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Conflict resolution strategies in expert scheduling systems: a survey and case study

JAY LIEBOWITZ
Department of Management Science, George Washington University, Washington, DC 20052, USA

PATRICIA LIGHTFOOT and CAROLYN DENT
NASA Goddard Space Flight Center, Code 514, Greenbelt, MD 20771, USA

Abstract

In the coming years, scheduling will be an increasingly important activity in the manufacturing and aerospace industries, especially at the US National Aeronautics and Space Administration (NASA). Expert systems have successfully been used to aid in the scheduling function. This paper surveys some of the conflict resolution approaches used in building expert scheduling systems, and then examines the feasibility of using an expert systems approach for scheduling activities and resolving conflicts for experimenters to use NASA Goddard-supported satellites. Recommendations for further reading in expert scheduling systems are given.

1 Introduction

Scheduling is an important function in such fields as manufacturing, aeronautics and astronautics, and business. At the National Aeronautics and Space Administration (NASA), scheduling is becoming a critical concern. According to the Engineering Services group of McDonnell Douglas (Hedberg, 1989):

> "In particular, scheduling a Space Shuttle mission is a sizeable effort, requiring an estimated 100 person years work to schedule all the activities for one flight. Projecting out to the Space Station of the next decade, scheduling will be required for 365 days of the year, and could take 2000 to 3000 people working continuously.
>
> It has become clear that Mission Control for the Space Station needs automated scheduling tools that are highly reliable to schedule activities for the expensive and fragile space equipment."

In the NASA environment, the scheduling function will grow in increasing importance. This is evident in the routine activity of scheduling experimenter requests for using a satellite. While subsequent rescheduling resolves schedule conflicts, the increased competition for limited Tracking and Data Relay Satellite System (TDRSS) resources will lead to more constraints in getting schedule requests accepted (Computer Sciences Corp., 1988). This clearly points to the need for more efficient and less manpower-intensive scheduling systems.

One way to try to solve this scheduling problem is to use artificial intelligence (AI)/expert systems methods. Liebowitz and Lightfoot (1987) survey expert systems that have been used in scheduling. Expert systems may be a viable way to control this scheduling problem for several reasons, as explained by Geoffroy et al. (1990). First, because of combinatorics that could result in the scheduling domain, there is a great need for using intelligent search techniques. Through AI/expert systems, heuristics may be employed to reduce the possibility of combinatorial explosion of alternatives. Second, scheduling is a semantically rich domain, and expert system applications are particularly successful in this symbolic processing area. Third, scheduling problems deal with constraints, and AI/expert systems are very useful for constraint-based reasoning. Last, current scheduling enterprises rely heavily on human expertize. Expert systems allow for capturing the professional knowledge and experiential learnings of an expert. Thus, expert systems may be useful as a mechanism for preserving the institutional memory of the expert and organization.

It seems clear from reviewing the scheduling literature that there are several points of consensus for developing expert scheduling systems (Geoffroy et al., 1990):

- a variety of techniques are needed to solve the scheduling problem;
- they need to handle resource-constrained scheduling;
- incremental, rescheduling algorithms are needed (e.g., backtracking);
- AI techniques need to be integrated with other solution methods to ensure the best possible overall scheduling system.

Karl Kempf of Intel's Knowledge Applications Laboratory elaborates on this last point. He says (Hedberg, 1989):

> Working on an AI manufacturing (e.g., scheduling) problem you probably spend: 25% of your time with the user, educating him and having him educate you; 25% interfacing to existing programs; another 25% writing user interfaces that make the program usable; and maybe 25% of the time doing AI.

Kempt further states that expert scheduling systems can help us apply the heuristics to find the optimal or a good workable solution in as short a time as possible (Hedberg, 1989).

This paper surveys the conflict resolution strategies used in expert scheduling systems with special emphasis on the aerospace field. Then, a case study will be provided that looks at the challenge of scheduling experimenter requests, among satellites, to use satellites in the TDRSS era.

2 Survey of conflict resolution strategies used in scheduling

Generally speaking, there are three major classes of solution methodologies for scheduling. These are the mathematical (optimization) approach, the heuristic approach, and the "other" approaches. Each of these classes of approaches are highlighted below.

2.1 Mathematical class

There are three major mathematical approaches that have been used in scheduling problems. The first is the operations research methodology. Linear and nonlinear programming, project planning, decision analysis and dynamic programming techniques are operations research methodologies that have been employed for scheduling problems. NP-Complete and NP-Hard problem solution techniques have also been applied for scheduling applications, particularly in resource-constrained scheduling.

The second approach used that might be considered under the mathematical class is simulated annealing. This method of solving combinatorial optimization problems uses techniques derived from statistical mechanics (Collins et al., 1989). The four major components of this technique as applied to scheduling problems are:

1. Description of all possible solution configurations, e.g., problem is to find a schedule that minimizes resource conflicts; another part of the goal may be to maximize the scheduling of high priority activities; the possible solution configurations are the possible schedules.
2. A generator of random changes in a given configuration, e.g., random selection may be made of the number of start times to change, the distance each is changed, and the direction that each is changed.
3. An objective function to minimize, e.g., minimize the sum of the priorities of the unscheduled activities.

4. An analog of temperature—a value that decreases over time, restricting the allowed changes as it decreases.

The third approach under the mathematical class is the use of polynomial algorithms. According to a study of optimization techniques for activity scheduling (Reddy, 1989), a polynomial time algorithm for approximate optimal solution does exist for the scheduling of TDRSS resources. This algorithm involves a weighted number of tardy activities with concurrent resource usage, relative start times and activity priorities on parallel resources of multiple types (Reddy, 1989). The activity specific usage levels of capacitated resources need to be taken into account in this TDRSS scheduling application.

2.2 *Heuristic approaches*

With the heuristic approach, the idea of "satisficing" plays a role; that is, a workable solution is obtained, and it may not necessarily be the optimal solution. With the heuristic approach, rules of thumb (often obtained by the scheduling experts) are used to limit the search space used to obtain a workable scheduling solution. A number of expert scheduling systems have used the heuristic approach. These include: NOA (Das et al., 1988), Expert System for Dynamic Scheduling of Space Station Payloads (Floyd & Ford, 1986), PARR (McLean & Dent, 1989), EPPS (McLean et al., 1990), ROSE (Odubiyi & Zoch, 1989), ASAP (Matlin, 1988), EMPRESS (Hankins et al., 1985), DR (Brown, 1988), TRACKEX (Mitchell, 1989) and SURE (Thalman & Sparn, 1990).

Different scheduling strategies have been employed in the heuristic class of methods. "Unit boundaries" (as in ROSE (Odubiyi & Zoch, 1989) is one approach used for scheduling. Plan-It-2 (Eggemeyer & Cruz, 1990) uses this approach, where each resource in an activity sequence creates a list of change times (unit boundaries) that includes the starting times and ending times of the activities and the times at which the resource amounts available change (Collins et al., 1989). A master list of all the unit boundary times on the individual lists is formed, and the average of the values in each of the new intervals is found. The resulting list is simplified, and the unit boundary times of the entries with the highest numbers are the times sent to the event for final selection (Collins et al., 1989).

The use of profiles, as in the expert scheduling system RALPH (Durham et al., 1990), is another scheduling strategy whereby the profile (i.e., assignment likelihoods for each resource) of each unscheduled activity is weighted by the relative priority of the activity with the chosen activity. The usage profile of each scheduled activity is weighted heavily. The timeline is searched for a place to schedule the chosen activity which minimizes the total weight of the profiles of the other activities over the scheduled time period (Collins et al., 1989).

Other heuristic approaches to scheduling include the following (note that many expert scheduling systems use these techniques but the "jargon" varies from one project to another):

- one pass resolve (e.g., EPPS (McLean, 1990), OPIS)—schedule each activity at its earliest acceptable starting time and resolve conflicts in time order (Collins et al., 1989);
- foveation (e.g., EPPS)—using information samples (information gathered in a time interval about the activity) for resolving scheduling and conflict resolution (Collins et al., 1989);
- dynamic quick strategy—checks the inter-request dependencies of a selected request instance with other requests, and only when the dynamic constraint(s) are not violated, places the request instance at the first opportunity along the timeline (Goodman, 1989);
- largest resource remainder strategy—searches all the available resource time slots (intervals) on the timeline and schedules the request instance in an interval that leaves the largest amount of the resource after the request instance is scheduled (Goodman, 1989);
- lookahead scheduling—less backtracking, but can result in unnecessary constraint propagation (Zweben, 1988);
- delayed evaluation strategy—a system employing delayed evaluation does not completely evaluate its data structures until they are accessed (Zweben, 1988);

- schedule the most constrained activities on the timeline first (e.g., EPPS);
- constraint-based representation—uses a variety of different types of constraints to guide the search, and is able to selectively relax conflicting constraints, e.g., EPPS, ISIS (Fox et al., 1982), OSA (Brindle & Anderson, 1986), ESP2 (Stacy & Japp, 1988; Japp & Davis, 1988), MAESTRO (Britt et al., 1988), Elecchem (Muller et al., 1987) and SCS (Straguzzi, 1990).

2.3 "Other" class of approaches

Besides the mathematical (optimization) and heuristic classes of scheduling, there is a third category of "other" approaches. Neural networks might fit under this category. SPIKE (Miller et al., 1988), an expert system used for the scheduling of the Hubble Space Telescope activities, uses a version of the Hopfield neural net model for scheduling. The incorporation of this neural net model offers the potential for implementation on parallel hardware, which might provide even more dramatic performance improvements in the scheduling of Space Telescope activities. Hybrid approaches using both optimization techniques and heuristics (e.g., SPIKE) are being employed in the scheduling area. Table 1 highlights some of the aforementioned expert scheduling systems and their corresponding scheduling/conflict resolution strategies.

The next few sections discuss a specific problem of resolving conflicts in scheduling experimenter requests for NASA-supported satellites. First, the task domain will be explained, and a discussion of the conflict resolution strategy selection process will then be made.

3 Scheduling experimenter requests: task domain

The Network Control Center's (NCC) major responsibility is scheduling and monitoring the NASA Space Network (SN) resources, primarily TDRSS. The periods of communication when users send commands for specific activity to the spacecraft and receive resulting data from the spacecraft must be scheduled through the NCC (Computer Sciences Corp., 1990). In vying for the TDRSS resources, such as when more than one request is made for an overlapping time and TDRS antenna, the NCC accepts or denies a request based on priority and urgency.

To assist the user in scheduling access to the NASA communications resources, a system called the User Planning System (UPS) is being developed to accept user communication service requests, transmit them to the NCC, receive the confirmed schedules back from the NCC, and present them to the user. The UPS will replace the current system performing this function, the Mission Planning Terminal (MPT) (Computer Sciences Corp., 1990). The UPS is being designed for the Multi-satellite Operations Control Center (MSOCC) users. MSOCC currently supports two satellites, but in the near term, MSOCC will support five spacecraft. An important element considered by the UPS is a mechanism for resolving conflicts among the users in order to better ensure the likelihood of the NCC accepting a user's request. This conflict resolution strategy plays an increasingly important role in the years ahead, as by 1995, the NCC expects 1600 events per week to be scheduled. A way proposed for remedying these scheduling conflicts is a generic scheduling concept which expresses all resource requirements, constraints, and flexibility within the request (Computer Sciences Corp., 1990).

In looking at the next five years, there are several challenges that will be faced in scheduling experimenter requests via the NCC-UPS. These challenges are influenced by the following factors (CTA Inc., 1990):

- having secured and non-secured missions and STS (Shuttle Transportation System) sharing scheduling resources makes scheduling and fault isolation very difficult;
- scheduling conflict resolution at NCC requires input from multiple missions personnel;
- complete knowledge of scheduling restrictions is not possessed by missions;
- TDRSS users are responsible for preparing their own operating schedule requests, but do not have access to needed information (e.g., available times);

Table 1 Conflict resolution strategies and scheduling approaches

Major aerospace expert *scheduling systems*	
• Expert system by Monte Zweben (Ames AI Research Lab)	Constraint-based scheduling; constraint satisfaction with delayed evaluation; using data structure "streams", a system employing delayed evaluation does not completely evaluate its data structures until they are accessed.
• Onboard Scheduling Assistant (Boeing Aerospace)	Rescheduling approaches: (1) resource substitution; (2) task deletion; (3) task insertion; uses constraint-based representation.
• Network Operator Assistant (Computer Sciences Corp.)	Methodology for efficient optimization of a number of requests for single resource scheduling and its heuristic extension to multiple resources.
• ROSE (Loral Ford Aerospace)	External representation; different conflict resolution strategies (relax the requirements of unscheduled requests; overbook certain resources; relax the requirements of scheduled requests or de-allocate certain resources; acquire additional resources from another scheduler in a distributed scheduling architecture; implement an incremental scheduling strategy; implement a reactive scheduling strategy which incorporates one or more of the courses of action); Use A* algorithm for rescheduling.
• NPAS (Bendix)	Repeat-expand strategy.
• RALPH (JPL)	Internal representation.
• ESP2 (MSFC)	Depth-first searching, backtracking, forward chaining.
• SPIKE/SPSS (STScI)	"Greedy" algorithm; best-first search based on A* algorithm.
• MAESTRO (Martin Marietta)	Constraint-based scheduling; constraints are of four basic types: (1) The availability of resources or conditions necessary to the performance of a subtask; (2) constraints relating the performance of two subtasks in the same activity; (3) constraints relating the performance of a subtask in one activity to that of a subtask in another; (4) constraints relating the performance of an activity or subtask to some event or interval on the timeline; schedule generation uses the select-place-update cycle.
• EMPRESS (Mitre)	Scheduling heuristics; infers schedule errors or inadequacies by forward chaining these rules and finding unsubstantiated rule consequents.
• IEPS/PARR (Bendix)	Constraint-based scheduling; emphasizes the use of heuristic conflict resolution strategies.
• PLAN-IT-2 (JPL)	Scheduling in three ways: two are performed by the tactical process, the third handled by the activity process.
• SURE (U. of Colorado)	Constraint-based scheduling.

- NCC has to verbally communicate with POCCs (Payload Operations Control Centers) to resolve conflicts—it needs knowledge of mission requirements;
- the greater the physical distribution of human beings, the greater the effects on timeliness and effectiveness of conflict resolution;
- requests have to be completely resubmitted if the request is rejected, rather than just allowing the necessary edits to be made and resubmitted;
- operational electronic interfaces still require human intervention;
- current interfaces make planning and scheduling aids unavailable for easy POCC usage;
- software deficiencies and conflicts are discovered late in the timeline.

These factors, coupled with the fact that more requests will be made as the number of spacecraft launched increases, will make the scheduling of these requests even more difficult in terms of the requests being granted. In fact, according to some NASA officials, the two most demanding areas for needed solutions in the coming years at NASA are scheduling and data analysis.

In the next section, the recommended approach for resolving scheduling conflicts in the NCC-UPS environment will be explained.

4 Recommended approach for resolving conflicts in scheduling experimenter requests in the NCC-UPS task domain

To decide upon the "best" approach for resolving conflicts in scheduling experimenter requests in the MSOCC NCC-UPS, the analytic hierarchy process (AHP) was used as the selection methodology. The AHP is a systematic procedure for representing the elements of a problem, hierarchically (Saaty & Kearns, 1985). AHP has been used as a problem solving methodology for a wide range of applications, ranging from determining the best location for an oil refinery to selecting an appropriate problem for expert system development (Liebowitz, 1989).

The specific steps in the AHP are (Saaty & Kearns, 1985):

1. Define the problem and determine what you want to know.
2. Structure the hierarchy from the top (the objectives from a managerial viewpoint) through the intermediate levels (criteria on which subsequent levels depend) to the lowest level (which usually is a list of the alternatives).
3. Construct a set of pairwise comparison matrices for each of the lower levels—one matrix for each element in the level immediately above. There are $n(n-1)/2$ judgements required to develop each matrix in this step.
4. Having made all the pairwise comparisons and entered the data, the consistency is determined using the eigenvalue.
5. Steps 3 and 4 are performed for all levels and clusters in the hierarchy.
6. Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria, and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.
7. The consistency of the entire hierarchy is found by multiplying each consistency index by the priority of the corresponding criterion and adding them together. The consistency ratio should be about 10% or less to be acceptable.

To ease the application of AHP, a microcomputer-based decision support system called Expert Choice (Decision Support Software, Inc., 1985) was used. Expert Choice automates the AHP so that the decision maker can easily interact with the computer and develop his/her application.

4.1 Use of AHP as applied to the NCC-UPS conflict resolution strategy selection

The objective of this application was to determine the "best" conflict resolution strategy to use for scheduling experimenter requests in the MSOCC NCC-UPS. After surveying the work that has been done in this area in the past (see section 3) and conducting numerous interviews*, the possible alternative conflict resolution/scheduling strategies were narrowed down to:

• POLY ALG:	Polynomial Time Algorithm.
• EXT-BACK:	External Expansion Architecture with Backtracking
• LOOK AHD:	Look-ahead Scheduling
• DYN PROG:	Dynamic Programming Scheduler
• DEL EVAL:	Delayed Evaluation Method
• HEURISTC:	Pure Heuristics

* Interviews with Nancy Goodman (NASA), Robert Dutilly (NASA), David McLean (Bendix), Mabel Monts (NASA), Carolyn Dent/Patricia Lightfoot (NASA), Dave Alldredge/John Brown (CSC), Jim Rash (NASA), Robert Lovisa/Arlington Morgan/Howard Hoge/K. Patel (CSC).

The polynomial time algorithm (POLY ALG) alternative refers to a weighted number of tardy activities with concurrent resource usage, relative start times and activity priorities on parallel resources of multiple types. This algorithm differs from the TDRSS problem only by the absence of activity specific usage levels of capacitated resources (Reddy, 1989).

The external expansion architecture with backtracking (EXT-BACK) alternative refers to combining the global view of inter-request dependencies with the ability to return to an earlier decision point in the scheduling process in an effort to schedule more requests (Goodman, 1989). The external expansion architecture expands all the generic requests into request instances before any requests are scheduled. It can process dependencies between the currently selected request and all other requests whether or not they have previously been processed (Goodman, 1989).

The look-ahead scheduler (LOOK AHD) uses constraints to allow one to specify the relationships between the problem's variables in a system, and enables the system to automatically determine the computation path from known variables to the unknown (Zweben, 1988). These representations can be used for look-ahead in a search process.

The dynamic programming scheduler (DYN PROG) is an approach to optimization which takes a sequential or multistage decision process containing many interdependent variables and converts it into a series of single-stage problems, each containing only a few variables (Nemhauser, 1966).

The delayed evaluation (DEL EVAL) alternative is a technique where the system employing delayed evaluation does not completely evaluate its data structures until they are accessed (Zweben, 1988). The use of delayed evaluation circumvents unnecessary constraint propagation and is transparent to knowledge engineers because stream operations are quite similar to list operations (Zweben, 1988).

The pure heuristics (HEURISTC) alternative employs the strategies that expert schedulers typically take in composing their schedules. Sample heuristic conflict resolution strategies include (McLean, 1990): changing the activity start time, trying before the conflict, trying after the conflict, removing the conflict, trying in the next orbit, trying in the previous orbit, changing the activity duration, bumping the start time, trying a different activity, and shifting the conflict.

Once the possible alternatives for conflict resolution/scheduling are known, the next step is to identify the criteria used in selecting among these alternatives. The criteria and comparison results are explained next.

4.2 Criteria and overall synthesis results for the NCC-UPS application

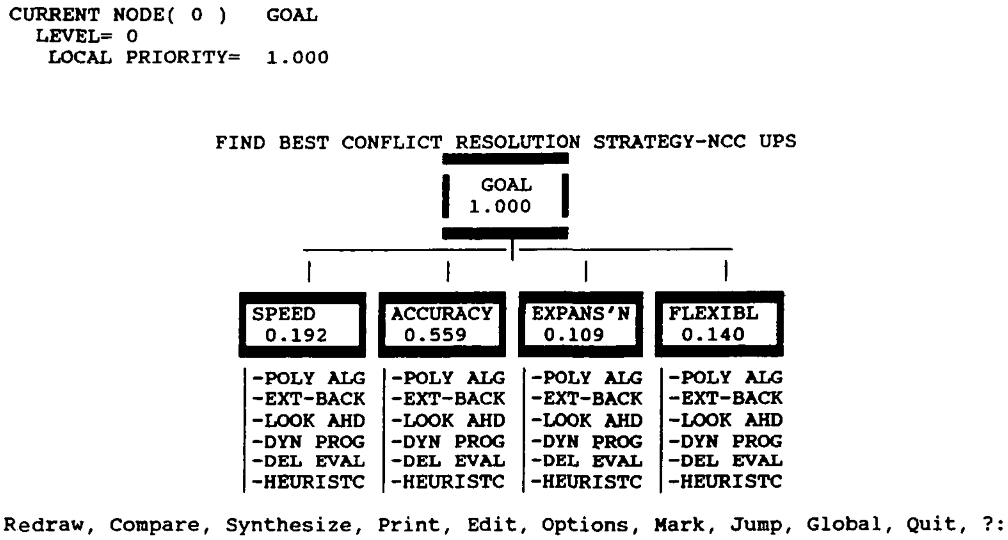
There are four primary criteria that were used to determine the most appropriate conflict resolution/scheduling strategy for the NCC-UPS application. The criteria are:

- speed: the ability to schedule experimenter requests on a timely basis;
- accuracy: the success in scheduling the experimenter requests (i.e., what percentage of the requests were scheduled);
- expansion (EXPANS'N): the ability to handle an increased number of requests, and the ability to expand for maintenance reasons;
- flexibility (FLEXIBL): the ability for the scheduling approach to handle a variety of factors.

After determining the criteria and alternatives, the next step involves employing the AHP, using Expert Choice, to first obtain a weighting of the priorities of the criteria with respect to the goal, and then to obtain the weights of the alternatives with respect to each criterion. Figure 1 shows the tree constructed for this application, and indicates the weighting of the criteria, after pairwise comparisons, as follows from most important criterion (highest weight) to less important (lower weight):

- ACCURACY = 0.559
- SPEED = 0.192
- FLEXIBL = 0.140
- EXPANS'N = 0.109

1.000



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CURRENT NODE( 0 )   GOAL
  LEVEL= 0
   LOCAL PRIORITY=  1.000


          FIND BEST CONFLICT RESOLUTION STRATEGY-NCC UPS

                          GOAL
                          1.000

    SPEED       ACCURACY    EXPANS'N    FLEXIBL
     0.192       0.559       0.109       0.140

   -POLY ALG   -POLY ALG   -POLY ALG   -POLY ALG
   -EXT-BACK   -EXT-BACK   -EXT-BACK   -EXT-BACK
   -LOOK AHD   -LOOK AHD   -LOOK AHD   -LOOK AHD
   -DYN PROG   -DYN PROG   -DYN PROG   -DYN PROG
   -DEL EVAL   -DEL EVAL   -DEL EVAL   -DEL EVAL
   -HEURISTC   -HEURISTC   -HEURISTC   -HEURISTC

Redraw, Compare, Synthesize, Print, Edit, Options, Mark, Jump, Global, Quit, ?:
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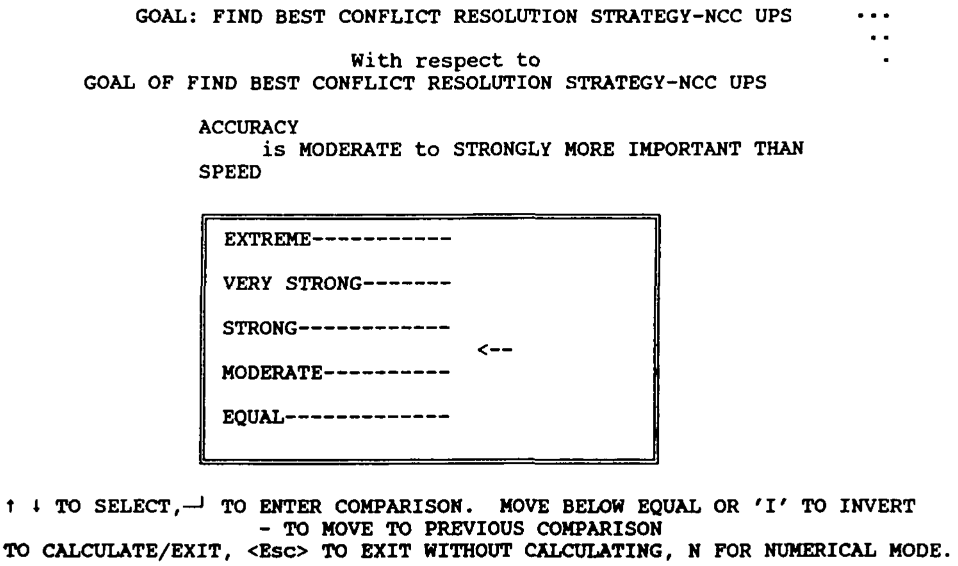
Figure 1 Tree hierarchy of the NCC-UPS application

These weights were derived from the pairwise comparisons among the criteria, according to the AHP, as shown in Figure 2. These weights represent the "best" judgements of the decision maker based upon reading the results of various studies, "best guesses", and subjectivity on the part of the decision maker.

After obtaining the weights of the criteria, the next step is to weight each alternative with respect to each criterion. Again, pairwise comparisons, as shown for example in Figure 3, were used to determine these priorities. Again, these weights, derived by using the AHP, reflect the views of the decision maker according to the readings of various studies and "best guesses." The synthesis step, as explained in section 4, was then invoked, which produced the ranking of the alternatives based upon the pairwise comparisons among the criteria and among the alternatives versus each criterion. Figure 4 shows the results of the synthesis. The ranking of alternatives is:

- EXT-BACK = 0.213
  (External Expansion Architecture With Backtracking)



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        GOAL: FIND BEST CONFLICT RESOLUTION STRATEGY-NCC UPS         ...
                                                                      ..
                          With respect to                              .
     GOAL OF FIND BEST CONFLICT RESOLUTION STRATEGY-NCC UPS

              ACCURACY
                  is MODERATE to STRONGLY MORE IMPORTANT THAN
              SPEED

              EXTREME-----------

              VERY STRONG-------

              STRONG------------
                                     <--
              MODERATE----------

              EQUAL-------------

↑ ↓ TO SELECT,↵ TO ENTER COMPARISON.  MOVE BELOW EQUAL OR 'I' TO INVERT
                 - TO MOVE TO PREVIOUS COMPARISON
*TO CALCULATE/EXIT, <Esc> TO EXIT WITHOUT CALCULATING, N FOR NUMERICAL MODE.
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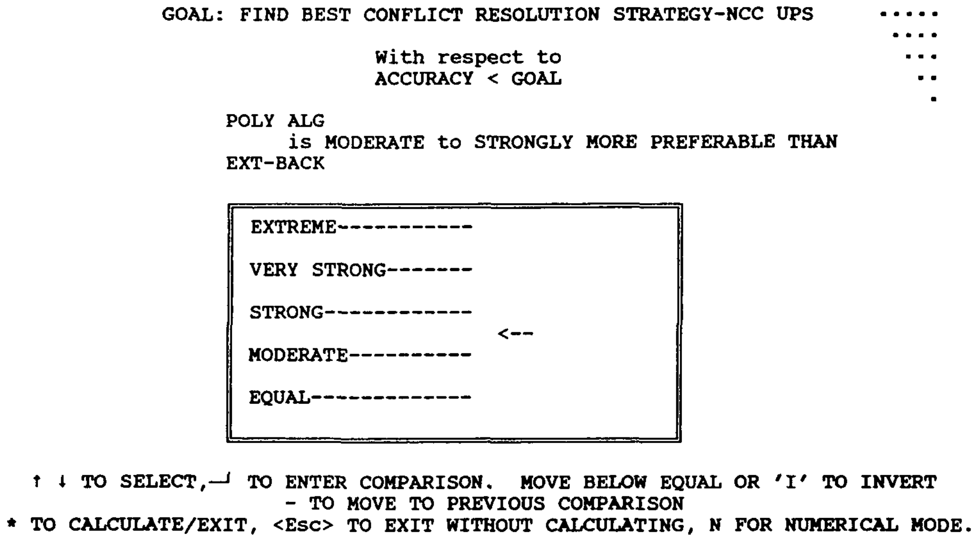
Figure 2 Sample pairwise comparison between criteria with respect to the goal



```
GOAL: FIND BEST CONFLICT RESOLUTION STRATEGY-NCC UPS          .....
                                                              ....
                    With respect to                            ...
                    ACCURACY < GOAL                             ..
                                                                 .
      POLY ALG
          is MODERATE to STRONGLY MORE PREFERABLE THAN
      EXT-BACK

      EXTREME-----------

      VERY STRONG-------

      STRONG------------
                             <--
      MODERATE----------

      EQUAL-------------

↑ ↓ TO SELECT,↵ TO ENTER COMPARISON. MOVE BELOW EQUAL OR 'I' TO INVERT
                 - TO MOVE TO PREVIOUS COMPARISON
* TO CALCULATE/EXIT, <Esc> TO EXIT WITHOUT CALCULATING, N FOR NUMERICAL MODE.
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Figure 3 Sample pairwise comparison between alternatives with respect to the criterion

- POLY ALG = 0.211
  (Polynomial Time Algorithm)
- HEURISTC = 0.202
  (Pure Heuristics)
- DYN PROG = 0.185
  Dynamic Programming Scheduler)
- DEL EVAL = 0.120
  (Delayed Evaluation)
- LOOK AHD = 0.069
  (Look-ahead Scheduler)

The inconsistency index, as shown in Figure 4, is 0.08 (about 92% consistent in our comparisons), which means it is in the tolerable range (0.10 or less). According to the results of the AHP, the top three alternatives are, in order: EXT-BACK, POLY ALG and HEURISTC.

5 Conclusions

This paper surveyed various approaches for handling conflict resolution in expert scheduling systems. Also presented is an actual case study in the aerospace field for determining the most appropriate conflict resolution strategy for scheduling the satellite experimenter requests in the NCC-UPS environment.

Based upon the survey and analysis above, the case study provides a methodology for assessing the appropriateness of conflict resolution strategies. In this specific case, there was not an overwhelmingly "best" choice for the conflict resolution/scheduling strategy based on the AHP. An actual test should be conducted in comparing how the three top choices fare using a 1995 timeframe (scheduling 1600/events a week). This experiment would allow for more specific, objective results in terms of accuracy, expandability, flexibility and speed/performance, and for benchmarks to be assessed by developing these architectures/strategies and testing them against each other. These test results would determine the most appropriate conflict resolution/scheduling strategy, and this information could then be incorporated into the critical design of the MSOCC NCC-UPS.

Future research in the expert scheduling systems field might also address the use of generic

```
                    FIND BEST CONFLICT RESOLUTION STRATEGY-NCC UPS

                                 TALLY FOR LEAF NODES

LEVEL 1               LEVEL 2              LEVEL 3      LEVEL 4      LEVEL 5

ACCURACY = 0.559
                      POLY ALG = 0.181
                      DYN PROG = 0.153
                      EXT-BACK = 0.090
                      HEURISTC = 0.062
                      DEL EVAL = 0.044
                      LOOK AHD = 0.029
SPEED    = 0.192
                      HEURISTC = 0.072
                      EXT-BACK = 0.050
                      DEL EVAL = 0.029
                      DYN PROG = 0.016
                      POLY ALG = 0.015
                      LOOK AHD = 0.011
FLEXIBLE = 0.140
                      HEURISTC = 0.046
                      EXT-BACK = 0.035
                      DEL EVAL = 0.025
                      LOOK AHD = 0.016
                      POLY ALG = 0.009
                      DYN PROG = 0.009
EXPANS'N = 0.109
                      EXT-BACK = 0.039
                      DEL EVAL = 0.021
                      HEURISTC = 0.021
                      LOOK AHD = 0.013
                      POLY ALG = 0.007
                      DYN PROG = 0.007
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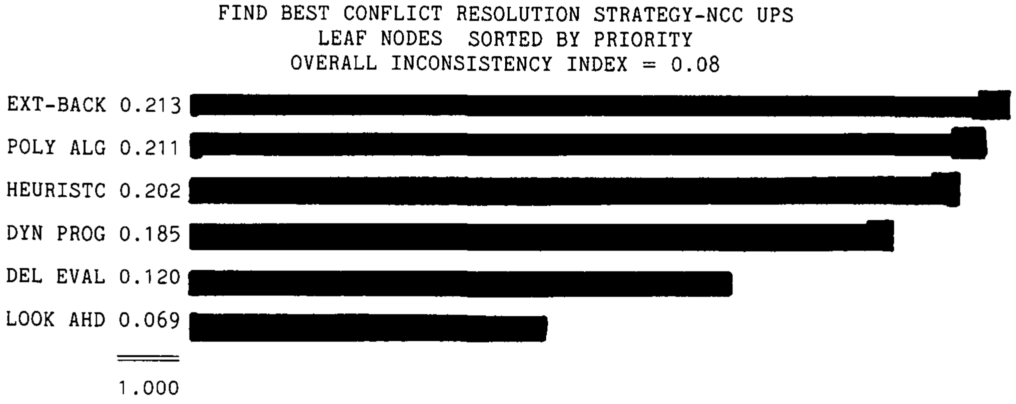

Figure 4 Synthesis results

scheduling and the development of expert scheduling system tools and shells that facilitate the use of multiple conflict resolution strategies.

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Further reading

Expert Scheduling Systems

- Liebowitz, J and Lightfoot, P, 1987. "Expert systems for scheduling: survey and preliminary design concepts" *Applied Artificial Intelligence Journal* **1** (3).

This paper addresses expert systems used for scheduling problems. It focuses first on a survey of expert systems for scheduling, both NASA-related and others. Components of the scheduling domain are discussed, and suggestions for requirements and preliminary design concepts for a generalized expert system scheduler are explained.

- Special issue on "AI in Scheduling" 1989. *The Spang Robinson Report on Artificial Intelligence* **5** (3) March.

This special issue looks at what has actually been done in the field in building and using expert scheduling systems. Expert scheduling system applications in production at Intel, Texas Instruments and McDonnell Douglas/NASA are discussed. Some research and development issues in expert scheduling systems are also cited.

- Kempf, K, Le Pape, C, Smith S and Fox, B, 1991. "Issues in the design of AI-based schedulers" *AI Magazine* **11** (5) January.

This article, based on the results of the AI-Based Scheduling Workshop at the International Joint Conference on Artificial Intelligence-89, examines a variety of topics related to AI-based schedulers, namely: the relative virtues of expert system, deep method and interactive approaches, the balance between predictive and reactive components in a scheduling system, the maintenance of convenient scheduling descriptions, the application of the ideas of chaos theory to scheduling, the state-of-the-art in schedulers which learn, and the practicality and desirability of a set of benchmark scheduling problems.

- Kempf, K, Russell, B, Sidhu, S and Barrett, S, 1991. "AI-based schedulers in manufacturing practice" *AI Magazine* **11** (5) January.

This paper concentrates on actual expert scheduling systems used in a production basis. Case studies are presented by Carnegie Group as a builder of scheduling systems for its customers, by Texas Instruments and Intel Corporation as builders of schedulers for their own use, and by Intellection as a consulting house specializing in scheduling problems.

Expert scheduling systems for aerospace applications

- Collins, C, George, J and Zamani, E, 1989. "Strategies for Automatic Planning: A Collection of Ideas" NASA Jet Propulsion Laboratory, JPL Publication Report 89-12, Pasadena, CA, May 1.

This report examines automated methods for resolving conflicting resource usages by activities in a schedule. As related to aerospace scheduling domains, this report explains methods, tools and ideas for automatic planning and scheduling systems.

- Rash, J, ed., 1990. Special issue on "Space Applications of Artificial Intelligence" *Telematics and Informatics* 7 (3/4).

This special issue, based on the NASA Goddard Conference on Space Applications of Artificial Intelligence, looks at the use of expert systems in a variety of functional areas in the aerospace domain. These functional areas include: planning and scheduling, fault isolation and diagnosis, interpretation, classification and monitoring and control. Expert scheduling systems used at NASA are described, as well as citing lessons learned.

- McLean, DR, 1991. "Expert system technology for scheduling satellite communication links" In: J Liebowitz (ed.), *Operational Expert Systems in the United States* Pergamon Press.

This chapter discusses an operational expert system used at NASA Goddard for scheduling satellite experimenter requests to use a NASA-supported satellite. This expert system was the first operational expert scheduling system used at NASA Goddard. It uses a heuristic-based approach, emphasizing conflict resolution versus conflict avoidance techniques.