICK 9 is an interactive computer planning tool designed to assist the operations analyst plan space station experiment programs. WICK 9 employs a timesharing computer to perform scheduling in a multiple constraint environment and to summarize implications of each schedule while allowing the analyst to make real-time scheduling decisions. WICK 9's man-in-the-loop approach provides several distinct advantages over batch approaches, including: direct participation of the expert in the planning process (no programmer intervention), rapid feedback of implications of planning decisions, and rapid cost effective generation of optimal solutions in a highly subjective environment. WICK 9 has been used to plan over 100 ten year experiment programs within the Earth Orbiting Space Station project. Experience has shown a considerable reduction (50 to 1) in manpower investment for scheduling when WICK 9 is employed. Additionally, the resulting schedules are more comprehensive (detailed) and better documented.

ACKNOWLEDGEMENT

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Figure 2. Delivery Times for Major Manufacturing End Items — 50 Replications
Figure 3. Sensitivity of Launch Operations
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**Figure 4. Crew Skill Utilization**
Figure 5. Space Station Facilities/Crew Skills Causing Significant Experimental Program Delays
Figure 6. Impact of Environmental Stochastics on Crew Skill Utilization and Experiment Completion Rate
Figure 7. TLGEN Off-Line Mode of Operation
Figure 8. TLGEN On-Line Mode of Operation
Figure 9. Functional Diagram of WICK 9
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Figure 10. Experiment Flight Schedule
Figure 11. Volume
Figure 12. Manpower
Figure 13. Cost by Year