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**AN EFFICIENT HEURISTIC  
SCHEDULER FOR HARD  
REAL-TIME SYSTEMS**

by

**John Glenn Levine**

**September 1991**

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| <p>The requirement for efficient scheduling algorithms for the development of hard real-time systems resulted in much effort directed toward the development of high performance scheduling algorithms. The algorithms developed up to this point for the Computer Aided Prototyping System (CAPS) do not satisfy the requirements for a efficient static scheduling algorithm. The existing static scheduler neither performs efficiently nor produces correct results for all input cases.</p> <p>This thesis represents the research conducted to develop a fast heuristic static scheduling algorithm based on the principles of simulated annealing. In addition, this thesis describes the development of new data structures that simplify the static scheduler and maximize system resources. Several of the existing scheduling algorithms were re-implemented to make use of the new data structures and provide correct results. Any feasible schedule produced by these scheduling algorithms guarantees that both timing and precedence constraints are met. The primary goal of this thesis was to produce an efficient and effective scheduler to support the CAPS system.</p> |       |                                           |                                                                                  |                                                         |                            |
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by  
*John Glenn Levine*  
*Cpt, U.S. Army*  
*B.S., U.S.M.A., 1983*

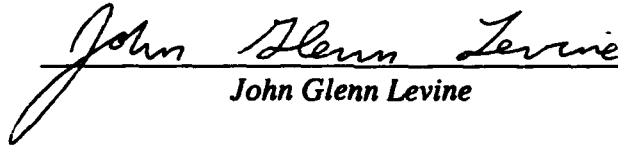
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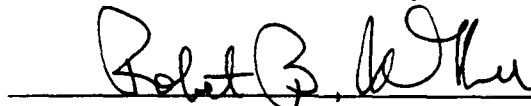
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## ABSTRACT

The requirement for efficient scheduling algorithms for the development of hard real-time systems resulted in much effort directed toward the development of high performance scheduling algorithms. The algorithms developed up to this point for the Computer Aided Prototyping System (CAPS) do not satisfy the requirements for a efficient static scheduling algorithm. The existing static scheduler neither performs efficiently nor produces correct results for all input cases.

This thesis represents the research conducted to develop a fast heuristic static scheduling algorithm based on the principles of simulated annealing. In addition, this thesis describes the development of new data structures that simplify the static scheduler and maximize system resources. Several of the existing scheduling algorithms were re-implemented to make use of the new data structures and provide correct results. Any feasible schedule produced by these scheduling algorithms guarantees that both timing and precedence constraints are met. The primary goal of this thesis was to produce an efficient and effective scheduler to support the CAPS system.

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## **I. INTRODUCTION**

### **A. BACKGROUND: HARD REAL-TIME SYSTEMS**

Large scale hard real-time systems are important to both civilian and military operations. Hard real-time systems are defined as those systems in which the correctness of the system depends not only on the logical results of the computation, but also on the time at which the results are produced. If results are not produced in a timely manner, disastrous results may occur. Examples of hard real-time systems include air traffic control systems, telecommunications systems, space shuttle control avionics systems, C<sup>3</sup>I systems, and future Strategic Defense Initiative (SDI) systems. Most hard real-time systems are specialized and complex, require a high degree of fault tolerance, and are typically embedded in a larger system. To overcome the complexity in the design and development of such systems, software engineers now use a new approach, called rapid prototyping, to build and maintain these systems. Rapid prototyping is a means for stabilizing and validating the requirements for complex systems (e.g. embedded control systems with hard real-time constraints) by helping the customer visualize system behavior prior to detailed implementation. The Computer Aided Prototyping System (CAPS), which is being developed at the Naval Postgraduate School, supports an iterative prototyping process characterized by exploratory design and extensive prototype evolution, thus enabling the engineers to produce complex systems that match user needs and reduce the need for expensive modifications after delivery.

## **B. THE COMPUTER AIDED PROTOTYPING SYSTEM (CAPS)**

CAPS consists of several modules. Figure 1 below describes the major software modules of CAPS. The user interface consists largely of a graphical editor for the formal prototyping language called Prototyping System Description Language (PSDL). Future implementations of this module will also have a syntax directed editor. The second module is the Software Database System which includes the Rewrite Subsystems, the Software Design Management Subsystem, and the Reusable Software Component Database. The third module is the Execution Support System (ESS). This module contains the PSDL Translator, the Static Scheduler, and the Dynamic Scheduler. Figure 2 shows the implementation and interfaces of the ESS. This thesis is concerned with the static scheduler component of the ESS.

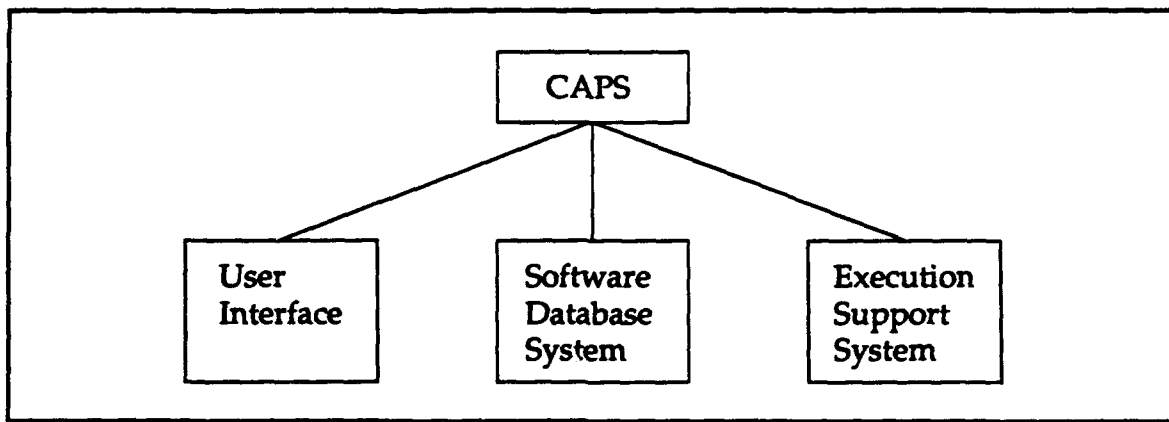


**Figure 1. Major Software Tools of CAPS**

The Dynamic Scheduler acts as a run-time executive when exercising the system. It schedules operators without timing constraints, which are not include in the static schedule, by using spare capacity in the static schedule. It

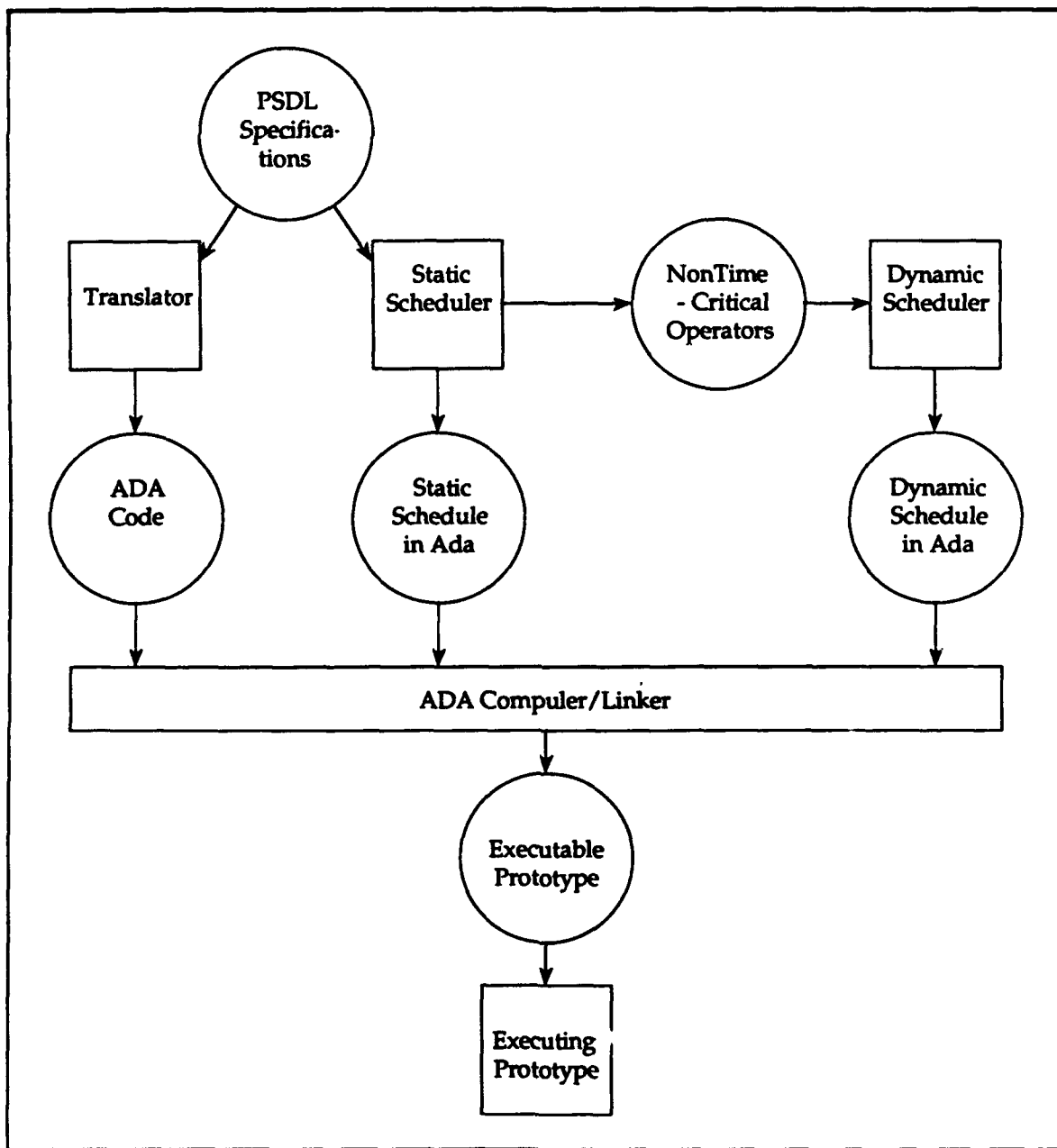


**Figure 2. The Execution Support System**

handles run-time exceptions and hardware/operator interrupts. It communicates with the user interface during prototype runs. Thus, it

performs like a miniature operating system. While the problems involved in this subsystem are interesting, it is the static scheduler that deals with the issues addressed in this proposal.

The purpose of the static scheduler is to build a static schedule for a set of tasks that must obey both precedence and timing constraints. This schedule gives the order of execution and the timing of the operators. The schedule is legal and feasible if both the precedence relationships are maintained and the timing constraints are guaranteed to be met.

The existing static scheduler is described in (Janson, 1988), (Killic 1989) and (Cervantes, 1988). Figure 3 is a data flow description of the static scheduler. The following paragraphs are a description of the static scheduler that was originally implemented by (Janson, 1988), (Killic, 1989), (Cervantes, 1988) and modified by the work described in this thesis. The Static Scheduler consists of five modules—PSDL\_READER, FILE\_PROCESSOR, TOPOLOGICAL\_SORTER, HARMONIC\_BLOCK\_BUILDER, and OPERATOR\_SCHEDULER.

The first component, PSDL\_READER, reads and processes the PSDL prototyping program. It is essentially a filter that removes information not needed by the Static Scheduler. The output of this module is the text file ATOMIC.INFO that contains all the operators along with any timing constraints the operators may have and the link statements which describe PSDL implementation graphs.

The second component, FILE\_PROCESSOR, analyzes the text file generated by the PSDL\_READER and separates the information into a linked list data structure called THE\_GRAPH and a file called NON\_CRITS. It then

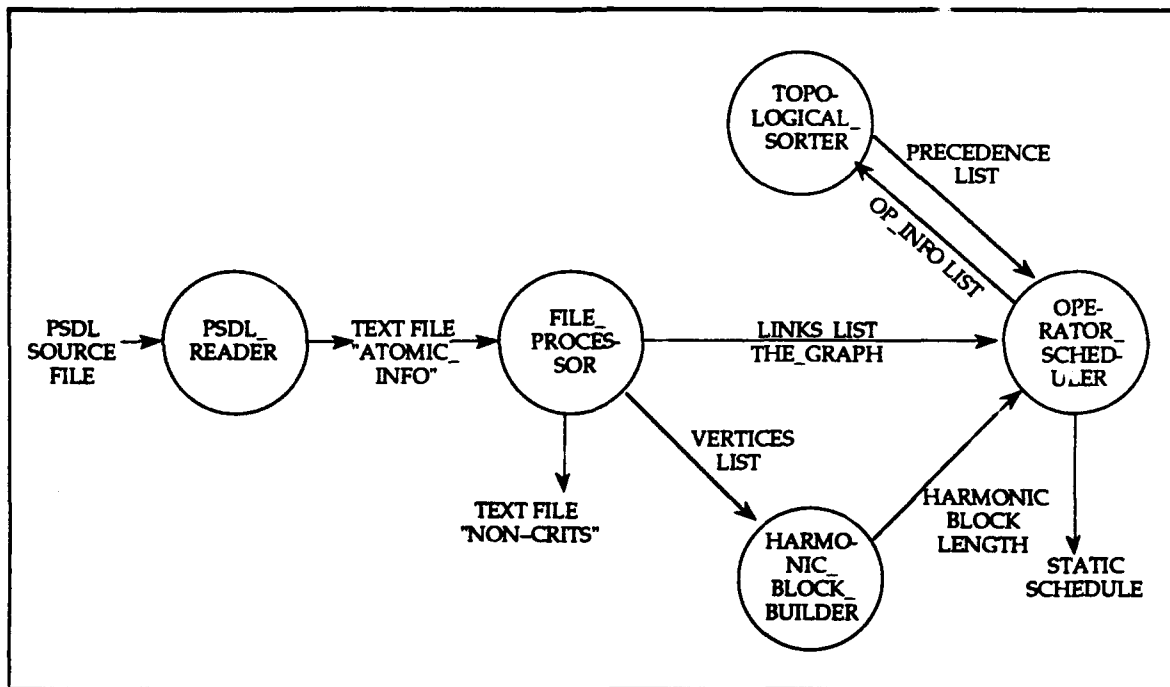


**Figure 3. Static Scheduler Data Flow Diagram**

converts sporadic operators into their periodic equivalents. The information is separated based on its destination and the additional processing required. **THE\_GRAPH**, which is a graph structure, as indicated in Figure 4 below contains two linked lists. The "VERTICES" list contains a list of all time-critical operators and their associated timing constraints. The "LINKS" list contains the link statements which are a syntactical description of the PSDL implementation graphs and indicates the data flows between operators. The "VERTICES" list is used by the **HARMONIC\_BLOCK\_BUILDER** module and the "LINKS" list is used by the **OPERATOR\_SCHEDULER** to develop a **OP\_INFO** list. The **OP\_INFO** list is then used by the **TOPOLOGICAL\_SORTER** to develop a precedence list for the operators to be scheduled. The entire structure **THE\_GRAPH** is also used by

OPERATOR\_SCHEDULER to develop a static schedule. The NON\_CRITS file contains a list of all non-critical operators that is used by the Dynamic Scheduler.

The third component, TOPOLOGICAL\_SORTER, performs a topological sort on the OP\_INFO data structure. Using the OP\_INFO list is a change from the previous implementations of the Static Scheduler. The TOPOLOGICAL\_SORTER has also been rewritten. It now develops a true topological ordering and is not dependent on a specific ordering of operators in the PSDL input file. The result is a total ordering of the operators depending on data flow. This total ordering is passed to OPERATOR\_SCHEDULER module as the PRECEDENCE\_LIST data structure.

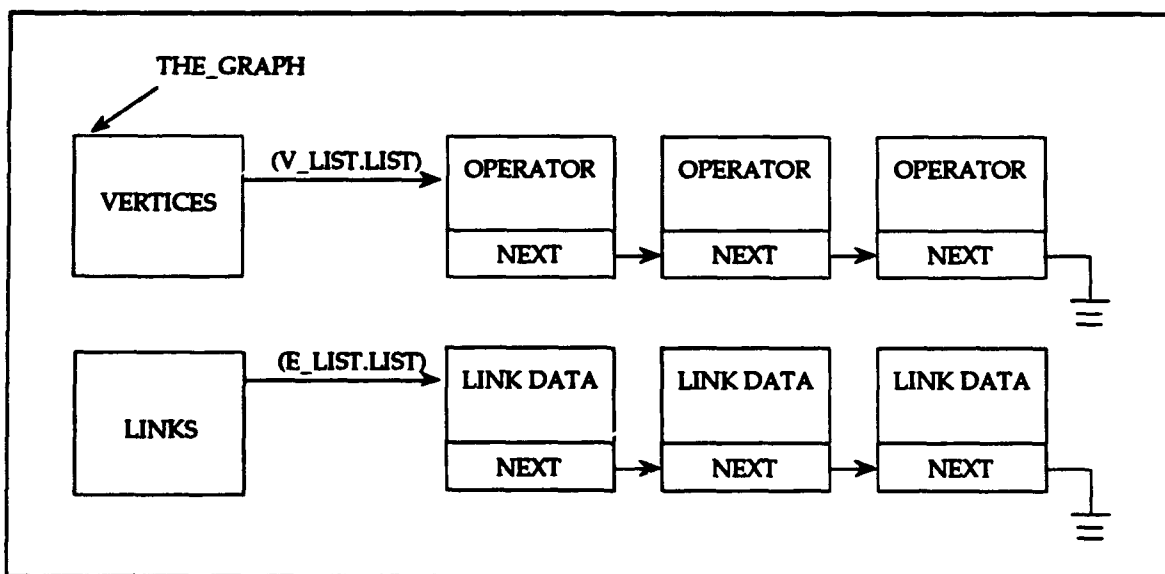


**Figure 4. Graphical Representation of THE\_GRAPH Linked List Structure**

The fourth component, HARMONIC\_BLOCK\_BUILDER determines the Harmonic Block Length of the static schedule to be developed. A harmonic

### C. PERIODIC OPERATORS

This section is based upon the background work done in (Cervantes, 1989). Periodic operators are triggered by temporal events and must occur at regular time intervals. The timing constraints of each periodic operator  $OP_i$  consists of a specific period  $period(OP_i)$ , a maximum execution time  $MET(OP_i)$ , and a deadline  $finish\_within(OP_i)$ . Denote the  $k$ th instance of  $OP_i$  by  $OP_{i,k}$ , the start time of  $OP_{i,k}$  by  $start\_time(OP_{i,k})$ , and the completion time of  $OP_{i,k}$  by  $completion(OP_{i,k})$ . For  $k > 1$ , define  $earliest\_start\_time(OP_{i,k})$ , the earliest starting time of  $OP_{i,k}$ , as  $start\_time(OP_{i,1}) + (k-1) * period(OP_i)$  and  $deadline(OP_{i,k})$ , the latest completion time of  $OP_{i,k}$ , as  $earliest\_start\_time(OP_{i,k}) + finish\_within(OP_i)$ . Then

$$start\_time(OP_{i,k}) \geq earliest\_start\_time(OP_{i,k})$$

and

$$start\_time(OP_{i,k}) + MET(OP_i) \leq deadline(OP_{i,k}).$$

The precedence constraints among a given set of operators are specified in the form of a directed acyclic graph  $G$ . The precedence constraints are defined by the communications among the operators that compose the system being developed. PSDL operators communicate by means of named data streams. All data values carried by a data stream must be instances of a specific abstract data type associated with the stream. There are two different types of data streams in PSDL, dataflow streams and sampled streams. Dataflow streams are used in applications where the values in the stream must not be lost or replicated and the period of the producer and consumer of the data must be the same (lockstep performance). Sampled streams are used in applications

#### **D. ORGANIZATION**

The objective of this thesis is to describe a new heuristic static scheduling algorithm that uses the principles of simulated annealing to develop a feasible schedule if one exists. To do so this thesis is organized as follows: Chapter II describes the static scheduling algorithms that exist in CAPS for a single processor environment; Chapter III is a description of the new heuristic scheduling algorithm. It includes a description of the simulated annealing process and the implementation of this process in the static scheduler; Chapter IV is a description of the new data structure and modifications made to existing modules that improve the performance of the static scheduler; Chapter V is an evaluation of this new algorithm; and Chapter VI presents conclusions and recommendations for future work.

addressed in (Janson, 1988). This chapter examines the five scheduling algorithms currently implemented in CAPS. These five algorithms are Harmonic Block with Precedence Constraints, Earliest Start, Earliest Deadline, Branch and Bound, and Exhaustive Enumeration. The first three algorithms were described in detail in (Kilic, 1989), and the remaining two were described in detail in (Fan, 1990).

#### **B. HARMONIC BLOCK WITH PRECEDENCE CONSTRAINTS**

This algorithm attempts to find a feasible schedule by scheduling the operators in the order that they appear in a topological ordering. If any of the operators violate a timing constraint, the schedule being developed is rejected. Since in most hard real-time systems there exists more than one topological ordering of operators there are cases where one ordering will produce a feasible schedule while another will not. This algorithm does not adjust the topological ordering in order to find a feasible schedule.

#### **C. EARLIEST START TIME SCHEDULING ALGORITHM**

In the original algorithm (Bra, 1971), each transaction must have an earliest start time. That is, each transaction becomes available at time  $a_i$ , must be completed by  $b_i$ , and requires  $c_i$  units of time. Pre-emption of transactions is allowed in this algorithm but transaction precedence is normally not allowed. The version of the algorithm that is implemented in CAPS allows precedence but does not allow pre-emption. Transactions are scheduled in this algorithm based on the system clock, the earliest start time of a transaction, and the priority of the transaction. The algorithm assigns a time slot to the newest transaction based on its earliest start time. If two or more

## **E. THE NEED FOR A NEW SCHEDULING ALGORITHM**

There is a gap in the current static scheduler. Three algorithms exist that attempt to develop a quick solution. These algorithms only find feasible solutions for very simple hard real-time systems but fail to find a feasible solution as systems become more complex. Exhaustive Enumeration and Branch and Bound, on the other hand, will find a feasible schedule if such a schedule exists, but both are very costly due to their time complexity.

There exists a need for a fast algorithm that is capable of producing a feasible solution. The proposed heuristic algorithm, which is based on the simulated annealing approach, appears to be the best compromise between simple-minded and exponential time algorithms already implemented in CAPS.

## **F. SUMMARY**

This chapter presented a sample of previous algorithms developed to solve the real-time scheduling requirement. These algorithms have inherent weaknesses such as an inability to handle complex topological orderings that do not immediately produce solutions or they have a high degree of time complexity. Since the static scheduling problem is NP-hard (Zdrzalka, 1988), systemic global search is the only guaranteed way to return a feasible static schedule for a hard real-time system if such a schedule exists. The exhaustive enumeration algorithm has already been implemented in CAPS to accomplish this. This algorithm has demonstrated to be very costly in practice.

### **III. DESCRIPTION OF THE ALGORITHM TO HANDLE THE HARD REAL-TIME SCHEDULING PROBLEM**

#### **A. SIMULATED ANNEALING**

The use of simulated annealing to solve combinatorial optimization problems is an area that has received much attention lately. Combinatorial optimization problems are those whose configuration of elements are finite or countably infinite. An example combinatorial optimization problem is the assignment problem where there are a number of personnel available to do an equal number of jobs. The cost for each person to do each job is known. The goal is to assign each person to a job so that the total cost is as small as possible (Otten, 1989). There are a wide range of combinatorial optimization problems that the simulated annealing approach can be utilized for. These include graph partitioning, graph coloring, number partitioning, VLSI design, and travelling salesman type problems.

Simulated annealing is based on the behavior of physical systems and the laws of thermodynamics. The way that liquids freeze and crystalize or metals cool and anneal are the principles upon which simulated annealing is based. At high temperature, liquid molecules move freely with respect to one another. As the liquid cools, this mobility is lost. Atoms line up and form a pure crystal that is at a minimum energy level. As the system cools slowly nature finds the minimum energy state (Flannery, 1984). Examining simulated annealing in non-physical terms, a comparison is made to the concept of local optimization or iterative improvement. Local optimization

energy states the probability for making an uphill move still exists. As indicated in Figure 5 above, uphill moves allow the algorithm to leave a poor local solution (point A or point B) and reach a better solution in the vicinity of point C. This general scheme of always taking a downhill step while occasionally taking an uphill step is known as the Metropolis algorithm, named after Metropolis, the scientist, who with his coworkers first investigated simulated annealing in 1953 (Press, 1984).

The choice of a probability function to determine if an uphill movement is allowed is an important consideration. At each step of the simulated annealing algorithm a new state is constructed based on the current state. This new state is constructed by randomly displacing or adjusting a randomly selected element. If this new state has a lower cost than the current state, the new state is accepted as the current state. If the new state has a higher cost than the current state, the new state is accepted with the probability:

$$\exp(-\Delta e/kT).$$

This probability function is known as the Boltzman probability distribution where:

$\Delta e$  = difference in cost between new state and current state

$k$  = Boltzman's constant of nature relating temperature to energy

$T$  = Current Temperature

A characteristic of this probability function is that at very high temperatures every new state has an almost even chance of being accepted as the current state. At low temperatures the states with a lower cost have a higher probability of being accepted as the current state.

The annealing schedule sets after how many random changes in the configuration is each downward step in  $T$  taken, and how large that step is. The range of the annealing temperature and the value of the annealing schedule are normally established from trial and error experimentation (Flannery, 1984).

A pseudocode representation of the simulated annealing algorithm based on the algorithm proposed in (Johnson, 1989) follows:

```

BEGIN
  GET AN INITIAL SOLUTION
  SET INITIAL TEMPERATURE  $T > 0$ 
  WHILE  $T > 0$  LOOP
    FOR  $I$  IN  $1..L$  LOOP
      GENERATE A NEW SOLUTION
       $\Delta e = E(\text{NEW SOLUTION}) - E(\text{CURRENT SOLUTION})$ 
      IF  $\Delta e \leq 0$  THEN
        CURRENT SOLUTION := NEW SOLUTION
      ELSE
        CURRENT SOLUTION := NEW SOLUTION
          WITH PROBABILITY  $\exp(-\Delta e/T)$ 
      END IF
    END LOOP
    ADJUST TEMPERATURE ( $T = rT$ )
  END LOOP
END

WHERE
   $T$  = TEMPERATURE
   $r$  = COOLING FACTOR
   $L$  = NUMBER OF TRIALS TO PERFORM AT EACH TEMPERATURE
   $\Delta e$  = DIFFERENCE IN COSTS BETWEEN TWO SOLUTIONS

```

The choice of values for  $T$ ,  $r$ , and  $L$  have a significant impact on the annealing schedule. The higher the initial temperature, the higher the cooling factor, and the larger the number of trials at each temperature result in more solutions being examined in order to find an optimum solution. The goal in choosing these parameters is to pick them so that a sufficient but not excessive number of solutions are examined. These values are normally chosen arbitrarily and adjusted through experimentation. The next section of

The goal of the hard real-time scheduler is to find a feasible schedule for the operators, not the optimum schedule. This means that simulated annealing can be terminated as soon as a feasible schedule is found. Both loops of the annealing algorithm are modified so that if a feasible schedule is found, the loop condition for both loops is satisfied and annealing is terminated. This means that when each iterative solution is tested, it is examined to see if it is a feasible solution. The next section describes what a feasible solution is. If the current schedule is feasible, boolean flags are set so that both loop conditions of the algorithm are satisfied.

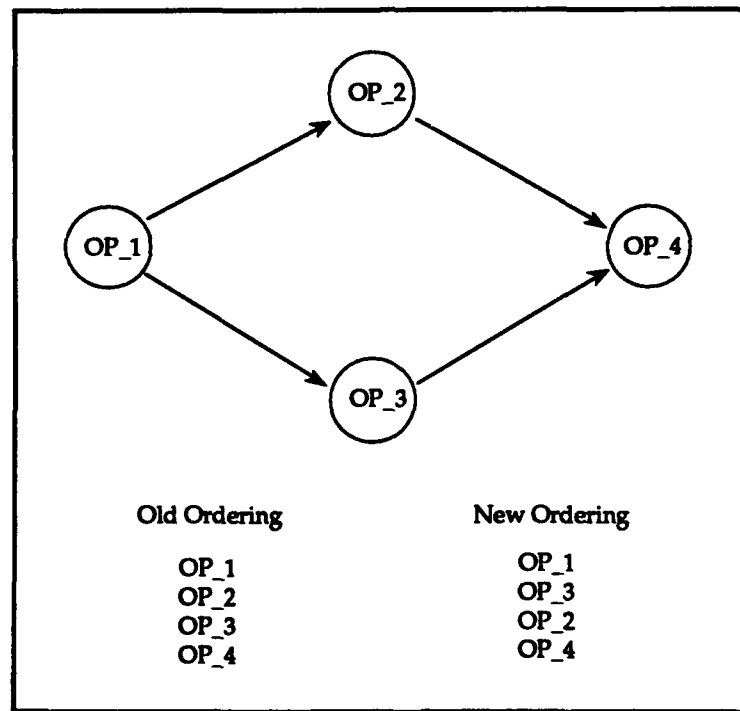


**Figure 6. Reordering of Operators Preserving Precedence**

The proposed schedule must also be examined to check that the finish time of the last operator in the schedule does not exceed the harmonic block length. The concept of harmonic block length is covered in (Kilic, 1989). The basic idea is that a schedule is developed to fit inside a harmonic block. The length of the harmonic block is the greatest common multiple of the periods of all operators to be scheduled. Once a schedule is developed that fits within the harmonic block, subsequent copies of the block can be made to maintain the hard real-time schedule. Each proposed schedule is examined to insure that the schedule does not exceed the harmonic block length. If a schedule does exceed the harmonic block length, the schedule is not valid since subsequent copies of the schedule will violate the hard real-time timing constraints.

If a schedule is examined and all timing constraints are satisfied and the harmonic block length is not violated then a feasible schedule exists. At this point the simulated annealing algorithm is terminated and the feasible schedule is returned to CAPS.

#### **E. METHOD FOR PRODUCING A FEASIBLE SCHEDULE FOR A PROPOSED REAL-TIME SYSTEM**

The simulated annealing algorithm uses a step by step method to find a feasible solution. These steps include developing an initial solution, testing the initial and subsequent solutions, and adjusting the solution while guaranteeing that operator precedence is maintained. The simulated annealing algorithm is a heuristic (or approximate) approach to solving the scheduling problem for hard real-time systems. It does not guarantee to find a valid solution even if one exists. The goal of this thesis is to develop an

schedule as possible while maintaining precedence. Figure 8 demonstrates the annealing that occurs. Each operator ahead of the operator in question is examined to determine if it is a parent of the operator that violated its timing constraints. The operator continues to move up the schedule until we come to its parent. At this point we insert the operator in question after its parent. Each operator in the new schedule begins at its lower bound or immediately after the preceding operator, whichever is greater. This new schedule is then examined to determine what its cost is and if it is in fact a feasible schedule.

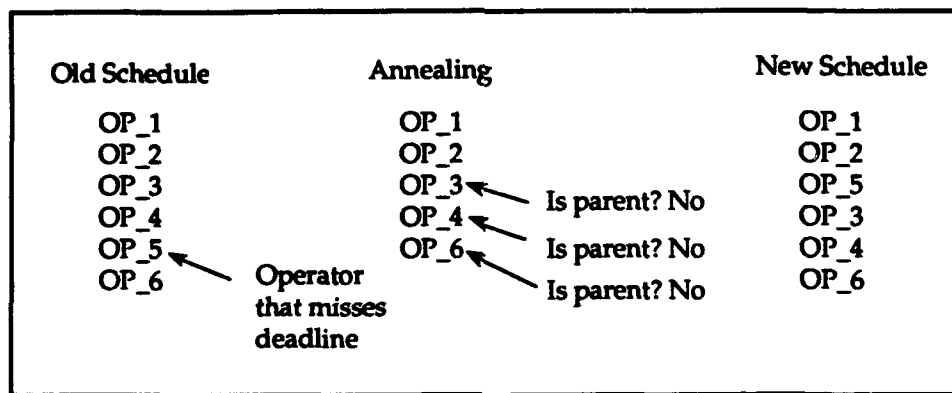


**Figure 8. Use of Annealing to Modify a Schedule**

If the new schedule has a positive cost that is lower than that of the current schedule, this new schedule is adopted and annealing continues. If the new schedule is costlier than the current schedule, a random choice is made whether to accept the new schedule with its higher cost or keep the current schedule. This choice is made in accordance with the annealing function, which takes into account the current temperature of the system and the difference in cost between the current solution and the new solution. The choice of accepting the new solution with a higher cost over the current

## **IV. IMPLEMENTATION OF THE STATIC SCHEDULER**

### **A. OBSERVATIONS**

The previous implementation of the static scheduler, although functional, does not perform scheduling in the most efficient manner, nor does it handle all types of input. During the development of the new scheduling algorithm problems were identified and corrected in several of the existing packages, which are part of the static scheduler. Development of more efficient data structures resulted in faster execution of all scheduling algorithms and eliminated the requirement for cumbersome input/output between the various components of the static scheduler.

The modification of existing packages and the development of new data structures greatly improved the performance of the new static scheduler while increasing modularity and simplifying the code of the various scheduling algorithms. The implementation of additional scheduling algorithms in the future will become a simpler task because of the work done in this thesis.

### **B. MODIFICATIONS TO EXISTING PACKAGES**

Four packages that made up the static scheduler underwent modification in order to correct errors, increase functionality and improve performance. These four packages are the generic package SEQUENCES, which contained all the linked list routines, the TOPOLOGICAL\_SORTER package, the FILE\_PROCESSOR package, and the FILES package, which contained all of the global variables and data structures used by the static scheduler.

traverses a linked list freeing each node in that list. The second COPY\_LIST, allows the contents of one list to be copied into another list. This procedure will work with lists of the same or different lengths. The need for these two routines to improve memory management came about as a result of the development of the simulated annealing algorithm. Since this algorithm repeatedly generates new schedules, a computer system's memory would rapidly fill to capacity if discarded schedules were not reclaimed for their memory.

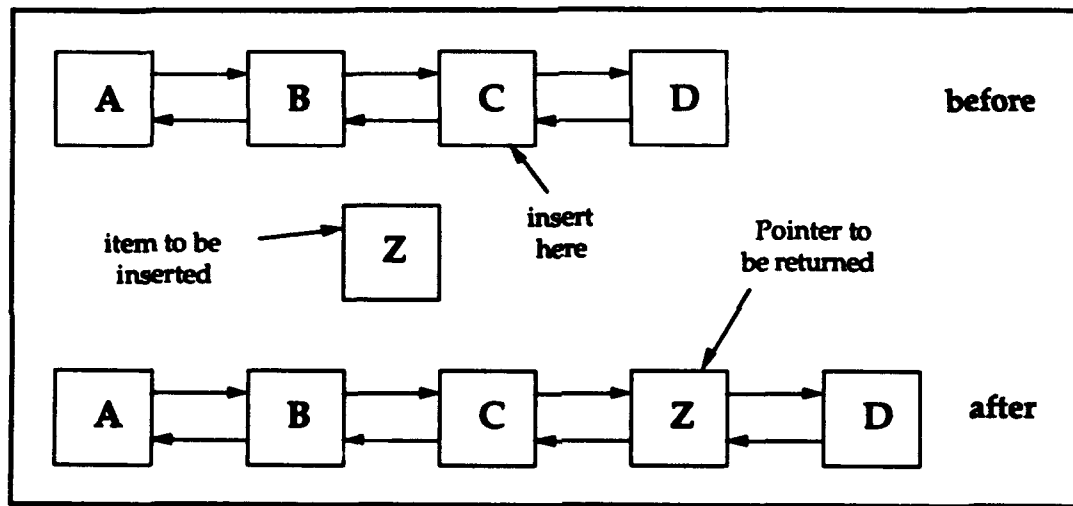


Figure 10. Effect of the INSERT\_NEXT Linked List Routine

## 2. TOPOLOGICAL\_SORTER

The original topological sorter only worked when the input was received in a certain order. True topological orderings were not found. This sorter did not handle cases of multiple data links between operators. The sorter also required numerous traversals of various linked lists in order to accomplish a topological ordering of operators.

The new `TOPOLOGICAL_SORTER` (`T_SORT`) is a simpler and faster implementation of the topological ordering algorithm. It uses an array that is initialized to the in-degree of each operator. The new scheduler always augments the given precedence graph with a dummy start node. This dummy start node has in-degree zero and is connected to all the operators with in-degree zero in the original precedence graph. The dummy start node is the only operator in the queue of operators to be processed initially. We remove the operator *v* from the head of the queue and place it in the precedence list (topological ordering). The in-degree value of each of *v*'s children is decremented by one. Once an operator has an in-degree value of zero in the array the operator is placed at the end of the queue of those operators waiting to be processed. As each operator is processed it is removed from the queue and placed in the precedence list. This process continues until the queue is empty. The new topological sort can handle input in any order.

### **3. `FILE_PROCESSOR`**

This package, which processed the initial input and tested the input to determine if the operators could be scheduled on a single processor system, now only tests the input and calculates periods for the non-periodic operators. This package is renamed `PROCESSOR`. Processing of the input now occurs in the packages `FRONT_END` and `NEW_DATA_STRUCTURES`.

### **4. Files**

The original `FILES` package contained the definitions of all the types, instantiation of all the generic packages, and global variables used by the static scheduler. The new package contains the same type of information. This new

package is named DATA. Since the data structures used by the static scheduler are different, the new package reflects these changes.

### **C. PACKAGES REMOVED FROM THE STATIC SCHEDULER**

During development of the new algorithm the existing data structures were examined. In addition to modifying several packages to improve their performance, several packages were eliminated because they were inefficient in their execution and thus were replaced by new packages. The removed packages are DIGRAPH, the HARMONIC\_BLOCK\_BUILDER scheduling algorithm, and OPERATOR\_SCHEDULER.

The instantiation of the generic package GRAPHIS resulted in the package DIGRAPH, which was a linked list representation of the operators and their precedence relationships. This package, once created, did not require any changes throughout the execution of the static scheduler. Using linked lists to represent graphs with their associated parent-child relationships is very inefficient. Numerous linked list traversals were required in order to determine the parents or children of a specific operator. The graph structure was not internal to this package but was passed as a parameter from procedure to procedure within the static scheduler increasing the input/output requirements. Procedures also existed within this package allowing for the removal and addition of nodes and edges in the graph. This could result in the unintentional removal or addition of information or changes to the relationships between operators. The generic package GRAPHIS has been replaced by a new generic package NEW\_DATA\_STRUCTURES which is described in detail in the next section.

The HARMONIC\_BLOCK\_BUILDER scheduling algorithm is incorporated into the simulated annealing scheduling algorithm. The HARMONIC\_BLOCK\_BUILDER algorithm is used to develop the initial solution. If all the timing constraints are satisfied, simulated annealing does not occur since a legal schedule exists and the static scheduler terminates.

The OPERATOR\_SCHEDULER package, which contained the routines TEST\_DATA, the HARMONIC\_BLOCK\_BUILDER, EARLIEST\_START, and EARLIEST\_DEADLINE algorithms, is removed and replaced by the SCHEDULER package. The procedure TEST\_DATA is moved to the package FRONT\_END. Correct implementations of the EARLIEST\_START and EARLIEST\_DEADLINE scheduling algorithms that make use of the new packages and data structures are contained in the package SCHEDULER.

#### **D. NEW PACKAGES AND DATA STRUCTURES**

Several new packages and data structures are contained in the new version of the static scheduler. These modifications improve performance and correctness, streamline input/output, and simplify the static scheduler. These new packages are FRONT\_END, NEW\_DATA\_STRUCTURES, PRIORITY\_QUEUE, SCHEDULER, and ANNEAL.

##### **1. FRONT\_END**

This package contains the procedures PRODUCE\_OP\_LIST and TEST\_DATA. The procedure PRODUCE\_OP\_LIST reads the text input file ATOMIC.INFO. Depending on the keywords, which are declared as constants, the procedure separates the information in the file and stores the time critical operator information in a linked list that is used by the package

**NEW\_DATA\_STRUCTURES.** This procedure also produce a count of the number of operators to be scheduled.

The procedure **TEST\_DATA**, described in detail and implemented in (Janson, 1988) is also contained in this package. This allows the input to be examined as soon as a linked list of operators is established so that system resources are not wasted if a feasible schedule is not possible for a given input.

The new representation of the graph **NEW\_GRAPH**, is instantiated from the generic package **NEW\_DATA\_STRUCTURES**, in the package **FRONT\_END**. This allows for visibility of **NEW\_GRAPH** by the rest of the packages within the static scheduler.

## **2. NEW\_DATA\_STRUCTURES**

This generic package replaces the generic package **GRAPHS**. It represents an acyclic graph structure of operators of the hard real-time system in a simpler and easily accessible data structure. The new graph is a record that consists of two entries, **OP\_ARRAY** and **OP\_MATRIX** (see Figure 11). Unlike the old graphical representation all information about the operators; i.e their name, period, maximum execution time, etc. as well as their parent-child relationships only exist within this package. All relevant information about the operators that is required by the static scheduler is accessible by way of procedures and functions that are instantiated within the package and visible outside of it.

Since the operator information does not change once the new graph is created, the decision was made to streamline this data structure. Using the Ada principle of information hiding, the graph structure and its contents are

private so that this information cannot inadvertently be changed. This was not the case with the old graph structure.

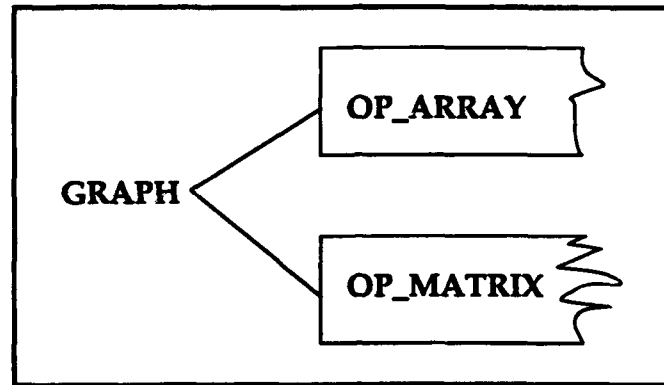


**Figure 11. Graph Structure**

The generic package `NEW_DATA_STRUCTURES` is instantiated in the declarative part of the package `FRONT_END`. However, `OP_ARRAY` and `OP_MATRIX` cannot be instantiated at this point because the number of operators to be scheduled is not known until `ATOMIC.INFO` is processed. By once again using the principles of Ada this is possible by creating the record structure called `GRAPH` and declaring a pointer type to this data structure. Once the number of operators to be scheduled is known the Ada allocator "new" is used to create an instance of `GRAPH` that contains the proper size `OP_ARRAY` and `OP_MATRIX`. This allows for efficient use of memory.

The data structure `OP_ARRAY` contains all relevant information about the operators. Once the operators are stored in the array they are identified by their index position in the array, which are integers. This allows for immediate access of all relevant operator information instead of having to traverse a linked list in order to find the desired operator. Identifying

operators by their index position as opposed to their name reduces the storage required for operator identification throughout the static scheduler.

The data structure OP\_MATRIX, which is a two dimensional array, greatly speeds up execution of the static scheduler. In the old graph data structure numerous linked lists traversals were required in order to determine the parent-child relationships of operators. The new graph data structure, illustrated in Figure 13, streamlines the execution of this requirement. Each operator has a row and column in the matrix. Each cell in the matrix has two entries, one for a parent operator and one for a child operator. The diagonal cells  $[i,i]$  in the matrix act as header nodes for two circularly linked lists, one containing the parents of node  $i$  in the graph, and the other containing the children of node  $i$ . For all  $i \neq j$ , the child operator (respectively parent operator) field of the  $[i,j]^{\text{th}}$  entry is -1 if  $OP_j$  is not a child (respectively parent) of  $OP_i$ . Otherwise, the child operator (respectively parent operator) field will contain the index number of the next child (respectively parent) in the circular linked list. For example, using Figures 13 and 14, the children of  $Op_2$  can be retrieved as follows: starting at cell  $[2,2]$  retrieve the value 5 from the corresponding child operator field. Moving to cell  $[2,5]$ , retrieve the value 6 from the child position. Moving to cell  $[2,6]$  we see that there is a value of 2 in the child position, returning us back to the starting cell. At this point we know  $OP_2$  has no more children. A similar routine is used to identify an operators parent's, only moves are made column wise as opposed to row wise. To check a parent-child relationship we can go right to the cell in question. If the value of the appropriate field is not -1, then a relationship exists.

| 0                              | 1            | 2            | 3            | 4            | 5            | ... |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|-----|
| Dummy<br>Starr<br>Node<br>Info | OP_1<br>Info | OP_2<br>Info | OP_3<br>Info | OP_4<br>Info | OP_5<br>Info |     |

Figure 12. Operator Array

|         |   | CHILDREN |          |          |          |          |          |          |          |          |          |
|---------|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
|         |   | 0        | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        |
| PARENTS | 0 | 1<br>0   | 2<br>1   | 3<br>2   | 0<br>3   | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 |
|         | 1 | -1<br>-1 | 4<br>0   | -1<br>-1 | -1<br>-1 | 5<br>4   | 1<br>2   | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 |
|         | 2 | -1<br>-1 | -1<br>-1 | 5<br>0   | -1<br>-1 | -1<br>-1 | 6<br>5   | 2<br>3   | -1<br>-1 | -1<br>-1 | -1<br>-1 |
|         | 3 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 6<br>0   | -1<br>-1 | -1<br>-1 | 3<br>6   | -1<br>-1 | -1<br>-1 | -1<br>-1 |
|         | 4 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 7<br>1   | -1<br>-1 | -1<br>-1 | 4<br>5   | -1<br>-1 | -1<br>-1 |
|         | 5 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 7<br>1   | -1<br>-1 | 8<br>7   | 5<br>6   | -1<br>-1 |
|         | 6 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 8<br>2   | -1<br>-1 | 9<br>8   | 6<br>9   |
|         | 7 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 7<br>4   | -1<br>-1 | -1<br>-1 |
|         | 8 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 8<br>5   | -1<br>-1 |
|         | 9 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | -1<br>-1 | 9<br>6   |

CHILD  
OP  
PARENT  
OP  
OPERATOR

Figure 13. Operator Matrix

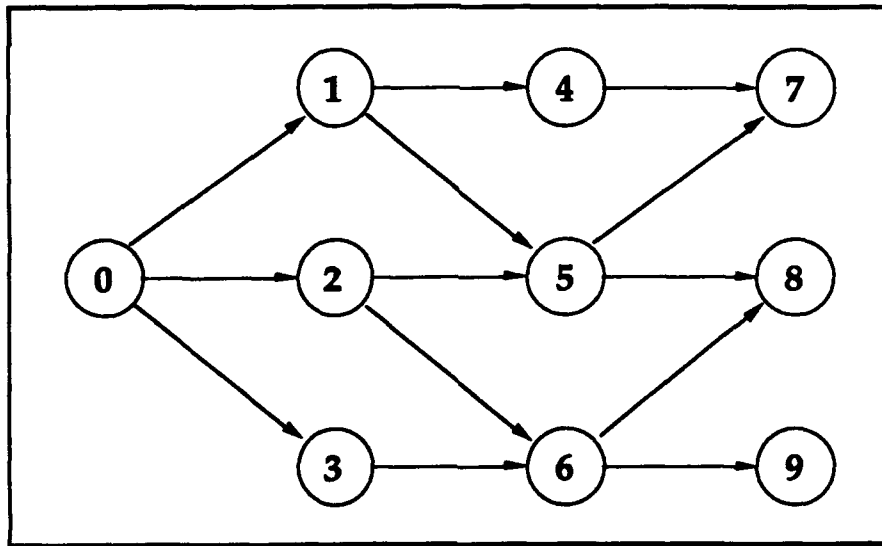


**Figure 14. Matrix Representation of Graph**

### **3. PRIORITY\_QUEUE**

This generic package is used by the earliest start and earliest deadline scheduling algorithms. During instantiation of this package three parameters are passed in to the generic template. The first is the type of element that is to be placed in the priority queue. The second is the type of the value used to order this priority queue. The third is the function used to order the priority queue. By using a priority queue the code for both the earliest start and earliest deadline algorithms is simplified. Under the Ada principle of code reusability, the generic priority queue package is a reusable software component that has a wide range of uses.

### **4. Anneal**

This package contains the code for the new scheduling algorithm that is described in detail in Chapter III of this thesis. It contains all the necessary procedures and functions required to perform simulated annealing.

## **E. DESCRIPTION OF THE NEW STATIC SCHEDULER**

The new implementation of the static scheduler still takes the same input, `ATOMIC.INFO` and produces the same output, the Ada textfile `SS.a`. Figure 15 shows the dataflow of the new static scheduler. As illustrated in Figure 15, once the input is stored in the new data structure, the requirement for cumbersome input/output is removed. All necessary information is accessible through the package `NEW_DATA_STRUCTURE`. The new static scheduler accomplishes the same functions as the old static scheduler, but it does so in a more efficient, simplified, and correct manner.

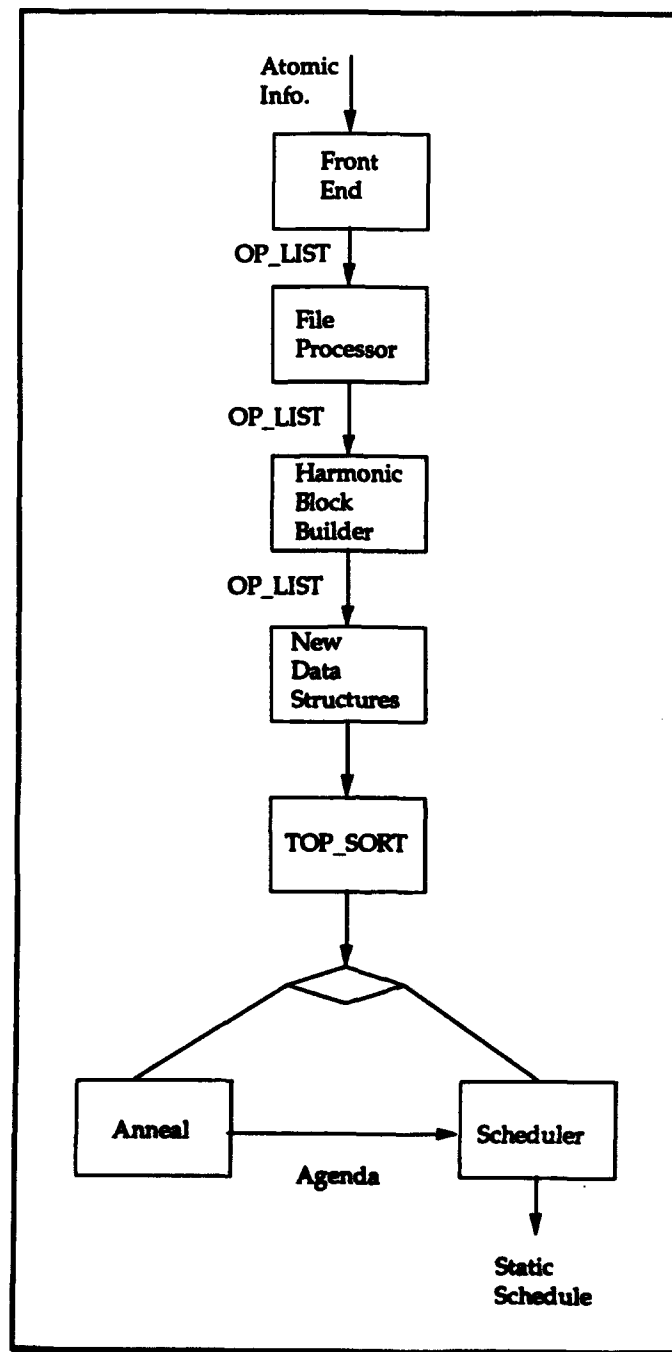


**Figure 15. Data Flow Diagram of Static Schedule**

## **V. EVALUATION OF THE NEW ALGORITHM**

### **A. IMPROVEMENTS IN PERFORMANCE OF THE NEW ALGORITHM OVER PREVIOUS ALGORITHMS**

The simulated annealing scheduling algorithm starts with an initial solution that satisfies the precedence constraints of the hard real-time system, and attempts to find a feasible solution that satisfies the system timing constraints. The simulated annealing algorithm is not intended to run faster than either the earliest start or earliest deadline scheduling algorithm. It is intended to find feasible schedules that cannot be found by the earliest start or earliest deadline algorithms and to serve as an alternative to the more costly branch and bound and exhaustive enumeration scheduling algorithms. Based on the initial testing results simulated annealing accomplishes this goal.

The performance and results of both the earliest start and earliest deadline scheduling algorithm improved as a result of the changes implemented in the static scheduler. These changes, discussed in detail in Chapter IV of this thesis, resulted in a rewriting of both of these algorithms. These algorithms now find correct solutions for cases that were not solved in the previous version of the static scheduler. In particular, the algorithm does not output incorrect schedules that exceed the harmonic block length, which they did in the previous version of the static scheduler.

Any new scheduling algorithm that is implemented in the static scheduler should utilize the packages and the data structures that were

implemented as a result of this thesis. These data structures are efficient and do not require large amounts of memory.

## **B. EXAMINATION OF THE SIMULATED ANNEALING ALGORITHM ON HARD REAL-TIME SYSTEM PROBLEMS**

The algorithm's initial performance in handling hard real-time system problems is satisfactory. Two test cases are presented in this thesis and the simulated annealing algorithm was able to find a feasible solution when both earliest start and earliest deadline scheduling algorithms failed to find a feasible solution. Simulated annealing was not costly time wise when it came to finding these solutions. This indicates that the parameters chosen for the simulated annealing scheduling algorithm (i.e. freezing temperature, cooling factor, the number of trials at each temperature) are satisfactory choices.

The first case consisted of eight operators. The input file and the precedence graph are included in Appendix A of this thesis and the results are presented in Table 1 below. This case was relatively simple in that there was a single starting node and there was not a wide variance in periods between the various operators. Due to the tight timing constraints both earliest start and earliest deadline were unable to find a solution. Simulated annealing, on the other hand, quickly found a feasible solution. By starting with an initial solution that did not satisfy the hard real-time systems timing constraints, simulated annealing adjusted the operators while maintaining operator precedence and quickly found a feasible solution. The solution satisfied all timing constraints, including the one failed by earliest start and earliest

**TABLE 1. RESULTS OF THE FIRST TEST CASE**

| OPERATOR         | START TIME | STOP TIME | EARLIEST START |       |
|------------------|------------|-----------|----------------|-------|
|                  |            |           | LOWER          | UPPER |
| DUMMY START NODE | 0          | 0         | 30010          | 0     |
| OP_1             | 0          | 2000      | 0              | 0     |
| OP_4             | 2000       | 3000      | 0              | 0     |
| OP_3             | 3000       | 8000      | 0              | 0     |
| OP_7             | 8000       | 9000      | 0              | 0     |
| OP_2             | 9000       | 10000     | 0              | 0     |
| OP_5             | 10000      | 13000     | 0              | 0     |
| OP_1             | 13000      | 15000     | 10000          | 0     |
| OP_6             | 15000      | 16000     | 0              | 0     |
| OP_8             | 16000      | 17000     | 0              | 0     |
| OP_1             | 20000      | 22000     | 20000          | 0     |
| OP_2             | 24000      | 25000     | 24000          | 0     |
| OP_5             | 25000      | 28000     | 25000          | 0     |
| OP_6             | 30000      | 31000     | 30000          | 0     |
| OP_8             | 31000      | 32000     | 31000          | 0     |

← Violate Harmonic  
← Block Length

| OPERATOR         | START TIME | STOP TIME | EARLIEST DEADLINE |       |
|------------------|------------|-----------|-------------------|-------|
|                  |            |           | LOWER             | UPPER |
| DUMMY START NODE | 0          | 0         | 30010             | 0     |
| OP_1             | 0          | 2000      | 0                 | 0     |
| OP_4             | 2000       | 3000      | 0                 | 0     |
| OP_3             | 3000       | 8000      | 0                 | 0     |
| OP_7             | 8000       | 9000      | 0                 | 0     |
| OP_2             | 9000       | 10000     | 0                 | 0     |
| OP_5             | 10000      | 13000     | 0                 | 0     |
| OP_1             | 13000      | 15000     | 10000             | 17000 |
| OP_6             | 15000      | 16000     | 0                 | 0     |
| OP_8             | 16000      | 17000     | 0                 | 0     |
| OP_1             | 20000      | 22000     | 20000             | 27000 |
| OP_2             | 24000      | 25000     | 24000             | 33000 |
| OP_5             | 25000      | 28000     | 25000             | 33000 |
| OP_8             | 31000      | 32000     | 31000             | 40000 |
| OP_6             | 32000      | 33000     | 30000             | 41000 |

← Violate Harmonic  
← Block Length

| OPERATOR         | START TIME | STOP TIME | SIMULATED ANNEALING |       |
|------------------|------------|-----------|---------------------|-------|
|                  |            |           | LOWER               | UPPER |
| DUMMY START NODE | 0          | 0         | 30010               | 0     |
| OP_1             | 0          | 2000      | 0                   | 7000  |
| OP_4             | 2000       | 3000      | 2000                | 16000 |
| OP_3             | 3000       | 8000      | 3000                | 13000 |
| OP_7             | 8000       | 9000      | 8000                | 25000 |
| OP_2             | 9000       | 10000     | 9000                | 18000 |
| OP_5             | 10000      | 13000     | 10000               | 18000 |
| OP_6             | 13000      | 14000     | 13000               | 24000 |
| OP_8             | 14000      | 15000     | 14000               | 23000 |
| OP_1             | 15000      | 17000     | 10000               | 17000 |
| OP_1             | 20000      | 22000     | 20000               | 27000 |
| OP_2             | 24000      | 25000     | 24000               | 33000 |
| OP_5             | 25000      | 28000     | 25000               | 33000 |
| OP_6             | 28000      | 29000     | 28000               | 39000 |
| OP_8             | 29000      | 30000     | 29000               | 38000 |

deadline, because they exceed the harmonic block length. The previous version of the static scheduler would have output these schedules as correct schedules, even though they are not correct.

The second test case is based on the functional specifications of the C<sup>3</sup>I work station described in (Anderson, 1990) and implemented in Coskun, 1990). The input file and precedence graph are presented in Appendix B of this thesis and the results are presented in Table 2. This case is more complicated than the first test case. It consists of 19 time critical operators. There is no specific starting operator. Any one of five operators may begin execution at the start of the harmonic block. There is a variance in periods between the various operators. The precedence relationships in this example are more complicated than the first case. As in the first case, due to the tight timing constraints, earliest start and earliest deadline fail to find a feasible schedule. Simulated annealing, however, is able to rapidly find a feasible schedule.

These two test cases indicate that simulated annealing shows promising results in solving the hard real-time scheduling problem. It appears that simulated annealing will perform well as a scheduling tool when both earliest start and earliest deadline fail. The cost of using simulated annealing is low enough for it to be used before trying a more costly enumeration algorithm.

TABLE 2. RESULTS OF THE SECOND TEST CASE

| OPERATOR                   | EARLIEST START |           |       |       |
|----------------------------|----------------|-----------|-------|-------|
|                            | START TIME     | STOP TIME | LOWER | UPPER |
| DUMMY START NODE           | 0              | 0         | 21010 | 0     |
| WEAPONS_SYSTEMS            | 0              | 100       | 0     | 0     |
| WEAPONS_INTERFACE          | 100            | 200       | 0     | 0     |
| CREATE_POSITION_DATA       | 200            | 700       | 0     | 0     |
| MONITOR_OWNERSHIP_POSITION | 700            | 1200      | 0     | 0     |
| CREATE_SENSOR_DATA         | 1200           | 1300      | 0     | 0     |
| ANALYZE_SENSOR_DATA        | 1300           | 1550      | 0     | 0     |
| PREPARE_SENSOR_TRACK       | 1550           | 1800      | 0     | 0     |
| FILTER_SENSOR_TRACKS       | 1800           | 2300      | 0     | 0     |
| ADD_SENSOR_TRACK           | 2300           | 2800      | 0     | 0     |
| PREPARE_PERIODIC_REPORT    | 2800           | 3300      | 0     | 0     |
| WEAPONS_SYSTEMS            | 3300           | 3400      | 3000  | 0     |
| WEAPONS_INTERFACE          | 3400           | 3500      | 3100  | 0     |
| CREATE_POSITION_DATA       | 3500           | 4000      | 3200  | 0     |
| MONITOR_OWNERSHIP_POSITION | 4000           | 4500      | 3700  | 0     |
| MAKE_ROUTING               | 4500           | 4800      | 0     | 0     |
| FORWARD_FOR_TRANSMISSION   | 4800           | 4900      | 0     | 0     |
| CONVERT_TO_TEXT_FILE       | 4900           | 5000      | 0     | 0     |
| COMMS_LINKS                | 5000           | 5100      | 0     | 0     |
| PARSE_INPUT_FILE           | 5100           | 5350      | 0     | 0     |
| DECIDE_FOR_ARCHIVING       | 5350           | 5450      | 0     | 0     |
| EXTRACT_TRACKS             | 5450           | 5600      | 0     | 0     |
| FILTER_COMMS_TRACKS        | 5600           | 6100      | 0     | 0     |
| WEAPONS_SYSTEMS            | 6100           | 6200      | 6000  | 0     |
| WEAPONS_INTERFACE          | 6200           | 6300      | 6100  | 0     |
| CREATE_POSITION_DATA       | 6300           | 6800      | 6200  | 0     |
| MONITOR_OWNERSHIP_POSITION | 6800           | 7300      | 6700  | 0     |
| ADD_COMMS_TRACK            | 7300           | 7400      | 0     | 0     |
| CREATE_SENSOR_DATA         | 8200           | 8300      | 8200  | 0     |
| ANALYZE_SENSOR_DATA        | 8300           | 8550      | 8300  | 0     |
| PREPARE_SENSOR_TRACK       | 8550           | 8800      | 8550  | 0     |
| FILTER_SENSOR_TRACKS       | 8800           | 9300      | 8800  | 0     |
| WEAPONS_SYSTEMS            | 9300           | 9400      | 9000  | 0     |
| WEAPONS_INTERFACE          | 9400           | 9500      | 9100  | 0     |
| CREATE_POSITION_DATA       | 9500           | 10000     | 9200  | 0     |
| ADD_SENSOR_TRACK           | 10000          | 10500     | 9300  | 0     |
| MONITOR_OWNERSHIP_POSITION | 10500          | 11000     | 9700  | 0     |
| PREPARE_PERIODIC_REPORT    | 11000          | 11500     | 9800  | 0     |
| MAKE_ROUTING               | 11500          | 11800     | 11500 | 0     |
| FORWARD_FOR_TRANSMISSION   | 11800          | 11900     | 11800 | 0     |
| CONVERT_TO_TEXT_FILE       | 11900          | 12000     | 11900 | 0     |
| COMMS_LINKS                | 12000          | 12100     | 12000 | 0     |
| WEAPONS_SYSTEMS            | 12100          | 12200     | 12000 | 0     |
| PARSE_INPUT_FILE           | 12200          | 12450     | 12100 | 0     |
| WEAPONS_INTERFACE          | 12450          | 12550     | 12100 | 0     |
| CREATE_POSITION_DATA       | 12550          | 13050     | 12200 | 0     |
| DECIDE_FOR_ARCHIVING       | 13050          | 13150     | 12350 | 0     |
| EXTRACT_TRACKS             | 13150          | 13300     | 12450 | 0     |
| FILTER_COMMS_TRACKS        | 13300          | 13800     | 12600 | 0     |
| MONITOR_OWNERSHIP_POSITION | 13800          | 14300     | 12700 | 0     |
| ADD_COMMS_TRACK            | 14300          | 14400     | 14300 | 0     |
| WEAPONS_SYSTEMS            | 15000          | 15100     | 15000 | 0     |
| WEAPONS_INTERFACE          | 15100          | 15200     | 15100 | 0     |
| CREATE_SENSOR_DATA         | 15200          | 15300     | 15200 | 0     |
| CREATE_POSITION_DATA       | 15300          | 15800     | 15200 | 0     |
| ANALYZE_SENSOR_DATA        | 15800          | 16050     | 15300 | 0     |
| PREPARE_SENSOR_TRACK       | 16050          | 16300     | 15550 | 0     |

TABLE 2. RESULTS OF THE SECOND TEST CASE (CONTINUED)

|                            |       |       |       |   |                                 |
|----------------------------|-------|-------|-------|---|---------------------------------|
| MONITOR_OWNERSHIP_POSITION | 16300 | 16800 | 15700 | 0 |                                 |
| FILTER_SENSOR_TRACKS       | 16800 | 17300 | 15800 | 0 |                                 |
| ADD_SENSOR_TRACK           | 17300 | 17800 | 16300 | 0 |                                 |
| PREPARE_PERIODIC_REPORT    | 17800 | 18300 | 16800 | 0 |                                 |
| WEAPONS_SYSTEMS            | 18300 | 18400 | 18000 | 0 |                                 |
| WEAPONS_INTERFACE          | 18400 | 18500 | 18100 | 0 |                                 |
| CREATE_POSITION_DATA       | 18500 | 19000 | 18200 | 0 |                                 |
| MAKE_ROUTING               | 19000 | 19300 | 18500 | 0 |                                 |
| MONITOR_OWNERSHIP_POSITION | 19300 | 19800 | 18700 | 0 |                                 |
| FORWARD_FOR_TRANSMISSION   | 19800 | 19900 | 18800 | 0 |                                 |
| CONVERT_TO_TEXT_FILE       | 19900 | 20000 | 18900 | 0 |                                 |
| COMMS_LINKS                | 20000 | 20100 | 19000 | 0 |                                 |
| PARSE_INPUT_FILE           | 20100 | 20350 | 19100 | 0 |                                 |
| DECIDE_FOR_ARCHIVING       | 20350 | 20450 | 19350 | 0 |                                 |
| EXTRACT_TRACKS             | 20450 | 20600 | 19450 | 0 |                                 |
| FILTER_COMMS_TRACKS        | 20600 | 21100 | 19600 | 0 | ← Violate Harmonic Block Length |

EARLIEST DEADLINE

THE BEST SCHEDULE FOLLOWS:

| OPERATOR                   | START TIME | STOP TIME | LOWER | UPPER |
|----------------------------|------------|-----------|-------|-------|
| DUMMY START NODE           | 0          | 0         | 21010 | 0     |
| WEAPONS_SYSTEMS            | 0          | 100       | 0     | 0     |
| WEAPONS_INTERFACE          | 100        | 200       | 0     | 0     |
| CREATE_POSITION_DATA       | 200        | 700       | 0     | 0     |
| MONITOR_OWNERSHIP_POSITION | 700        | 1200      | 0     | 0     |
| CREATE_SENSOR_DATA         | 1200       | 1300      | 0     | 0     |
| ANALYZE_SENSOR_DATA        | 1300       | 1550      | 0     | 0     |
| PREPARE_SENSOR_TRACK       | 1550       | 1800      | 0     | 0     |
| FILTER_SENSOR_TRACKS       | 1800       | 2300      | 0     | 0     |
| ADD_SENSOR_TRACK           | 2300       | 2800      | 0     | 0     |
| PREPARE_PERIODIC_REPORT    | 2800       | 3300      | 0     | 0     |
| CREATE_POSITION_DATA       | 3300       | 3800      | 3200  | 5700  |
| WEAPONS_SYSTEMS            | 3800       | 3900      | 3000  | 5900  |
| WEAPONS_INTERFACE          | 3900       | 4000      | 3100  | 6000  |
| MONITOR_OWNERSHIP_POSITION | 4000       | 4500      | 3700  | 6200  |
| MAKE_ROUTING               | 4500       | 4800      | 0     | 0     |
| FORWARD_FOR_TRANSMISSION   | 4800       | 4900      | 0     | 0     |
| CONVERT_TO_TEXT_FILE       | 4900       | 5000      | 0     | 0     |
| COMMS_LINKS                | 5000       | 5100      | 0     | 0     |
| PARSE_INPUT_FILE           | 5100       | 5350      | 0     | 0     |
| DECIDE_FOR_ARCHIVING       | 5350       | 5450      | 0     | 0     |
| EXTRACT_TRACKS             | 5450       | 5600      | 0     | 0     |
| FILTER_COMMS_TRACKS        | 5600       | 6100      | 0     | 0     |
| ADD_COMMS_TRACK            | 6100       | 6200      | 0     | 0     |
| CREATE_POSITION_DATA       | 6200       | 6700      | 6200  | 8700  |
| WEAPONS_SYSTEMS            | 6700       | 6800      | 6000  | 8900  |
| WEAPONS_INTERFACE          | 6800       | 6900      | 6100  | 9000  |
| MONITOR_OWNERSHIP_POSITION | 6900       | 7400      | 6700  | 9200  |
| CREATE_POSITION_DATA       | 9200       | 9700      | 9200  | 11700 |
| WEAPONS_SYSTEMS            | 9700       | 9800      | 9000  | 11900 |
| WEAPONS_INTERFACE          | 9800       | 9900      | 9100  | 12000 |
| MONITOR_OWNERSHIP_POSITION | 9900       | 10400     | 9700  | 12200 |
| CREATE_POSITION_DATA       | 12200      | 12700     | 12200 | 14700 |
| WEAPONS_SYSTEMS            | 12700      | 12800     | 12000 | 14900 |
| WEAPONS_INTERFACE          | 12800      | 12900     | 12100 | 15000 |
| ANALYZE_SENSOR_DATA        | 12900      | 13150     | 8300  | 15050 |
| CREATE_SENSOR_DATA         | 13150      | 13250     | 8200  | 15100 |

TABLE 2. RESULTS OF THE SECOND TEST CASE (CONTINUED)

|                            |       |       |       |       |   |
|----------------------------|-------|-------|-------|-------|---|
| MONITOR_OWNERSHIP_POSITION | 13250 | 13750 | 12700 | 15200 |   |
| PREPARE_SENSOR_TRACK       | 13750 | 14000 | 8550  | 15300 |   |
| FILTER_SENSOR_TRACKS       | 14000 | 14500 | 8800  | 15300 |   |
| ADD_SENSOR_TRACK           | 14500 | 15000 | 9300  | 15800 |   |
| PREPARE_PERIODIC_REPORT    | 15000 | 15500 | 9800  | 16300 |   |
| CREATE_POSITION_DATA       | 15500 | 16000 | 15200 | 17700 |   |
| WEAPONS_SYSTEMS            | 16000 | 16100 | 15000 | 17900 |   |
| WEAPONS_INTERFACE          | 16100 | 16200 | 15100 | 18000 |   |
| MAKE_ROUTING               | 16200 | 16500 | 11500 | 18200 |   |
| MONITOR_OWNERSHIP_POSITION | 16500 | 17000 | 15700 | 18200 |   |
| FORWARD_FOR_TRANSMISSION   | 17000 | 17100 | 11800 | 18700 |   |
| CONVERT_TO_TEXT_FILE       | 17100 | 17200 | 11900 | 18800 |   |
| PARSE_INPUT_FILE           | 17200 | 17450 | 12100 | 18850 |   |
| COMMS_LINKS                | 17450 | 17550 | 12000 | 18900 |   |
| FILTER_COMMS_TRACKS        | 17550 | 18050 | 12600 | 19100 |   |
| DECIDE_FOR_ARCHIVING       | 18050 | 18150 | 12350 | 19250 |   |
| EXTRACT_TRACKS             | 18150 | 18300 | 12450 | 19300 |   |
| ADD_COMMS_TRACK            | 18300 | 18400 | 13100 | 20000 |   |
| CREATE_POSITION_DATA       | 18400 | 18900 | 18200 | 20700 |   |
| WEAPONS_SYSTEMS            | 18900 | 19000 | 18000 | 20900 |   |
| WEAPONS_INTERFACE          | 19000 | 19100 | 18100 | 21000 |   |
| MONITOR_OWNERSHIP_POSITION | 19100 | 19600 | 18700 | 21200 |   |
| ANALYZE_SENSOR_DATA        | 19600 | 19850 | 15300 | 22050 |   |
| CREATE_SENSOR_DATA         | 19850 | 19950 | 15200 | 22100 |   |
| PREPARE_SENSOR_TRACK       | 19950 | 20200 | 15550 | 22300 |   |
| FILTER_SENSOR_TRACKS       | 20200 | 20700 | 15800 | 22300 |   |
| ADD_SENSOR_TRACK           | 20700 | 21200 | 16300 | 22800 | ← |
| PREPARE_PERIODIC_REPORT    | 21200 | 21700 | 16800 | 23300 | ← |
| MAKE_ROUTING               | 21700 | 22000 | 18500 | 25200 | ← |
| FORWARD_FOR_TRANSMISSION   | 22000 | 22100 | 18800 | 25700 | ← |
| CONVERT_TO_TEXT_FILE       | 22100 | 22200 | 18900 | 25800 | ← |
| PARSE_INPUT_FILE           | 22200 | 22450 | 19100 | 25850 | ← |
| COMMS_LINKS                | 22450 | 22550 | 19000 | 25900 | ← |
| FILTER_COMMS_TRACKS        | 22550 | 23050 | 19600 | 26100 | ← |
| DECIDE_FOR_ARCHIVING       | 23050 | 23150 | 19350 | 26250 | ← |
| EXTRACT_TRACKS             | 23150 | 23300 | 19450 | 26300 | ← |
| ADD_COMMS_TRACK            | 23300 | 23400 | 20100 | 27000 | ← |

{ Violate  
Harmonic  
Block  
Length

Simulated Annealing

| OPERATOR                   | START TIME | STOP TIME | LOWER | UPPER |
|----------------------------|------------|-----------|-------|-------|
| DUMMY START NODE           | 0          | 0         | 21010 | 0     |
| CREATE_POSITION_DATA       | 0          | 500       | 0     | 2500  |
| CREATE_SENSOR_DATA         | 500        | 600       | 500   | 7400  |
| WEAPONS_SYSTEMS            | 600        | 700       | 600   | 3500  |
| ANALYZE_SENSOR_DATA        | 700        | 950       | 700   | 7450  |
| COMMS_LINKS                | 950        | 1050      | 950   | 7850  |
| WEAPONS_INTERFACE          | 1050       | 1150      | 1050  | 3950  |
| MONITOR_OWNERSHIP_POSITION | 1150       | 1650      | 1150  | 3650  |
| PREPARE_SENSOR_TRACK       | 1650       | 1900      | 1650  | 8400  |
| FILTER_SENSOR_TRACKS       | 1900       | 2400      | 1900  | 8400  |
| ADD_SENSOR_TRACK           | 2400       | 2900      | 2400  | 8900  |
| PREPARE_PERIODIC_REPORT    | 2900       | 3400      | 2900  | 9400  |
| MAKE_ROUTING               | 3400       | 3700      | 3400  | 10100 |
| WEAPONS_SYSTEMS            | 3700       | 3800      | 3600  | 6500  |
| FORWARD_FOR_TRANSMISSION   | 3800       | 3900      | 3700  | 10600 |
| CONVERT_TO_TEXT_FILE       | 3900       | 4000      | 3800  | 10700 |
| PARSE_INPUT_FILE           | 4000       | 4250      | 3900  | 10650 |

TABLE 2. RESULTS OF THE SECOND TEST CASE (CONTINUED)

|                            |       |       |       |       |
|----------------------------|-------|-------|-------|-------|
| WEAPONS_INTERFACE          | 4250  | 4350  | 4050  | 6950  |
| DECIDE_FOR_ARCHIVING       | 4350  | 4450  | 4150  | 11050 |
| EXTRACT_TRACKS             | 4450  | 4600  | 4250  | 11100 |
| FILTER_COMMS_TRACKS        | 4600  | 5100  | 4400  | 10900 |
| ADD_COMMS_TRACK            | 5100  | 5200  | 4900  | 11800 |
| CREATE_POSITION_DATA       | 5200  | 5700  | 3000  | 5500  |
| MONITOR_OWNERSHIP_POSITION | 5700  | 6200  | 4150  | 6650  |
| CREATE_POSITION_DATA       | 6200  | 6700  | 6000  | 8500  |
| WEAPONS_SYSTEMS            | 6700  | 6800  | 6600  | 9500  |
| WEAPONS_INTERFACE          | 7050  | 7150  | 7050  | 9950  |
| MONITOR_OWNERSHIP_POSITION | 7150  | 7650  | 7150  | 9650  |
| CREATE_SENSOR_DATA         | 7650  | 7750  | 7500  | 14400 |
| ANALYZE_SENSOR_DATA        | 7750  | 8000  | 7700  | 14450 |
| COMMS_LINKS                | 8000  | 8100  | 7950  | 14850 |
| PREPARE_SENSOR_TRACK       | 8650  | 8900  | 8650  | 15400 |
| FILTER_SENSOR_TRACKS       | 8900  | 9400  | 8900  | 15400 |
| CREATE_POSITION_DATA       | 9400  | 9900  | 9000  | 11500 |
| WEAPONS_SYSTEMS            | 9900  | 10000 | 9600  | 12500 |
| ADD_SENSOR_TRACK           | 10000 | 10500 | 9400  | 15900 |
| MONITOR_OWNERSHIP_POSITION | 10500 | 11000 | 10150 | 12650 |
| WEAPONS_INTERFACE          | 11000 | 11100 | 10050 | 12950 |
| PREPARE_PERIODIC_REPORT    | 11100 | 11600 | 9900  | 16400 |
| MAKE_ROUTING               | 11600 | 11900 | 10400 | 17100 |
| FORWARD_FOR_TRANSMISSION   | 11900 | 12000 | 10700 | 17600 |
| CONVERT_TO_TEXT_FILE       | 12000 | 12100 | 10800 | 17700 |
| CREATE_POSITION_DATA       | 12100 | 12600 | 12000 | 14500 |
| PARSE_INPUT_FILE           | 12600 | 12850 | 10900 | 17650 |
| WEAPONS_SYSTEMS            | 12850 | 12950 | 12600 | 15500 |
| DECIDE_FOR_ARCHIVING       | 12950 | 13050 | 11150 | 18050 |
| EXTRACT_TRACKS             | 13050 | 13200 | 11250 | 18100 |
| MONITOR_OWNERSHIP_POSITION | 13200 | 13700 | 13150 | 15650 |
| WEAPONS_INTERFACE          | 13700 | 13800 | 13050 | 15950 |
| FILTER_COMMS_TRACKS        | 13800 | 14300 | 11400 | 17900 |
| ADD_COMMS_TRACK            | 14300 | 14400 | 11900 | 18800 |
| CREATE_SENSOR_DATA         | 14500 | 14600 | 14500 | 21400 |
| ANALYZE_SENSOR_DATA        | 14700 | 14950 | 14700 | 21450 |
| COMMS_LINKS                | 14950 | 15050 | 14950 | 21850 |
| CREATE_POSITION_DATA       | 15050 | 15550 | 15000 | 17500 |
| WEAPONS_SYSTEMS            | 15600 | 15700 | 15600 | 18500 |
| PREPARE_SENSOR_TRACK       | 15700 | 15950 | 15650 | 22400 |
| FILTER_SENSOR_TRACKS       | 15950 | 16450 | 15900 | 22400 |
| MONITOR_OWNERSHIP_POSITION | 16450 | 16950 | 16150 | 18650 |
| WEAPONS_INTERFACE          | 16950 | 17050 | 16050 | 18950 |
| ADD_SENSOR_TRACK           | 17050 | 17550 | 16400 | 22900 |
| PREPARE_PERIODIC_REPORT    | 17550 | 18050 | 16900 | 23400 |
| CREATE_POSITION_DATA       | 18050 | 18550 | 18000 | 20500 |
| MAKE_ROUTING               | 18550 | 18850 | 17400 | 24100 |
| WEAPONS_SYSTEMS            | 18850 | 18950 | 18600 | 21500 |
| FORWARD_FOR_TRANSMISSION   | 18950 | 19050 | 17700 | 24600 |
| CONVERT_TO_TEXT_FILE       | 19050 | 19150 | 17800 | 24700 |
| WEAPONS_INTERFACE          | 19150 | 19250 | 19050 | 21950 |
| MONITOR_OWNERSHIP_POSITION | 19250 | 19750 | 19150 | 21650 |
| PARSE_INPUT_FILE           | 19750 | 20000 | 17900 | 24650 |
| DECIDE_FOR_ARCHIVING       | 20000 | 20100 | 18150 | 25050 |
| EXTRACT_TRACKS             | 20100 | 20250 | 18250 | 25100 |
| FILTER_COMMS_TRACKS        | 20250 | 20750 | 18400 | 24900 |
| ADD_COMMS_TRACK            | 20750 | 20850 | 18900 | 25800 |

## **VI. CONCLUSIONS AND RECOMMENDATIONS**

### **A. CONCLUSIONS**

This thesis intended to develop a fast heuristic static scheduling algorithm. Simulated annealing was chosen as a basis for developing such a static scheduling algorithm because of the promising results simulated annealing demonstrated in solving other NP-Hard type problems. Simulated annealing proved to be useful in solving optimization type problems, and the development of hard real-time schedules is a subclass of this type of problem. The initial results of the simulated annealing static scheduling algorithm are promising.

The major emphasis of this thesis was the development of a new static scheduling algorithm. In addition, this thesis built on previous research conducted during the development of the static scheduler. Modifications made to data structures and scheduling algorithms already implemented improved the performance of the static scheduler portion of CAPS. Several of the new packages and data structures are generic in nature and are available to be used beyond the scope of this thesis. This is possible due to the use of the Ada principles of modularity and software reusability.

This thesis provides a running static scheduler that offers several choices of algorithms to use to find a feasible static schedule. Additional algorithms can be added to the static scheduler by using the data structures developed for this thesis. Additional research and development can continue to build on the work done in this thesis.

## B. RECOMMENDATIONS

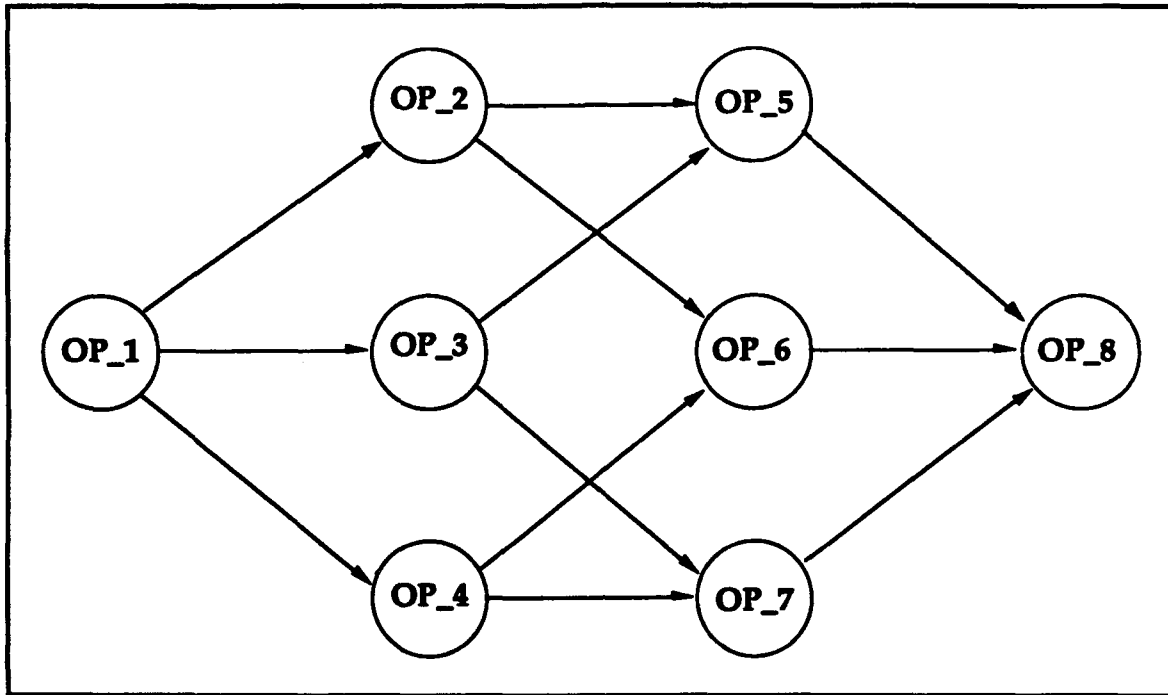
As a result of this thesis, several weaknesses and areas requiring improvement within the static scheduler were identified. Many shortcomings were corrected, but others require further effort. Due to the complexity of the static scheduler, all problems identified were not corrected.

In the current static scheduler, no differentiation is made between data flow and sampled stream data links. The performance and results of all scheduling algorithms would most likely improve if this information were utilized.

The algorithm described and implemented in (Coskun, 1990) that calculates periodic equivalents for non-periodic time critical operators merits further examination. This algorithm is based on a theorem described in (Mok, 1985). Linked list data structures are used in the algorithm when arrays could suffice, saving execution time. Four separate linked list traversals are made in this algorithm. The performance and output of this indicate that it could be improved.

The development of a PSDL data type implemented in Ada will simplify the package FRONT\_END described in Chapter IV of this thesis. When this package is available (see S. Baromoglu, *The Design and Implementation of an Expander for the Hierarchical Real-Time Constraints of Computer-Aided Prototyping System (CAPS)*, Master's Thesis, Naval Postgraduate School, Monterey, CA, September 1991) the FRONT\_END package should be modified to use the PSDL datatypes to provide input to the static scheduler. Once this occurs, the requirement for the ATOMIC.INFO file becomes unnecessary.

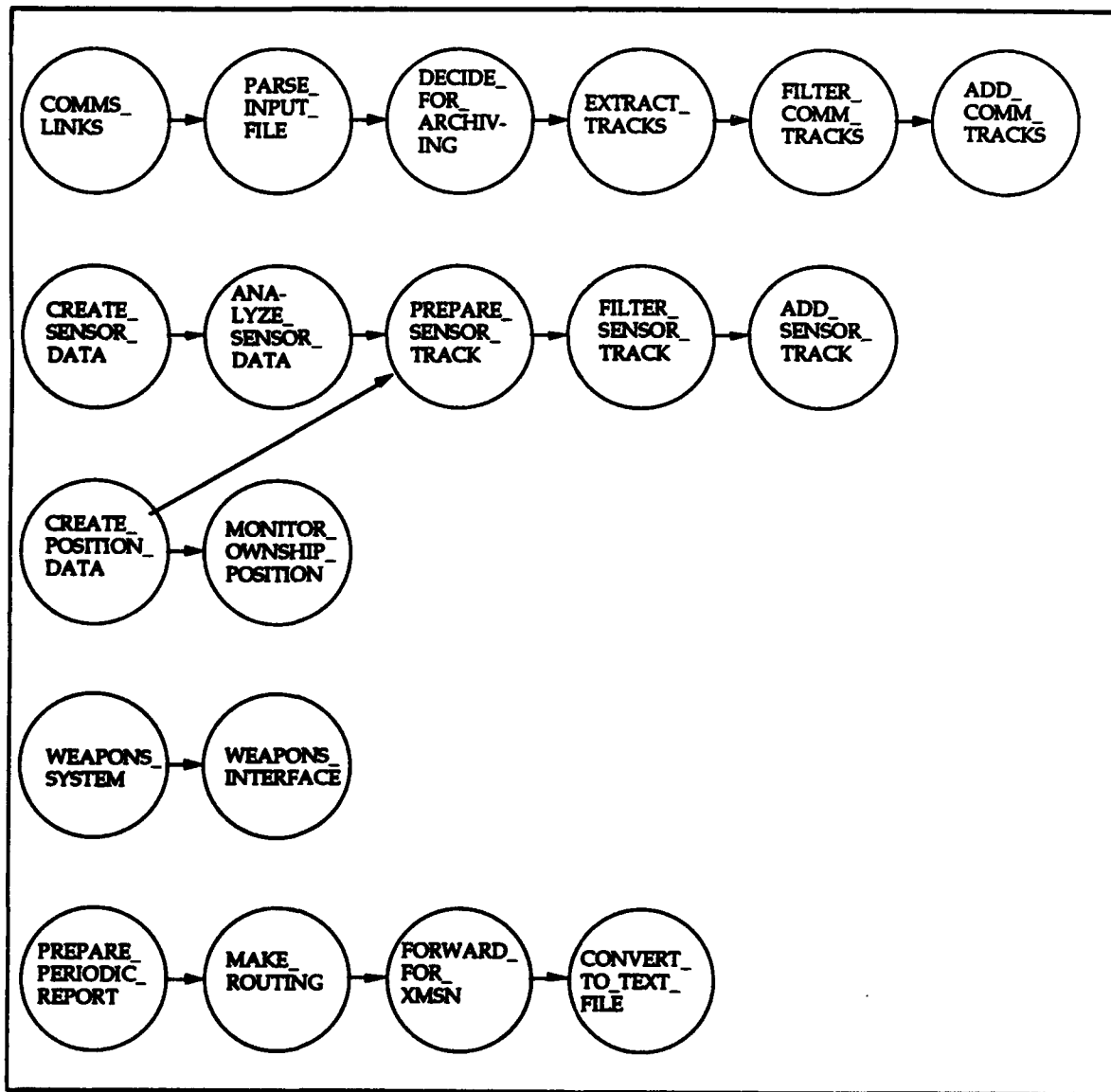
# APPENDIX A. CASE 1 TEST DATA



Precedence Graph, Test Case 1

|        |        |        |        |      |      |      |
|--------|--------|--------|--------|------|------|------|
| ATOMIC | PERIOD | ATOMIC | PERIOD | D    | H    | L    |
| OP_1   | 30000  | OP_6   | 15000  | OP_2 | OP_4 | OP_6 |
| MET    | WITHIN | MET    | WITHIN | 0    | 0    | 0    |
| 2000   | 15000  | 1000   | 10000  | OP_6 | OP_6 | OP_8 |
| PERIOD | ATOMIC | PERIOD | LINK   | LINK | LINK |      |
| 10000  | OP_4   | 15000  | A      | E    | I    |      |
| WITHIN | MET    | WITHIN | OP_1   | OP_2 | OP_4 |      |
| 9000   | 1000   | 12000  | 0      | 0    | 0    |      |
| ATOMIC | PERIOD | ATOMIC | OP_2   | OP_5 | OP_7 |      |
| OP_2   | 30000  | OP_7   | LINK   | LINK | LINK |      |
| MET    | WITHIN | MET    | B      | F    | J    |      |
| 1000   | 15000  | 1000   | OP_1   | OP_3 | OP_5 |      |
| PERIOD | ATOMIC | PERIOD | 0      | 0    | 0    |      |
| 15000  | OP_5   | 30000  | OP_3   | OP_5 | OP_8 |      |
| WITHIN | MET    | WITHIN | LINK   | LINK | LINK |      |
| 10000  | 3000   | 18000  | C      | G    | K    |      |
| ATOMIC | PERIOD | ATOMIC | OP_1   | OP_3 | OP_7 |      |
| OP_3   | 15000  | OP_8   | 0      | 0    | 0    |      |
| MET    | WITHIN | MET    | OP_4   | OP_7 | OP_8 |      |
| 5000   | 11000  | 1000   | LINK   | LINK | LINK |      |

## APPENDIX B. CASE 2 TEST DATA



Precedence graph, Case 2

ATOMIC  
COMMS\_LINKS  
MET  
100  
PERIOD  
7000  
ATOMIC  
PARSE\_INPUT\_FILE  
MET  
250  
PERIOD  
7000  
ATOMIC  
DECIDE\_FOR\_ARCHIVING  
MET  
100  
PERIOD  
7000  
ATOMIC  
EXTRACT\_TRACKS  
MET  
150  
PERIOD  
7000  
ATOMIC  
MAKE\_ROUTING  
MET  
300  
PERIOD  
7000  
ATOMIC  
FORWARD\_FOR\_TRANSMISSION  
MET  
100  
PERIOD  
7000  
ATOMIC  
CONVERT\_TO\_TEXT\_FILE  
MET  
100  
PERIOD  
7000  
ATOMIC  
PREPARE\_PERIODIC\_REPORT  
MET  
500  
PERIOD  
7000  
ATOMIC  
FILTER\_COMMS\_TRACKS  
MET

500  
PERIOD  
7000  
ATOMIC  
ADD\_COMMS\_TRACK  
MET  
100  
PERIOD  
7000  
ATOMIC  
FILTER\_SENSOR\_TRACKS  
MET  
500  
PERIOD  
7000  
ATOMIC  
ADD\_SENSOR\_TRACK  
MET  
500  
PERIOD  
7000  
ATOMIC  
MONITOR\_OWNERSHIP\_POSITION  
MET  
500  
PERIOD  
3000  
ATOMIC  
CREATE\_SENSOR\_DATA  
MET  
100  
PERIOD  
7000  
ATOMIC  
ANALYZE\_SENSOR\_DATA  
MET  
250  
PERIOD  
7000  
ATOMIC  
PREPARE\_SENSOR\_TRACK  
MET  
250  
PERIOD  
7000  
ATOMIC  
CREATE\_POSITION\_DATA  
MET  
500  
PERIOD  
3000

ATOMIC  
 WEAPONS\_INTERFACE  
 MET  
 100  
 PERIOD  
 3000  
 ATOMIC  
 WEAPONS\_SYSTEMS  
 MET  
 100  
 PERIOD  
 3000  
 ATOMIC  
 DISPLAY\_TRACKS  
 ATOMIC  
 GET\_USER\_INPUTS  
 ATOMIC  
 MANAGE\_USER\_INTERFACE  
 ATOMIC  
 STATUS\_SCREEN  
 ATOMIC  
 EMERGENCY\_STATUS\_SCREEN  
 ATOMIC  
 MESSAGE\_EDITOR  
 ATOMIC  
 MESSAGE\_ARRIVAL\_PANEL  
 LINK  
 INPUT\_LINK\_MESSAGE  
 COMMS\_LINKS  
 1200  
 PARSE\_INPUT\_FILE  
 LINK  
 INPUT\_TEXT\_RECORD  
 PARSE\_INPUT\_FILE  
 500  
 DECIDE\_FOR\_ARCHIVING  
 LINK  
 TDD\_ARCHIVE\_SETUP  
 GET\_USER\_INPUTS  
 0  
 DECIDE\_FOR\_ARCHIVING  
 LINK  
 COMMS\_TEXT\_FILE  
 DECIDE\_FOR\_ARCHIVING  
 500  
 EXTRACT\_TRACKS  
 LINK  
 COMMS\_EMAIL  
 DECIDE\_FOR\_ARCHIVING  
 500  
 MESSAGE\_ARRIVAL\_PANEL

LINK  
 COMMS\_ADD\_TRACK  
 EXTRACT\_TRACKS  
 500  
 FILTER\_COMMS\_TRACKS  
 LINK  
 TDD\_FILTER  
 GET\_USER\_INPUTS  
 0  
 FILTER\_COMMS\_TRACKS  
 LINK  
 FILTERED\_COMMS\_TRACK  
 FILTER\_COMMS\_TRACKS  
 500  
 ADD\_COMMS\_TRACK  
 LINK  
 TDD\_FILTER  
 GET\_USER\_INPUTS  
 0  
 ADD\_COMMS\_TRACK  
 LINK  
 OUT\_TRACKS  
 ADD\_COMMS\_TRACK  
 500  
 DISPLAY\_TRACKS  
 LINK  
 SENSOR\_DATA  
 CREATE\_SENSOR\_DATA  
 800  
 ANALYZE\_SENSOR\_DATA  
 LINK  
 SENSOR\_CONTACT\_DATA  
 ANALYZE\_SENSOR\_DATA  
 500  
 PREPARE\_SENSOR\_TRACK  
 LINK  
 POSITION\_DATA  
 CREATE\_POSITION\_DATA  
 800  
 PREPARE\_SENSOR\_TRACK  
 LINK  
 SENSOR\_ADD\_TRACK  
 PREPARE\_SENSOR\_TRACK  
 500  
 FILTER\_SENSOR\_TRACKS  
 LINK  
 TDD\_FILTER  
 GET\_USER\_INPUTS  
 0  
 FILTER\_SENSOR\_TRACKS  
 LINK

FILTERED\_SENSOR\_TRACK  
 FILTER\_SENSOR\_TRACKS  
 500  
 ADD\_SENSOR\_TRACK  
 LINK  
 TDD\_FILTER  
 GET\_USER\_INPUTS  
 0  
 ADD\_SENSOR\_TRACK  
 LINK  
 OUT\_TRACKS  
 ADD\_SENSOR\_TRACK  
 500  
 DISPLAY\_TRACKS  
 LINK  
 POSITION\_DATA  
 CREATE\_POSITION\_DATA  
 800  
 MONITOR\_OWNERSHIP\_POSITION  
 LINK  
 TD\_TRACK\_REQUEST  
 GET\_USER\_INPUTS  
 0  
 DISPLAY\_TRACKS  
 LINK  
 OUT\_TRACKS  
 MONITOR\_OWNERSHIP\_POSITION  
 500  
 DISPLAY\_TRACKS  
 LINK  
 WEAPON\_STATUS\_DATA  
 WEAPONS\_SYSTEMS  
 500  
 WEAPONS\_INTERFACE  
 LINK  
 WEAPONS\_STATREP  
 WEAPONS\_INTERFACE  
 500  
 STATUS\_SCREEN  
 LINK  
 TCD\_STATUS\_QUERY  
 GET\_USER\_INPUTS  
 0  
 STATUS\_SCREEN  
 LINK  
 WEAPONS\_EMREP  
 WEAPONS\_INTERFACE  
 500  
 EMERGENCY\_STATUS\_SCREEN  
 LINK  
 EDITOR\_SELECTED

GET\_USER\_INPUTS  
 0  
 MESSAGE\_EDITOR  
 LINK  
 TCD\_TRANSMIT\_COMMAND  
 MESSAGE\_EDITOR  
 0  
 MAKE\_ROUTING  
 LINK  
 TCD\_NETWORK\_SETUP  
 GET\_USER\_INPUTS  
 0  
 MAKE\_ROUTING  
 LINK  
 TRANSMISSION\_MESSAGE  
 MAKE\_ROUTING  
 500  
 FORWARD\_FOR\_TRANSMISSION  
 LINK  
 TCD\_EMISSION\_CONTROL  
 GET\_USER\_INPUTS  
 0  
 FORWARD\_FOR\_TRANSMISSION  
 LINK  
 OUTPUT\_MESSAGES  
 FORWARD\_FOR\_TRANSMISSION  
 500  
 CONVERT\_TO\_TEXT\_FILE  
 LINK  
 INITIATE\_TRANS  
 GET\_USER\_INPUTS  
 0  
 PREPARE\_PERIODIC\_REPORT  
 LINK  
 TERMINATE\_TRANS  
 GET\_USER\_INPUTS  
 0  
 PREPARE\_PERIODIC\_REPORT  
 LINK  
 TCD\_TRANSMIT\_COMMAND  
 PREPARE\_PERIODIC\_REPORT  
 800  
 MAKE\_ROUTING

## APPENDIX C. MODIFIED PACKAGES

```
with VSTRINGS;  
with SEQUENCES;  
with TEXT_IO;
```

```
--* This package contains all of the global declarations and definitions  
--* of data structures that are necessary for the Static Scheduler
```

package DATA is

```
package VARSTRING is new VSTRINGS(80);  
use VARSTRING;  
subtype OPERATOR_ID is VSTRING;  
subtype VALUE is NATURAL;  
subtype MET is VALUE;  
subtype MRT is VALUE;  
subtype MCP is VALUE;  
subtype PERIOD is VALUE;  
subtype WITHIN is VALUE;  
subtype STARTS is VALUE;  
subtype STOPS is VALUE;  
subtype LOWERS is VALUE;  
subtype UPPERS is VALUE;
```

```
Exception_Operator : OPERATOR_ID;
```

```
TEST_VERIFIED : BOOLEAN := TRUE;
```

type OPERATOR is

```
record  
  THE_OPERATOR_ID      : OPERATOR_ID;  
  THE_MET               : MET := 0;  
  THE_MRT               : MRT := 0;  
  THE_MCP               : MCP := 0;  
  THE_PERIOD            : PERIOD := 0;  
  THE_WITHIN            : WITHIN := 0;  
end record;
```

```
package V_LISTS is new SEQUENCES(OPERATOR);  
use V_LISTS;
```

type SCHEDULE\_INPUTS is

```
record  
  THE_OPERATOR          : INTEGER;  
  THE_START              : STARTS := 0;  
  THE_STOP               : STOPS := 0;  
  THE_LOWER              : LOWERS := 0;  
  THE_UPPER              : UPPERS := 0;  
  THE_INSTANCE           : INTEGER := 1;  
end record;
```

```
package SCHEDULE_INPUTS_LIST is new SEQUENCES(SCHEDULE_INPUTS);
```

```
package NODE_LIST is new SEQUENCES(INTEGER);
```

```
NON_CRITS              : TEXT_IO.FILE_TYPE;  
AG_OUTFILE              : TEXT_IO.FILE_TYPE;  
INPUT                   : TEXT_IO.FILE_MODE := TEXT_IO.IN_FILE;  
OUTPUT                  : TEXT_IO.FILE_MODE := TEXT_IO.OUT_FILE;
```

Current\_Value : VALUE;  
New\_Word : VARSTRING.VSTRING;  
Cur\_Opt : OPERATOR;

OP\_COUNT : INTEGER;  
OP\_LIST : V\_LISTS.LIST;

end DATA;

```

generic
  type ITEM is private;

  package SEQUENCES is

    type NODE;
    type LIST is access NODE;
    type NODE is
      record
        ELEMENT      : ITEM;
        NEXT         : LIST := null;
        PREVIOUS     : LIST := null; --* (APR 91)
      end record;

    BAD_VALUE : exception;

    function EQUAL(L1 : in LIST; L2 : in LIST) return BOOLEAN;

    procedure EMPTY(L : out LIST);

    function NON_EMPTY(L : in LIST) return BOOLEAN;

    function SUBSEQUENCE(L1 : in LIST; L2 : in LIST) return BOOLEAN;

    function MEMBER(X : in ITEM; L : in LIST) return BOOLEAN;

    procedure ADD(X : in ITEM; L : in out LIST);

    procedure REMOVE(X : in ITEM; L : in out LIST);

    procedure LIST_REVERSE(L1 : in LIST; L2 : in out LIST);

    procedure FREE_LIST(L : in out LIST);
    --* (JUL 91) Used by annealling and Exhaustive Enumeration to reclaim
    --* memory space that is no longer needed.

    procedure DUPLICATE(L1 : in LIST; L2 : in out LIST);

    function LOOK4(X : in ITEM; L : in LIST) return LIST;

    procedure NEXT(L : in out LIST);

    procedure PREVIOUS(L : in out LIST);
    --* (APR 91) Used by annealling

    function VALUE(L : in LIST) return ITEM;

    procedure INSERT_NEXT(X : in ITEM; L : in out LIST);
    --* (June 91) Item is inserted in proper position in list

    procedure REPLACE_ITEM(X : in ITEM; L : in out LIST);
    --* (JUL 91) Used by annealling

    procedure COPY_LIST(L1 : in LIST; L2 : in out LIST);
    --* (JUL 91) Used by annealling to reclaim memory that is no longer needed

  end SEQUENCES;

```

```

with UNCHECKED_DEALLOCATION;
with TEXT_IO; --* test(Apr 91)

```

```

package body SEQUENCES is

```

```

    pragma LINK_WITH("heaplib.sparc.ar");

```

```

    procedure FREE is new UNCHECKED_DEALLOCATION(NODE, LIST);

```

```

    function NON_EMPTY(L : in LIST) return BOOLEAN is

```

```

    begin
        if L = null then
            return FALSE;
        else
            return TRUE;
        end if;
    end NON_EMPTY;

```

```

    procedure NEXT(L : in out LIST) is

```

```

    begin
        if L /= null then
            L := L.NEXT;
        end if;
    end NEXT;

```

```

    procedure PREVIOUS(L : in out LIST) is --* This procedure was added 10 Apr 91

```

```

    begin
        if L /= null then
            L := L.PREVIOUS;
        end if;
    end PREVIOUS;
    --* to allow the annealling routine to
    --* traverse through Agenda in Reverse
    --* order.

```

```

    function LOOK4(X : in ITEM; L : in LIST) return LIST is

```

```

    L1 : LIST := L;
    begin
        while NON_EMPTY(L1) loop
            if L1.ELEMENT = X then
                return L1;
            end if;
            NEXT(L1);
        end loop;
        return null;
    end LOOK4;

```

```

    procedure ADD(X : in ITEM; L : in out LIST) is

```

```

    -- ITEM IS ADDED TO THE HEAD OF THE LIST

```

```

    T : LIST := new NODE;

```

```

    begin
        T.ELEMENT := X;
        T.PREVIOUS := null; --* (Apr 91)
        if L = null then
            T.NEXT := null;
        else
            T.NEXT := L;
            L.PREVIOUS := T; --* (Apr 91)
        end if;
    end ADD;

```

```

    end if;
    L := T;
end ADD;

```

```

function SUBSEQUENCE(L1 : in LIST; L2 : in LIST) return BOOLEAN is
    L : LIST := L1;
begin
    while NON_EMPTY(L) loop
        if not MEMBER(VALUE(L), L2) then
            return FALSE;
        end if;
        NEXT(L);
    end loop;
    return TRUE;
end SUBSEQUENCE;

```

```

function EQUAL(L1 : in LIST; L2 : in LIST) return BOOLEAN is
begin
    return (SUBSEQUENCE(L1, L2) and SUBSEQUENCE(L2, L1));
end EQUAL;

```

```

procedure EMPTY(L : out LIST) is
begin
    L := null;
end EMPTY;

```

```

function MEMBER(X : in ITEM; L : in LIST) return BOOLEAN is
begin
    if LOOK4(X, L) /= null then
        return TRUE;
    else
        return FALSE;
    end if;
end MEMBER;

```

```

procedure REMOVE(X : in ITEM; L : in out LIST) is
    HEADER, --* ADDED ON 21 MAY 91 TO CORRECT ERROR
    CURR : LIST := L;
    PREV : LIST := null;
    TEMP : LIST := null;
begin
    while NON_EMPTY(CURR) loop
        if VALUE(CURR) = X then
            TEMP := CURR;
            NEXT(CURR);
            TEMP.PREVIOUS := null;
            TEMP.NEXT := null;
            FREE(TEMP);
            if PREV /= null then --* Operator we are removing is within list
                PREV.NEXT := CURR;
            else
                HEADER := CURR; --* ADDED 21 MAY 91 TO CORRECT ERROR
            end if;
            if CURR /= null then --* List contains other items so we must relink
                CURR.PREVIOUS := PREV; --* the list in reverse. --* (Apr 91)
            end if;
        else
            PREV := CURR;
            NEXT(CURR);
        end if;
    end loop;
end REMOVE;

```

```

if NON_EMPTY(HEADER) then --* How do we handle removal of first item in list?
  L := HEADER; --* ADDED 21 MAY 91 TO CORRECT ERROR
else --* diagnostics 2 June 91
  L := CURR; --* diagnostics 2 June 91
end if; --* diagnostics 2 June 91
end REMOVE;

```

```

procedure LIST_REVERSE(L1 : in LIST; L2 : in out LIST) is
  L : LIST := L1;
begin
  EMPTY(L2);
  while NON_EMPTY(L) loop
    ADD(VALUE(L), L2);
    NEXT(L);
  end loop;
end LIST_REVERSE;

```

```

procedure FREE_LIST(L : in out LIST) is
  CURR : LIST := L;
  TEMP : LIST;
begin
  while NON_EMPTY(L) loop
    NEXT(CURR);
    if NON_EMPTY(CURR) then
      CURR.PREVIOUS := null;
    end if;
    L.NEXT := null;
    FREE(L);
    L := CURR;
  end loop;
end FREE_LIST;

```

```

procedure DUPLICATE(L1 : in LIST; L2 : in out LIST) is
  TEMP : LIST := null;
  L : LIST := L1;
begin
  FREE_LIST(L2);
  while NON_EMPTY(L) loop
    ADD(VALUE(L), TEMP);
    NEXT(L);
  end loop;
  LIST_REVERSE(TEMP, L2);
end DUPLICATE;

```

```

function VALUE(L : in LIST) return ITEM is
begin
  if NON_EMPTY(L) then
    return L.ELEMENT;
  else
    raise BAD_VALUE;
  end if;
end VALUE;

```

```

procedure INSERT_NEXT(X : in ITEM; L : in out LIST) is
  T : LIST := new NODE;
begin
  T.ELEMENT := X;
  if NON_EMPTY(L) then
    if L.NEXT /= null then
      L.NEXT.PREVIOUS := T;
    end if;
  end if;
end INSERT_NEXT;

```

```

    T.PREVIOUS := L;
    T.NEXT := L.NEXT;
    L.NEXT := T;
  end if;
  L := T;
end INSERT_NEXT;

procedure REPLACE_ITEM(X : in ITEM; L : in out LIST) is
begin
  L.ELEMENT := X;
end REPLACE_ITEM;

procedure COPY_LIST(L1 : in LIST; L2 : in out LIST) is

  CURR: LIST := L1;
  HEAD: LIST := L2;
  TEMP: LIST;
  PREV: LIST;

begin
  while NON_EMPTY(CURR) and NON_EMPTY(L2) loop
    L2.ELEMENT := VALUE(CURR);
    NEXT(CURR);
    PREV := L2;
    NEXT(L2);
  end loop;
  --* HANDLE CASE WHEN L2 IS LONGER THAN L1;
  if not NON_EMPTY(CURR) and NON_EMPTY(L2) then
    PREV.NEXT := null; --* DISCONNECT EXCESS FROM L2
    while NON_EMPTY(L2) loop
      TEMP := L2;
      TEMP.PREVIOUS := null;
      NEXT(L2);
      TEMP.NEXT := null;
      FREE(TEMP);
    end loop;
  --* HANDLE CASE WHEN L1 IS LONGER THAN L2;
  elsif NON_EMPTY(CURR) and not NON_EMPTY(L2) then
    while NON_EMPTY(CURR) loop
      TEMP := new NODE;
      PREV.NEXT := TEMP;
      TEMP.ELEMENT := VALUE(CURR);
      TEMP.PREVIOUS := PREV;
      PREV := TEMP;
      NEXT(CURR);
    end loop;
  end if;
  L2 := HEAD;
end COPY_LIST;

end SEQUENCES;

```

```

with TEXT_IO;
with DATA;
with SEQUENCES;
with FRONT_END; use FRONT_END;

```

```

package TOP_SORT is

```

```

    procedure T_SORT(PRECEDENCE_LIST: in out DATA.NODE_LIST.LIST;
                     COUNT: in INTEGER);
    --* This procedure produces a topological sort of the operators that are in
    --* the NEW_GRAPH structure.

```

```

end TOP_SORT;

```

```

package body TOP_SORT is

```

```

    procedure T_SORT(PRECEDENCE_LIST : in out DATA.NODE_LIST.LIST;
                     COUNT           : in INTEGER) is

```

```

        package int_io is new TEXT_IO.integer_io(integer);
        use int_io;

```

```

        type DEGREES is array (0..COUNT) of INTEGER;

```

```

        IN_DEGREE: DEGREES := --* Indegree Array used in sorting

```

```

        package QUEUES is new SEQUENCES(INTEGER);

```

```

        PARENT_LIST      : DATA.NODE_LIST.LIST;
        CHILD_LIST        : DATA.NODE_LIST.LIST;
        PARENT_COUNT      : INTEGER;
        CHILD_COUNT       : INTEGER;

```

```

        QUEUE             : QUEUES.LIST;
        HEAD               : QUEUES.LIST;

```

```

        REVERSED_PREC_LIST : DATA.NODE_LIST.LIST;

```

```

begin

```

```

    for OP in 1..COUNT loop
        FRONT_END.NEW_GRAPH.RETURN_PARENT_LIST(PARENT_LIST, OP, PARENT_COUNT);
        IN_DEGREE(OP) := PARENT_COUNT;
    end loop;
    QUEUES.ADD(0,QUEUE); --* BECAUSE OF THE USE OF A DUMMY START NODE THIS NODE
--* WILL ALWAYS BE THE FIRST ELEMENT IN THE QUEUE WITH
--* AN IN_DEGREE OF ZERO.
    HEAD := QUEUE;
    while QUEUES.NON_EMPTY(QUEUE) loop
        FRONT_END.NEW_GRAPH.RETURN_CHILD_LIST(CHILD_LIST, QUEUES.VALUE(HEAD),
        CHILD_COUNT);
        while DATA.NODE_LIST.NON_EMPTY(CHILD_LIST) loop
            IN_DEGREE(DATA.NODE_LIST.VALUE(CHILD_LIST)) :=
            IN_DEGREE(DATA.NODE_LIST.VALUE(CHILD_LIST)) - 1;
            if IN_DEGREE(DATA.NODE_LIST.VALUE(CHILD_LIST)) = 0 then
                QUEUES.ADD(DATA.NODE_LIST.VALUE(CHILD_LIST), QUEUE);
            end if;
        end loop;
    end loop;

```

```
    DATA.NODE_LIST.NEXT(CHILD_LIST);  
  end loop;  
  DATA.NODE_LIST.ADD(QUEUES.VALUE(HEAD), REVERSED_PREC_LIST);  
  QUEUES.REMOVE(QUEUES.VALUE(HEAD), QUEUE);  
  HEAD := QUEUE;  
  end loop;  
  DATA.NODE_LIST.LIST_REVERSE(REVERSED_PREC_LIST, PRECEDENCE_LIST);  
end T_SORT;  
end TOP_SORT;
```

with DATA; use DATA;

package PROCESSOR is

    procedure FIND\_PERIODS(OP\_LIST : in out V\_LISTS.LIST);

    procedure VALIDATE\_DATA (OP\_LIST : in out V\_LISTS.LIST);

|                                   |              |
|-----------------------------------|--------------|
| NOT_FEASIBLE                      | : exception; |
| CRIT_OP_LACKS_MET                 | : exception; |
| MET_NOT_LESS_THAN_PERIOD          | : exception; |
| MET_NOT_LESS_THAN_MRT             | : exception; |
| MCP_NOT_LESS_THAN_MRT             | : exception; |
| MCP_LESS_THAN_MET                 | : exception; |
| MET_IS_GREATER_THAN_FINISH_WITHIN | : exception; |
| SPORADIC_OP_LACKS_MCP             | : exception; |
| SPORADIC_OP_LACKS_MRT             | : exception; |
| PERIOD_LESS_THAN_FINISH_WITHIN    | : exception; |

end PROCESSOR;

with TEXT\_IO;  
with DATA; use DATA;

package body PROCESSOR is

procedure FIND\_PERIODS(OP\_LIST : in out V\_LISTS.LIST) is

|            |                     |
|------------|---------------------|
| TARGET     | : V_LISTS.LIST;     |
| N          | : NATURAL := 0;     |
| L          | : FLOAT := 0.0;     |
| NEW_PERIOD | : NATURAL := 0;     |
| OP         | : OPERATOR;         |
| C          | : FLOAT;            |
| FIRST      | : BOOLEAN := true;  |
| FOUND      | : BOOLEAN := false; |
| FRACTION   | : NATURAL;          |
| FR_GCD     | : NATURAL;          |
| LCM        | : NATURAL;          |
| UNIT       | : NATURAL;          |
| ALPHA      | : FLOAT;            |
| GCD        | : NATURAL;          |

package I\_IO is new TEXT\_IO.INTEGER\_IO(NATURAL);

procedure CALCULATE\_NEW\_PERIOD (O : in OPERATOR;  
NEW\_PERIOD : in out NATURAL) is

DIFFERENCE : NATURAL;  
package VALUE\_IO is new TEXT\_IO.INTEGER\_IO(NATURAL);  
begin  
    DIFFERENCE := O.THE\_MRT - O.THE\_MET;  
    if DIFFERENCE < O.THE\_MCP then  
        NEW\_PERIOD := DIFFERENCE;  
    else  
        NEW\_PERIOD := O.THE\_MCP;  
    end if;

end CALCULATE\_NEW\_PERIOD;

function FIND\_GCD (SMALL : in VALUE; LARGE : in VALUE) return VALUE is  
    REMAINDER : VALUE := SMALL;

begin  
    if LARGE mod SMALL = 0 then  
        return REMAINDER;  
    else  
        REMAINDER := FIND\_GCD(LARGE mod SMALL, SMALL);  
        return REMAINDER;  
    end if;  
end FIND\_GCD;

function FIND\_LCM (NUMBER1, NUMBER2 : VALUE) return VALUE is  
begin  
    return (NUMBER1 \* NUMBER2) / GCD;  
end FIND\_LCM;

function REDUCE\_TO\_EVEN\_FRACTION (GCD, PERIOD : NATURAL) return NATURAL is  
    N : NATURAL := GCD / PERIOD;

```

begin
  if N * PERIOD = GCD then
    return N;
  else
    return N + 1;
  end if;
end REDUCE_TO_EVEN_FRACTION;

begin
-- FIRST PASS
-- Calculates the load factor for all periodic operators, and greatest common
-- divisor of the periods of the periodic operators
  TARGET := OP_LIST;
  while V_LISTS.NON_EMPTY(TARGET) loop
    OP := V_LISTS.VALUE(TARGET);
    if OP.THE_MET = 0 then
      Exception_Operator := OP.THE_OPERATOR_ID;
      raise CRIT_OP_LACKS_MET;
    elsif OP.THE_PERIOD /= 0 then -- a periodic operator
      L := L + FLOAT(OP.THE_MET)/FLOAT(OP.THE_PERIOD);
      if FIRST then
        GCD := OP.THE_PERIOD;
        FIRST := false;
      else
        if GCD > OP.THE_PERIOD then
          GCD := FIND_GCD(OP.THE_PERIOD,GCD);
        else
          GCD := FIND_GCD(GCD,OP.THE_PERIOD);
        end if;
      end if;
    end if;
  end loop;
  V_LISTS.NEXT(TARGET);
end loop;

-- SECOND PASS
-- Finds the total number of sporadic operators (N)
-- For the sporadic operators with user defined MRT or MCP values, calculates
-- the undefined value of MCP or MRT with given MRT or MCP
-- And finds the unit factor(UNIT) for the sporadic operators with user defined
-- MCP or MRT with calculated periods less than GCD found above

  TARGET := OP_LIST;
  FIRST := true;
  while V_LISTS.NON_EMPTY(TARGET) loop
    OP := V_LISTS.VALUE(TARGET);
    if OP.THE_PERIOD = 0 then -- a sporadic operator
      if OP.THE_MCP /= 0 and OP.THE_MRT = 0 then
        OP.THE_MRT := OP.THE_MET + OP.THE_MCP;
        TARGET.ELEMENT.THE_MRT := OP.THE_MRT;
      elsif OP.THE_MCP = 0 and OP.THE_MRT /= 0 then
        OP.THE_MCP := OP.THE_MRT - OP.THE_MET;
        TARGET.ELEMENT.THE_MCP := OP.THE_MCP;
      end if;
      if OP.THE_MCP /= 0 and OP.THE_MRT /= 0 then
        CALCULATE_NEW_PERIOD(OP,NEW_PERIOD);
        if NEW_PERIOD < GCD then
          FOUND := true;
          FRACTION := GCD/REDUCE_TO_EVEN_FRACTION(GCD,NEW_PERIOD);
          if FIRST then
            FR_GCD := FRACTION;
            LCM := FRACTION;
          end if;
        end if;
      end if;
    end if;
  end loop;

```

```

        FIRST := false;
    else
        if FRACTION > FR_GCD then
            FR_GCD := FIND_GCD(FR_GCD, FRACTION);
        else
            FR_GCD := FIND_GCD(FRACTION, FR_GCD);
        end if;
        LCM := FIND_LCM(LCM, FRACTION);
    end if;
end if;
else
    N := N + 1;
end if;
end if;
V_LISTS.NEXT(TARGET);
end loop;
if FOUND then
    UNIT := LCM;
else
    UNIT := GCD;
end if;

-- THIRD PASS
-- Calculates and writes the periods for the sporadic operators with user defined
-- MCP or MRT by using the UNIT factor calculated above. Modifies the load factor
-- L calculated in the first pass. Finds coefficient ALPHA.

```

```

TARGET := OP_LIST;
while V_LISTS.NON_EMPTY(TARGET) loop
    OP := V_LISTS.VALUE(TARGET);
    if OP.THE_PERIOD = 0 then -- a sporadic operator
        if OP.THE_MRT /= 0 and OP.THE_MCP /= 0 then
            CALCULATE_NEW_PERIOD(OP, NEW_PERIOD);
            NEW_PERIOD := NEW_PERIOD - NEW_PERIOD mod UNIT;
            OP.THE_PERIOD := NEW_PERIOD;
            TEXT_IO.PUT("New PERIOD for operator ");
            VARSTRING.PUT(OP.THE_OPERATOR_ID);
            TEXT_IO.PUT(" is ");
            I_IO.PUT(NEW_PERIOD, 1);
            TEXT_IO.NEW_LINE;
            TARGET.ELEMENT.THE_PERIOD := OP.THE_PERIOD;
            L := L + FLOAT(OP.THE_MET)/FLOAT(NEW_PERIOD);
        end if;
    end if;
    V_LISTS.NEXT(TARGET);
end loop;

if L < 0.5 then
    C := 0.5;
elseif L >= 0.5 and L < 1.0 then
    C := (1.0 + L) / 2.0;
else
    raise NOT_FEASIBLE;
end if;
ALPHA := FLOAT(N)/(C - L) + 1.0;
if ALPHA < 2.0 then
    ALPHA := 2.0;
end if;

```

```

-- FOURTH PASS

```

-- Calculates and writes the PERIOD, MRT, MCP values for the sporadic operators  
 -- without user defined MCP or MRT values

```
TARGET := OP_LIST;
while V_LISTS.NON_EMPTY(TARGET) loop
  OP := V_LISTS.VALUE(TARGET);
  if OP.THE_PERIOD = 0 then -- a sporadic operator
    if OP.THE_MRT = 0 and OP.THE_MCP = 0 then
      OP.THE_MRT := NATURAL(ALPHA) * OP.THE_MET;
      OP.THE_MCP := OP.THE_MRT - OP.THE_MET;
    if (OP.THE_MCP / UNIT) * UNIT /= OP.THE_MCP then
      OP.THE_PERIOD := OP.THE_MCP + UNIT - (OP.THE_MCP mod UNIT);
    else
      OP.THE_PERIOD := OP.THE_MCP;
    end if;
    TEXT_IO.PUT("New PERIOD for operator ");
    VARSTRING.PUT(OP.THE_OPERATOR_ID);
    TEXT_IO.PUT(" is ");
    I_IO.PUT(OP.THE_PERIOD,1);
    TEXT_IO.NEW_LINE;
  end if;
end if;
TARGET.ELEMENT.THE_PERIOD := OP.THE_PERIOD;
TARGET.ELEMENT.THE_MRT := OP.THE_MRT;
TARGET.ELEMENT.THE_MCP := OP.THE_MCP;
V_LISTS.NEXT(TARGET);
end loop;
end FIND_PERIODS;
```

procedure VALIDATE\_DATA (OP\_LIST : in out V\_LISTS.LIST) is

```
  TARGET : V_LISTS.LIST;
  package VAL_IO is new TEXT_IO.INTEGER_IO(VALUE);
begin
  TARGET := OP_LIST;
  while V_LISTS.NON_EMPTY(TARGET) loop

    -- ensure that there is no operator without an MET.
    if V_LISTS.VALUE(TARGET).THE_MET = 0 then
      Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
      raise CRIT_OP_LACKS_MET;
    end if;

    if V_LISTS.VALUE(TARGET).THE_PERIOD = 0 then
      -- Check to ensure that MCP has a value for sporadic operators
      if V_LISTS.VALUE(TARGET).THE_MCP = 0 then
        Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
        raise SPORADIC_OP_LACKS_MCP;
      elsif V_LISTS.VALUE(TARGET).THE_MET >
        V_LISTS.VALUE(TARGET).THE_MCP then
        Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
        raise MCP_LESS_THAN_MET;
      end if;

      -- Check to ensure that MRT has a value for sporadic operators
      if V_LISTS.VALUE(TARGET).THE_MRT = 0 then
        Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
        raise SPORADIC_OP_LACKS_MRT;
      end if;

      -- Check to ensure that the MRT is greater than the MET.
    end if;
  end loop;
end;
```

```

        if V_LISTS.VALUE(TARGET).THE_MET > V_LISTS.VALUE(TARGET).THE_MRT then
            Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
            raise MET_NOT_LESS_THAN_MRT;
        end if;

        -- Guarantees that an operator can fire at least once
        -- before a response expected.
        if V_LISTS.VALUE(TARGET).THE_MCP > V_LISTS.VALUE(TARGET).THE_MRT then
            Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
            raise MCP_NOT_LESS_THAN_MRT;
        end if;

    else
        -- Check to ensure that the PERIOD is greater than the MET.
        if V_LISTS.VALUE(TARGET).THE_MET > V_LISTS.VALUE(TARGET).THE_PERIOD then
            Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
            raise MET_NOT_LESS_THAN_PERIOD;
        end if;

        -- Check to ensure that the FINISH_WITHIN is grater than the MET.
        if V_LISTS.VALUE(TARGET).THE_WITHIN /= 0 then
            if V_LISTS.VALUE(TARGET).THE_MET > V_LISTS.VALUE(TARGET).THE_WITHIN then
                Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
                raise MET_IS_GREATER_THAN_FINISH_WITHIN;
            elsif V_LISTS.VALUE(TARGET).THE_PERIOD <
                V_LISTS.VALUE(TARGET).THE_WITHIN then
                Exception_Operator := V_LISTS.VALUE(TARGET).THE_OPERATOR_ID;
                raise PERIOD_LESS_THAN_FINISH_WITHIN;
            end if;
        end if;

    end if;

    V_LISTS.NEXT(TARGET);
end loop;
end VALIDATE_DATA;

end PROCESSOR;

```

## APPENDIX D. NEW PACKAGES

with TEXT\_IO;  
with DATA; use DATA;

--\* This package contains the specifications for a graph data structure that can  
--\* represent an acyclic graph. Functions and procedures exist to access the  
--\* information that is stored in the graph as well as to find out the relationships  
--\* between vertices in the graph.

generic

package NEW\_DATA\_STRUCTURES is

type GRAPH (SIZE : INTEGER) is limited private;

type GRAPH\_LINK is access GRAPH;

THE\_GRAPH : GRAPH\_LINK;

procedure PRODUCE\_OP\_ARRAY (INFO\_LIST : in out V\_LISTS.LIST;  
COUNT : in INTEGER);

--\* Transfer operator info from linked list to array

function OP\_POSITION (OP\_NAME : in VARSTRING.VSTRING;  
COUNT : in INTEGER) return INTEGER;

--\* Given an operator name return the operator's position in the array

procedure PRODUCE\_OP\_MATRIX (COUNT: in INTEGER);  
--\* Create a Matrix to represent the acyclic graph of operator relationship

function OP\_RETURN (OP\_POSITION: in INTEGER) return OPERATOR;  
--\* Given an operator's position in the array, return the operator

function IS\_PARENT (OP\_1 : in INTEGER;  
OP\_2 : in INTEGER) return BOOLEAN;  
--\* Return true if OP\_1 is a parent of OP\_2 or if OP\_1 is OP\_2

function IS\_CHILD (OP\_1 : in INTEGER;  
OP\_2 : in INTEGER) return BOOLEAN;  
--\* Return true if OP\_1 is a child of OP\_2 or if OP\_1 is OP\_2

procedure RETURN\_PARENT\_LIST (PARENT\_LIST : in out NODE\_LIST.LIST;  
OP : in INTEGER;  
COUNT : in out INTEGER);  
--\* Return a list of all the parents of an operator

procedure RETURN\_CHILD\_LIST (CHILD\_LIST : in out NODE\_LIST.LIST;  
OP : in INTEGER;  
COUNT : in out INTEGER);  
--\* Return a list of all the children of an operator

procedure FREE\_GRAPH (A\_GRAPH: in out GRAPH\_LINK);  
--\* Free the memory space used by the graph  
private

type INFO\_ARRAY is array (INTEGER range <>) of OPERATOR;

type MATRIX\_OP\_INFO is

```
record
  PARENT  : INTEGER := -1;
  CHILD   : INTEGER := -1;
end record;
```

type MATRIX is array (INTEGER range  $\diamond$ , INTEGER range  $\diamond$ ) of MATRIX\_OP\_INFO;

type GRAPH (SIZE : INTEGER) is

```
record
  OP_ARRAY      : INFO_ARRAY(0..SIZE);
  OP_MATRIX     : MATRIX(0..SIZE, 0..SIZE);
end record;
```

end NEW\_DATA\_STRUCTURES;

```

with UNCHECKED_DEALLOCATION;

package body NEW_DATA_STRUCTURES is

pragma LINK_WITH ("heaplib.sparc.ar");

procedure FREE is new UNCHECKED_DEALLOCATION(GRAPH, GRAPH_LINK);

package int_io is new TEXT_IO.integer_io(integer);--put in for debugging
use int_io;

procedure PRODUCE_OP_ARRAY (INFO_LIST      : in out V_LISTS.LIST;
                           COUNT          : in INTEGER) is

    HEAD      : V_LISTS.LIST := INFO_LIST;

function MAKE_START_NODE return OPERATOR is

    START_OP    : OPERATOR;

begin
    START_OP.THE_OPERATOR_ID := VARSTRING.VSTR("DUMMY START NODE");
    START_OP.THE_MET := 0;
    START_OP.THE_MRT := 0;
    START_OP.THE_MCP := 0;
    START_OP.THE_WITHIN := 0;
    return START_OP;
end MAKE_START_NODE;

begin
    for INDEX in reverse 1..COUNT loop
        THE_GRAPH.OP_ARRAY(INDEX) := V_LISTS.VALUE(INFO_LIST);
        V_LISTS.NEXT(INFO_LIST);
    end loop;
    THE_GRAPH.OP_ARRAY(0) := MAKE_START_NODE;
    V_LISTS.FREE_LIST(HEAD); --* THIS LIST IS NO LONGER NEEDED.
end PRODUCE_OP_ARRAY;

function OP_POSITION (OP_NAME : in VARSTRING.VSTRING;
                     COUNT    : in INTEGER) return INTEGER is

--* This function is implemented now as a linear scan. Its performance
--* can be improved by using a hashing function. If a hashing function
--* is to be used, then the procedure PRODUCE_OP_ARRAY will also have
--* to be modified if hashing is to be used. 17 July 91

begin
    for INDEX in 1..COUNT loop
        if VARSTRING.EQUAL (OP_NAME,
                           THE_GRAPH.OP_ARRAY(INDEX).THE_OPERATOR_ID) then
            return INDEX;
        end if;
    end loop;
    return -1; --* Operator is external since it is not in the array.
end OP_POSITION;

```

```

procedure PRODUCE_OP_MATRIX (COUNT      : in INTEGER) is

    COLUMN,
    ROW,
    PARENT_OP,
    CHILD_OP      : INTEGER;

    LINK          : constant VARSTRING.VSTRING := VARSTRING.VSTR("LINK");

    procedure INITIALIZE (COUNT      : in INTEGER;
                          OP_MATRIX    : in out MATRIX) is

        begin
            for ROW in 0..COUNT loop
                for COLUMN in 0..COUNT loop
                    if ROW = COLUMN then
                        THE_GRAPH.OP_MATRIX(ROW,COLUMN).PARENT := ROW;
                        THE_GRAPH.OP_MATRIX(ROW,COLUMN).CHILD := ROW;
                    end if;
                end loop;
            end loop;
        end INITIALIZE;

    procedure INITIALIZE_START_NODE (COUNT      : in INTEGER;
                                     OP_MATRIX    : in out MATRIX) is

        begin
            for INDEX in 0..COUNT loop
                if THE_GRAPH.OP_MATRIX(INDEX, INDEX).PARENT = INDEX then
                    THE_GRAPH.OP_MATRIX(INDEX,INDEX).PARENT := 0;
                    THE_GRAPH.OP_MATRIX(0,INDEX).CHILD := THE_GRAPH.OP_MATRIX(0,0).CHILD;
                    THE_GRAPH.OP_MATRIX(0,0).CHILD := INDEX;
                    THE_GRAPH.OP_MATRIX(0,INDEX).PARENT := INDEX;
                end if;
            end loop;
        end INITIALIZE_START_NODE;

    begin
        TEXT_IO.OPEN (AG_OUTFILE,INPUT,"atomic.info");
        INITIALIZE(COUNT, THE_GRAPH.OP_MATRIX);
        VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
        while not TEXT_IO.END_OF_FILE(AG_OUTFILE) loop
            if VARSTRING.EQUAL (New_Word,LINK) then -- keyword "LINK"
                TEXT_IO.SKIP_LINE(AG_OUTFILE); -- skip LINK name
                VARSTRING.GET_LINE(AG_OUTFILE, New_Word);
                PARENT_OP := OP_POSITION(New_Word, DATA.OP_COUNT);
                TEXT_IO.SKIP_LINE(AG_OUTFILE);
                VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
                CHILD_OP := OP_POSITION(New_Word, DATA.OP_COUNT);

                -- when either starting node or ending node of a link is EXTERNAL,
                -- the link information will not be added to the graph. Assuming
                -- that all external data coming in is ready at start time.

                if PARENT_OP /= -1 and CHILD_OP /= -1 then
                    THE_GRAPH.OP_MATRIX(PARENT_OP,CHILD_OP).CHILD :=
                        THE_GRAPH.OP_MATRIX(PARENT_OP,PARENT_OP).CHILD;
                end if;
            end if;
        end loop;
    end;
end PRODUCE_OP_MATRIX;

```

```

    THE_GRAPH.OP_MATRIX(PARENT_OP,PARENT_OP).CHILD := CHILD_OP;
    THE_GRAPH.OP_MATRIX(PARENT_OP,CHILD_OP).PARENT :=
    THE_GRAPH.OP_MATRIX(CHILD_OP,CHILD_OP).PARENT;
    THE_GRAPH.OP_MATRIX(CHILD_OP,CHILD_OP).PARENT := PARENT_OP;
  end if;
  VARSTRING.GET_LINE ( AG_OUTFILE, New_Word);
else
  VARSTRING.GET_LINE ( AG_OUTFILE, New_Word); -- skip all other info
end if;
end loop;
TEXT_IO.CLOSE (AG_OUTFILE);
INITIALIZE_START_NODE(COUNT, THE_GRAPH.OP_MATRIX);
end PRODUCE_OP_MATRIX;

```

function OP\_RETURN (OP\_POSITION: in INTEGER) return OPERATOR is

OP : OPERATOR;

begin

OP := THE\_GRAPH.OP\_ARRAY(OP\_POSITION);

return OP;

end OP\_RETURN;

function IS\_PARENT (OP\_1 : in INTEGER;  
OP\_2 : in INTEGER) return BOOLEAN is

--\* Return true if OP\_1 is a parent of OP\_2 or if OP\_1 is OP\_2

PARENT : BOOLEAN := false;

begin

if OP\_1 = OP\_2 then

PARENT := true;

elsif THE\_GRAPH.OP\_MATRIX(OP\_1, OP\_2).PARENT /= -1 then

PARENT := true;

end if;

return PARENT;

end IS\_PARENT;

function IS\_CHILD (OP\_1 : in INTEGER;  
OP\_2 : in INTEGER) return BOOLEAN is

--\* Return true if OP\_1 is a child of OP\_2 or if OP\_1 is OP\_2

CHILD : BOOLEAN := false;

begin

if OP\_1 = OP\_2 then

CHILD := true;

elsif THE\_GRAPH.OP\_MATRIX(OP\_2, OP\_1).CHILD /= -1 then

CHILD := true;

end if;

return CHILD;

end IS\_CHILD;

procedure RETURN\_PARENT\_LIST (PARENT\_LIST : in out NODE\_LIST.LIST;  
OP : in INTEGER) is

COUNT : in out INTEGER) is

ROW : INTEGER := OP;

```

begin
  COUNT := 0;
  while THE_GRAPH.OP_MATRIX(ROW, OP).PARENT /= OP loop
    NODE_LIST.ADD(THE_GRAPH.OP_MATRIX(ROW, OP).PARENT, PARENT_LIST);
    COUNT := COUNT + 1;
    ROW := THE_GRAPH.OP_MATRIX(ROW, OP).PARENT;
  end loop;
end RETURN_PARENT_LIST;

procedure RETURN_CHILD_LIST (CHILD_LIST : in out NODE_LIST.LIST;
                             OP         : in INTEGER;
                             COUNT      : in out INTEGER) is
  COLUMN : INTEGER := OP;

begin
  COUNT := 0;
  while THE_GRAPH.OP_MATRIX(OP, COLUMN).CHILD /= OP loop
    NODE_LIST.ADD(THE_GRAPH.OP_MATRIX(OP, COLUMN).CHILD, CHILD_LIST);
    COUNT := COUNT + 1;
    COLUMN := THE_GRAPH.OP_MATRIX(OP, COLUMN).CHILD;
  end loop;
end RETURN_CHILD_LIST;

procedure FREE_GRAPH (A_GRAPH: in out GRAPH_LINK) is

begin
  FREE(A_GRAPH);
end FREE_GRAPH;

end NEW_DATA_STRUCTURES;

```

```

with TEXT_IO;
with DATA; use DATA;
with NEW_DATA_STRUCTURES;

```

```

package FRONT_END is

```

```

    procedure PRODUCE_OP_LIST(INFO_LIST      : in out V_LISTS.LIST;
                              COUNT          : in out INTEGER);

```

```

    --* Extract the operator information from the ATOMIC.INFO file
    --* and place it in a linked list.

```

```

    procedure TEST_DATA (INPUT_LIST          : in V_LISTS.LIST;
                        HARMONIC_BLOCK_LENGTH : in INTEGER);

```

```

    --* Determine if the operators can be feasibly scheduled on a single
    --* processor system.

```

```

    package NEW_GRAPH is new NEW_DATA_STRUCTURES;
    --* Instantiate the graph data structure so that it can be accessed by
    --* the rest of the Static Scheduler.

```

```

    NUMBER_OF_OPERATORS : INTEGER;

```

```

end FRONT_END;

```

```

package body FRONT_END is

```

```

    procedure PRODUCE_OP_LIST (INFO_LIST      : in out V_LISTS.LIST;
                              COUNT          : in out INTEGER) is

```

```

    -- This procedure reads the output file which has the link information with
    -- the Atomic operators and depending upon the keywords that are declared
    -- as constants separates the information in the file and stores it the
    -- operator array and the link matrix.

```

```

    package VALUE_IO is new TEXT_IO.INTEGER_IO(VALUE);

```

```

    MET      : constant VARSTRING.VSTRING := VARSTRING.VSTR("MET");
    MRT      : constant VARSTRING.VSTRING := VARSTRING.VSTR("MRT");
    MCP      : constant VARSTRING.VSTRING := VARSTRING.VSTR("MCP");
    PERIOD    : constant VARSTRING.VSTRING := VARSTRING.VSTR("PERIOD");
    WITHIN    : constant VARSTRING.VSTRING := VARSTRING.VSTR("WITHIN");
    LINK      : constant VARSTRING.VSTRING := VARSTRING.VSTR("LINK");
    ATOMIC    : constant VARSTRING.VSTRING := VARSTRING.VSTR("ATOMIC");
    EMPTY     : constant VARSTRING.VSTRING := VARSTRING.VSTR("EMPTY");

```

```

    procedure INITIALIZE_OPERATOR (OP : in out OPERATOR) is
    begin

```

```

        OP.THE_MET := 0;
        OP.THE_MRT := 0;
        OP.THE_MCP := 0;
        OP.THE_PERIOD := 0;
        OP.THE_WITHIN := 0;
    end INITIALIZE_OPERATOR;

```

```

begin
  TEXT_IO.OPEN (AG_OUTFILE, INPUT, "atomic.info");
  TEXT_IO.CREATE (NON_CRITS, OUTPUT, "non_crits");
  COUNT := 0;
  VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
  while not TEXT_IO.END_OF_FILE (AG_OUTFILE) loop
    if VARSTRING.EQUAL (New_Word, LINK) then -- keyword "LINK"
      TEXT_IO.SKIP_LINE (AG_OUTFILE); -- Skip over LINK
      TEXT_IO.SKIP_LINE (AG_OUTFILE); -- info for now.
      TEXT_IO.SKIP_LINE (AG_OUTFILE);
      TEXT_IO.SKIP_LINE (AG_OUTFILE);
      VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
    elsif VARSTRING.EQUAL (New_Word, ATOMIC) then -- keyword "ATOMIC"
      VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
      Cur_Opt.THE_OPERATOR_ID := New_Word;
      VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
      if (VARSTRING.EQUAL (New_Word, ATOMIC)) or
        (VARSTRING.EQUAL (New_Word, LINK)) or
        (TEXT_IO.END_OF_FILE (AG_OUTFILE)) then
        VARSTRING.PUT_LINE (NON_CRITS, Cur_Opt.THE_OPERATOR_ID);
      --* Non-periodic Operator, No need to be statically scheduled.
    else
      while VARSTRING.NOTEQUAL (New_Word, ATOMIC) and -- Loop to get
        VARSTRING.NOTEQUAL (New_Word, LINK) and -- timing info
        not TEXT_IO.END_OF_FILE (AG_OUTFILE) loop -- of operator

        if VARSTRING.EQUAL (New_Word, MET) then -- keyword "MET"
          VALUE_IO.GET (AG_OUTFILE, Current_Value);
          TEXT_IO.SKIP_LINE (AG_OUTFILE);
          Cur_Opt.THE_MET := Current_Value;
        elsif VARSTRING.EQUAL (New_Word, MRT) then -- keyword "MRT"
          VALUE_IO.GET (AG_OUTFILE, Current_Value);
          TEXT_IO.SKIP_LINE (AG_OUTFILE);
          Cur_Opt.THE_MRT := Current_Value;
        elsif VARSTRING.EQUAL (New_Word, MCP) then -- keyword "MCP"
          VALUE_IO.GET (AG_OUTFILE, Current_Value);
          TEXT_IO.SKIP_LINE (AG_OUTFILE);
          Cur_Opt.THE_MCP := Current_Value;
        elsif VARSTRING.EQUAL (New_Word, PERIOD) then -- keyword "PERIOD"
          VALUE_IO.GET (AG_OUTFILE, Current_Value);
          TEXT_IO.SKIP_LINE (AG_OUTFILE);
          Cur_Opt.THE_PERIOD := Current_Value;
        elsif VARSTRING.EQUAL (New_Word, WITHIN) then -- keyword "WITHIN"
          VALUE_IO.GET (AG_OUTFILE, Current_Value);
          TEXT_IO.SKIP_LINE (AG_OUTFILE);
          Cur_Opt.THE_WITHIN := Current_Value;
        end if;
        VARSTRING.GET_LINE (AG_OUTFILE, New_Word);
      end loop;
      V_LISTS.ADD (Cur_Opt, INFO_LIST);
      COUNT := COUNT + 1;
      INITIALIZE_OPERATOR (Cur_Opt);
    end if;
  end if;
end loop;
TEXT_IO.CLOSE (AG_OUTFILE);
NUMBER_OF_OPERATORS := COUNT;
end PRODUCE_OP_LIST;

```

```

procedure TEST_DATA (INPUT_LIST          : in V_LISTS.LIST;
                    HARMONIC_BLOCK_LENGTH : in INTEGER) is

procedure CALC_TOTAL_TIME (INPUT_LIST          : in V_LISTS.LIST;
                          HARMONIC_BLOCK_LENGTH : in INTEGER) is
    V          : V_LISTS.LIST := INPUT_LIST;
    TIMES      : FLOAT := 0.0;
    OP_TIME    : FLOAT := 0.0;
    TOTAL_TIME : FLOAT := 0.0;
    PER        : OPERATOR;
    BAD_TOTAL_TIME : exception;

    function CALC_NO_OF_PERIODS (HARMONIC_BLOCK_LENGTH : in INTEGER;
                                THE_PERIOD             : in INTEGER) return FLOAT is
    begin
        return FLOAT(HARMONIC_BLOCK_LENGTH) / FLOAT(THE_PERIOD);
    end CALC_NO_OF_PERIODS;

    function MULTIPLY_BY_MET (TIMES : in FLOAT;
                             THE_MET : in VALUE) return FLOAT is
    begin
        return TIMES * FLOAT(THE_MET);
    end MULTIPLY_BY_MET;

    function ADD_TO_SUM (OP_TIME : in FLOAT) return FLOAT is
    begin
        return TOTAL_TIME + OP_TIME;
    end ADD_TO_SUM;

begin --main CALC_TOTAL_TIME
    while V_LISTS.NON_EMPTY(V) loop
        PER := V_LISTS.VALUE(V);
        TIMES := CALC_NO_OF_PERIODS (HARMONIC_BLOCK_LENGTH, PER.THE_PERIOD);
        OP_TIME := MULTIPLY_BY_MET (TIMES, V_LISTS.VALUE(V).THE_MET);
        TOTAL_TIME := ADD_TO_SUM (OP_TIME);
        if TOTAL_TIME > FLOAT(HARMONIC_BLOCK_LENGTH) then
            raise BAD_TOTAL_TIME;
        else
            V_LISTS.NEXT(V);
        end if;
    end loop;

exception
    when BAD_TOTAL_TIME =>
        TEST_VERIFIED := FALSE;
        TEXT_IO.PUT("The total execution time of the operators exceeds ");
        TEXT_IO.PUT_LINE("the HARMONIC_BLOCK_LENGTH");
        TEXT_IO.NEW_LINE;
end CALC_TOTAL_TIME;

procedure CALC_HALF_PERIODS (INPUT_LIST : in V_LISTS.LIST) is

    V : V_LISTS.LIST := INPUT_LIST;
    HALF_PERIOD : FLOAT;
    FAIL_HALF_PERIOD : exception;

    function DIVIDE_PERIOD_BY_2 (THE_PERIOD : in VALUE) return FLOAT is
    begin
        return FLOAT(THE_PERIOD) / 2.0;
    end DIVIDE_PERIOD_BY_2;

```

```

begin --main CALC_HALF_PERIODS;
while V_LISTS.NON_EMPTY(V) loop
  HALF_PERIOD := DIVIDE_PERIOD_BY_2(V_LISTS.VALUE(V).THE_PERIOD);
  if FLOAT(V_LISTS.VALUE(V).THE_MET) > HALF_PERIOD then
    Exception_Operator := V_LISTS.VALUE(V).THE_OPERATOR_ID;
    raise FAIL_HALF_PERIOD;
  else
    V_LISTS.NEXT(V);
  end if;
end loop;

exception
when FAIL_HALF_PERIOD =>
  TEST_VERIFIED := FALSE;
  TEXT_IO.PUT ("The MET of Operator ");
  VARSTRING.PUT (Exception_Operator);
  TEXT_IO.PUT_LINE (" is greater than half of its period.");
end CALC_HALF_PERIODS;

procedure CALC_RATIO_SUM (INPUT_LIST : in V_LISTS.LIST) is
  V : V_LISTS.LIST := INPUT_LIST;
  RATIO : FLOAT;
  RATIO_SUM : FLOAT := 0.0;
  THE_MET : VALUE;
  THE_PERIOD : VALUE;
  RATIO_TOO_BIG : exception;

function DIVIDE_MET_BY_PERIOD (THE_MET : in VALUE;
  THE_PERIOD : in VALUE) return FLOAT is
begin
  return FLOAT(THE_MET) / FLOAT(THE_PERIOD);
end DIVIDE_MET_BY_PERIOD;

function ADD_TO_TIME (RATIO : in FLOAT) return FLOAT is
begin
  return RATIO_SUM + RATIO;
end ADD_TO_TIME;

begin --main CALC_RATIO_SUM
while V_LISTS.NON_EMPTY(V) loop
  THE_MET := V_LISTS.VALUE(V).THE_MET;
  THE_PERIOD := V_LISTS.VALUE(V).THE_PERIOD;
  RATIO := DIVIDE_MET_BY_PERIOD(THE_MET,THE_PERIOD);
  RATIO_SUM := ADD_TO_TIME(RATIO);
  V_LISTS.NEXT(V);
end loop;
if RATIO_SUM - 0.5 > 0.00000001 then
  raise RATIO_TOO_BIG;
end if;

exception
when RATIO_TOO_BIG =>
  TEST_VERIFIED := FALSE;
  TEXT_IO.PUT ("The total MET/PERIOD ratio sum of operators is ");
  TEXT_IO.PUT_LINE ("greater than 0.5");
end CALC_RATIO_SUM;

begin --main TEST_DATA
  CALC_TOTAL_TIME(INPUT_LIST, HARMONIC_BLOCK_LENGTH);
  CALC_HALF_PERIODS(INPUT_LIST);

```

```
CALC_RATIO_SUM(INPUT_LIST);  
end TEST_DATA;  
end FRONT_END;
```

--\* This package is a generic priority queue. It requires three parameters to be  
 --\* instantiated: A type of element to be stored in the priority queue, a value  
 --\* to order the queue by, and a function to order the queue with.

generic

type ELEMENT\_1 is private;  
 type ELEMENT\_2 is private;  
 with function ORDER\_QUEUE (VALUE\_1 : in ELEMENT\_2;  
                               VALUE\_2 : in ELEMENT\_2) return BOOLEAN;

package PRIORITY\_QUEUES is

type NODE;  
 type LINK is access NODE;  
 type NODE is  
 record  
   CONTENT                      : ELEMENT\_1;  
   VALUE                       : ELEMENT\_2;  
   NEXT                       : LINK;  
 end record;

function INITIALIZE\_PRIORITY\_QUEUE return LINK;

procedure INSERT\_IN\_PRIORITY\_QUEUE (ITEM              : in ELEMENT\_1;  
                                   ORDER\_VALUE      : in ELEMENT\_2;  
                                   QUEUE             : in out LINK);

function READ\_BEST\_FROM\_PRIORITY\_QUEUE (L: in LINK) return ELEMENT\_1;  
 --\* This function reads the head of the queue without removing the item

procedure REMOVE\_BEST\_FROM\_PRIORITY\_QUEUE (L: in out LINK);

function NON\_EMPTY(L : in LINK) return BOOLEAN;

end PRIORITY\_QUEUES;

with UNCHECKED\_DEALLOCATION;

package body PRIORITY\_QUEUES is

procedure FREE is new UNCHECKED\_DEALLOCATION(NODE, LINK);

function INITIALIZE\_PRIORITY\_QUEUE return LINK is

  L                              : LINK := null;  
 begin  
   return L;  
 end INITIALIZE\_PRIORITY\_QUEUE;

procedure INSERT\_IN\_PRIORITY\_QUEUE (ITEM: in ELEMENT\_1;  
   ORDER\_VALUE                  : in ELEMENT\_2;  
   QUEUE                       : in out LINK) is  
   FRONT                       : LINK := QUEUE;  
   PREVIOUS                     : LINK := null;  
   T                            : LINK := new NODE;  
   OP\_INSERTED                  : BOOLEAN := false;  
   NEW\_FRONT                    : BOOLEAN := true;

```

begin
  T.CONTENT := ITEM;
  T.VALUE := ORDER_VALUE;
  while QUEUE /= null loop
    if ORDER_QUEUE(ORDER_VALUE, QUEUE.VALUE) then
      if PREVIOUS /= null then
        PREVIOUS.NEXT := T;
      end if;
      T.NEXT := QUEUE;
      OP_INSERTED := true;
      exit;
    end if;
    PREVIOUS := QUEUE;
    NEW_FRONT := false;
    QUEUE := QUEUE.NEXT;
  end loop;
  if not OP_INSERTED and FRONT /= null then
    PREVIOUS.NEXT := T;
  end if;
  if NEW_FRONT then
    QUEUE := T;
  else
    QUEUE := FRONT;
  end if;
end INSERT_IN_PRIORITY_QUEUE;

function READ_BEST_FROM_PRIORITY_QUEUE (L : in LINK) return ELEMENT_1 is
  BEST      : ELEMENT_1;

begin
  BEST := L.CONTENT;
  return BEST;
end READ_BEST_FROM_PRIORITY_QUEUE;

procedure REMOVE_BEST_FROM_PRIORITY_QUEUE (L: in out LINK) is
  TEMP: LINK := L;

begin
  L := L.NEXT;
  FREE(TEMP);
end REMOVE_BEST_FROM_PRIORITY_QUEUE;

function NON_EMPTY(L : in LINK) return BOOLEAN is
begin
  if L = null then
    return FALSE;
  else
    return TRUE;
  end if;
end NON_EMPTY;

end PRIORITY_QUEUES;

```

with DATA; use DATA;

package SCHEDULER is

```
procedure EARLIEST_START(TOP_SORT          : in NODE_LIST.LIST;
                        AGENDA             : in out SCHEDULE_INPUTS_LIST.LIST;
                        COUNT               : in INTEGER;
                        H_B_LENGTH         : in INTEGER;
                        VALID_SCHEDULE      : in out BOOLEAN);

procedure EARLIEST_DEADLINE(TOP_SORT        : in NODE_LIST.LIST;
                           AGENDA          : in out SCHEDULE_INPUTS_LIST.LIST;
                           COUNT            : in INTEGER;
                           H_B_LENGTH      : in INTEGER;
                           VALID_SCHEDULE   : in out BOOLEAN);

procedure EXHAUSTIVE_ENUMERATION ( TOP_SORT: in NODE_LIST.LIST;
                                   AGENDA : in out SCHEDULE_INPUTS_LIST.LIST;
                                   OP_COUNT : in INTEGER;
                                   H_B_LENGTH : in INTEGER;
                                   VALID_SCHEDULE : in out BOOLEAN);

procedure CREATE_STATIC_SCHEDULE (OPERATOR_LIST : in NODE_LIST.LIST;
                                  THE_SCHEDULE_INPUTS : in SCHEDULE_INPUTS_LIST.LIST;
                                  HARMONIC_BLOCK_LENGTH : in INTEGER);

end SCHEDULER;
```

```

with TEXT_IO;
with DATA; use DATA;
with SEQUENCES;
with FRONT_END; use FRONT_END;
with PRIORITY_QUEUES;
with DIAGNOSTICS;

```

package body SCHEDULER is

```

procedure EARLIEST_START(TOP_SORT      : in NODE_LIST.LIST;
                          AGENDA       : in out SCHEDULE_INPUTS_LIST.LIST;
                          COUNT        : in INTEGER;
                          H_B_LENGTH   : in INTEGER;
                          VALID_SCHEDULE : in out BOOLEAN) is

```

```

package int_io is new TEXT_IO.integer_io(integer);
use int_io;

```

```

package EST_PRIORITY_QUEUES is new PRIORITY_QUEUES(DATA.SCHEDULE_INPUTS,
                                                    DATA.LOWERS,
                                                    "<");

```

```

PRIORITY_QUEUE      : EST_PRIORITY_QUEUES.LINK := null;
REV_AGENDA          : SCHEDULE_INPUTS_LIST.LIST;
T_SORT              : NODE_LIST.LIST := TOP_SORT;
NEW_NODE            : SCHEDULE_INPUTS;
BEST_NODE           : SCHEDULE_INPUTS;
ADDL_NODE           : SCHEDULE_INPUTS;
STOP_TIME           : INTEGER := 0;
OP_NUM              : INTEGER;
EST                 : INTEGER;
TEMP                : OPERATOR;

```

```

begin
  VALID_SCHEDULE := true;
  NEW_NODE.THE_OPERATOR := 0;
  NEW_NODE.THE_LOWER := H_B_LENGTH + 10;
  SCHEDULE_INPUTS_LIST.ADD(NEW_NODE, REV_AGENDA);
  NEW_NODE.THE_LOWER := 0;
  NODE_LIST.NEXT(T_SORT);
  while NODE_LIST.NON_EMPTY(T_SORT) or
    EST_PRIORITY_QUEUES.NON_EMPTY(PRIORITY_QUEUE) loop
    if NODE_LIST.NON_EMPTY(T_SORT) then
      OP_NUM := DATA.NODE_LIST.VALUE(T_SORT);
      TEMP := NEW_GRAPH.OP_RETURN(OP_NUM);
      NEW_NODE.THE_OPERATOR := OP_NUM;
    end if;
    if EST_PRIORITY_QUEUES.NON_EMPTY(PRIORITY_QUEUE) then
      BEST_NODE := EST_PRIORITY_QUEUES.READ_BEST_FROM_PRIORITY_QUEUE(PRIORITY_QUEUE);
    end if;
    if BEST_NODE.THE_LOWER < STOP_TIME and EST_PRIORITY_QUEUES.NON_EMPTY(PRIORITY_QUEUE) then
      NEW_NODE.THE_OPERATOR := BEST_NODE.THE_OPERATOR;
      NEW_NODE.THE_LOWER := BEST_NODE.THE_LOWER;
      NEW_NODE.THE_START := STOP_TIME;
      TEMP := NEW_GRAPH.OP_RETURN(NEW_NODE.THE_OPERATOR);
      STOP_TIME := STOP_TIME + TEMP.THE_MET;
    end if;
  end while;

```

```

NEW_NODE.THE_STOP := STOP_TIME;
NEW_NODE.THE_INSTANCE := BEST_NODE.THE_INSTANCE + 1;
EST := NEW_NODE.THE_LOWER + TEMP.THE_PERIOD;
if EST + TEMP.THE_MET <= H_B_LENGTH then
  ADDL_NODE.THE_OPERATOR := NEW_NODE.THE_OPERATOR;
  ADDL_NODE.THE_LOWER := EST;
  ADDL_NODE.THE_INSTANCE := NEW_NODE.THE_INSTANCE;
  EST_PRIORITY_QUEUES.INSERT_IN_PRIORITY_QUEUE(ADDL_NODE, ADDL_NODE.THE_LOWER, PRIORITY_QUEUE);
end if;
EST_PRIORITY_QUEUES.REMOVE_BEST_FROM_PRIORITY_QUEUE(PRIORITY_QUEUE);
elsif not NODE_LIST.NON_EMPTY(T_SORT) then
  NEW_NODE.THE_OPERATOR := BEST_NODE.THE_OPERATOR;
  NEW_NODE.THE_LOWER := BEST_NODE.THE_LOWER;
  if NEW_NODE.THE_LOWER > STOP_TIME then
    NEW_NODE.THE_START := NEW_NODE.THE_LOWER;
  else
    NEW_NODE.THE_START := STOP_TIME;
  end if;
  TEMP := NEW_GRAPH.OP_RETURN(NEW_NODE.THE_OPERATOR);
  STOP_TIME := NEW_NODE.THE_START + TEMP.THE_MET;
  NEW_NODE.THE_STOP := STOP_TIME;
  NEW_NODE.THE_INSTANCE := BEST_NODE.THE_INSTANCE + 1;
  EST := NEW_NODE.THE_LOWER + TEMP.THE_PERIOD;
  if EST + TEMP.THE_MET <= H_B_LENGTH then
    ADDL_NODE.THE_OPERATOR := NEW_NODE.THE_OPERATOR;
    ADDL_NODE.THE_LOWER := EST;
    ADDL_NODE.THE_INSTANCE := NEW_NODE.THE_INSTANCE;
    EST_PRIORITY_QUEUES.INSERT_IN_PRIORITY_QUEUE(ADDL_NODE, ADDL_NODE.THE_LOWER, PRIORITY_QUEUE);
  end if;
  EST_PRIORITY_QUEUES.REMOVE_BEST_FROM_PRIORITY_QUEUE(PRIORITY_QUEUE);
else --* Scheduling Initial Set of Operators
  NEW_NODE.THE_START := STOP_TIME;
  TEMP := NEW_GRAPH.OP_RETURN(NEW_NODE.THE_OPERATOR);
  STOP_TIME := STOP_TIME + TEMP.THE_MET;
  NEW_NODE.THE_STOP := STOP_TIME;
  NEW_NODE.THE_INSTANCE := 1;
  EST := NEW_NODE.THE_START + TEMP.THE_PERIOD;
  if EST + TEMP.THE_MET <= H_B_LENGTH or else NEW_NODE.THE_START >= TEMP.THE_PERIOD then
    ADDL_NODE.THE_OPERATOR := NEW_NODE.THE_OPERATOR;
    ADDL_NODE.THE_LOWER := EST;
    ADDL_NODE.THE_INSTANCE := 1;
    EST_PRIORITY_QUEUES.INSERT_IN_PRIORITY_QUEUE(ADDL_NODE, ADDL_NODE.THE_LOWER, PRIORITY_QUEUE);
  end if;
  NODE_LIST.NEXT(T_SORT);
end if;
if NEW_NODE.THE_STOP > H_B_LENGTH then
  VALID_SCHEDULE := false;
end if;
SCHEDULE_INPUTS_LIST.ADD(NEW_NODE, REV_AGENDA);
NEW_NODE.THE_LOWER := 0;
end loop;
SCHEDULE_INPUTS_LIST.LIST_REVERSE(REV_AGENDA, AGENDA);
SCHEDULE_INPUTS_LIST.FREE_LIST(REV_AGENDA);
end EARLIEST_START;

procedure EARLIEST_DEADLINE(TOP_SORT      : in NODE_LIST.LIST;
                             AGENDA       : in out SCHEDULE_INPUTS_LIST.LIST;
                             COUNT        : in INTEGER;
                             H_B_LENGTH   : in INTEGER;
                             VALID_SCHEDULE : in out BOOLEAN) is

```

```
package int_io is new TEXT_IO.integer_io(integer);
use int_io;
```

```
package EDL_PRIORITY_QUEUES is new PRIORITY_QUEUES(DATA.SCHEDULE_INPUTS,
                                                    DATA.UPPERS,
                                                    "<");
```

```
PRIORITY_QUEUE      : EDL_PRIORITY_QUEUES.LINK := null;
REV_AGENDA          : SCHEDULE_INPUTS_LIST.LIST;
T_SORT              : NODE_LIST.LIST := TOP_SORT;
NEW_NODE            : SCHEDULE_INPUTS;
BEST_NODE           : SCHEDULE_INPUTS;
ADDL_NODE           : SCHEDULE_INPUTS;
STOP_TIME           : INTEGER := 0;
OP_NUM              : INTEGER;
EST                 : INTEGER;
TEMP                : OPERATOR;
```

```
begin
  VAI.ID_SCHEDULE := true;
  NEW_NODE.THE_OPERATOR := 0;
  NEW_NODE.THE_LOWER := H_B_LENGTH + 10;
  SCHEDULE_INPUTS_LIST.ADD(NEW_NODE, REV_AGENDA);
  NEW_NODE.THE_LOWER := 0;
  NODE_LIST.NEXT(T_SORT);
  while NODE_LIST.NON_EMPTY(T_SORT) or EDL_PRIORITY_QUEUES.NON_EMPTY(PRIORITY_QUEUE) loop
    if NODE_LIST.NON_EMPTY(T_SORT) then
      OP_NUM := DATA.NODE_LIST.VALUE(T_SORT);
      TEMP := NEW_GRAPH.OP_RETURN(OP_NUM);
      NEW_NODE.THE_OPERATOR := OP_NUM;
    end if;
    if EDL_PRIORITY_QUEUES.NON_EMPTY(PRIORITY_QUEUE) then
      BEST_NODE := EDL_PRIORITY_QUEUES.READ_BEST_FROM_PRIORITY_QUEUE(PRIORITY_QUEUE);
    end if;
    if BEST_NODE.THE_LOWER < STOP_TIME and EDL_PRIORITY_QUEUES.NON_EMPTY(PRIORITY_QUEUE) then
      NEW_NODE.THE_OPERATOR := BEST_NODE.THE_OPERATOR;
      NEW_NODE.THE_LOWER := BEST_NODE.THE_LOWER;
      NEW_NODE.THE_UPPER := BEST_NODE.THE_UPPER;
      NEW_NODE.THE_START := STOP_TIME;
      TEMP := NEW_GRAPH.OP_RETURN(NEW_NODE.THE_OPERATOR);
      STOP_TIME := STOP_TIME + TEMP.THE_MET;
      NEW_NODE.THE_STOP := STOP_TIME;
      NEW_NODE.THE_INSTANCE := BEST_NODE.THE_INSTANCE + 1;
      EST := NEW_NODE.THE_LOWER + TEMP.THE_PERIOD;
      if EST + TEMP.THE_MET <= H_B_LENGTH then
        ADDL_NODE.THE_OPERATOR := NEW_NODE.THE_OPERATOR;
        ADDL_NODE.THE_LOWER := EST;
        ADDL_NODE.THE_INSTANCE := NEW_NODE.THE_INSTANCE;
        if TEMP.THE_WITHIN /= 0 then
          ADDL_NODE.THE_UPPER := EST + TEMP.THE_WITHIN - TEMP.THE_MET;
        else
          ADDL_NODE.THE_UPPER := EST + TEMP.THE_PERIOD - TEMP.THE_MET;
        end if;
        EDL_PRIORITY_QUEUES.INSERT_IN_PRIORITY_QUEUE(ADDL_NODE, ADDL_NODE.THE_UPPER, PRIORITY_QUEUE);
      end if;
      EDL_PRIORITY_QUEUES.REMOVE_BEST_FROM_PRIORITY_QUEUE(PRIORITY_QUEUE);
    elsif not NODE_LIST.NON_EMPTY(T_SORT) then
      NEW_NODE.THE_OPERATOR := BEST_NODE.THE_OPERATOR;
      NEW_NODE.THE_LOWER := BEST_NODE.THE_LOWER;
      NEW_NODE.THE_UPPER := BEST_NODE.THE_UPPER;
```

```

if NEW_NODE.THE_LOWER > STOP_TIME then
  NEW_NODE.THE_START := NEW_NODE.THE_LOWER;
else
  NEW_NODE.THE_START := STOP_TIME;
end if;
TEMP := NEW_GRAPH.OP_RETURN(NEW_NODE.THE_OPERATOR);
STOP_TIME := NEW_NODE.THE_START + TEMP.THE_MET;
NEW_NODE.THE_STOP := STOP_TIME;
NEW_NODE.THE_INSTANCE := BEST_NODE.THE_INSTANCE + 1;
EST := NEW_NODE.THE_LOWER + TEMP.THE_PERIOD;
if EST + TEMP.THE_MET <= H_B_LENGTH then
  ADDL_NODE.THE_OPERATOR := NEW_NODE.THE_OPERATOR;
  ADDL_NODE.THE_LOWER := EST;
  ADDL_NODE.THE_INSTANCE := NEW_NODE.THE_INSTANCE;
  if TEMP.THE_WITHIN /= 0 then
    ADDL_NODE.THE_UPPER := EST + TEMP.THE_WITHIN - TEMP.THE_MET;
  else
    ADDL_NODE.THE_UPPER := EST + TEMP.THE_PERIOD - TEMP.THE_MET;
  end if;
  EDL_PRIORITY_QUEUES.INSERT_IN_PRIORITY_QUEUE(ADDL_NODE, ADDL_NODE.THE_UPPER, PRIORITY_QUEUE);
end if;
EDL_PRIORITY_QUEUES.REMOVE_BEST_FROM_PRIORITY_QUEUE(PRIORITY_QUEUE);
else --* Scheduling Initial Set of Operators
  NEW_NODE.THE_START := STOP_TIME;
  TEMP := NEW_GRAPH.OP_RETURN(NEW_NODE.THE_OPERATOR);
  STOP_TIME := STOP_TIME + TEMP.THE_MET;
  NEW_NODE.THE_STOP := STOP_TIME;
  NEW_NODE.THE_INSTANCE := 1;
  EST := NEW_NODE.THE_START + TEMP.THE_PERIOD;
  if EST + TEMP.THE_MET <= H_B_LENGTH or else NEW_NODE.THE_START >= TEMP.THE_PERIOD then
    ADDL_NODE.THE_OPERATOR := NEW_NODE.THE_OPERATOR;
    ADDL_NODE.THE_LOWER := EST;
    ADDL_NODE.THE_INSTANCE := 1;
    if TEMP.THE_WITHIN /= 0 then
      ADDL_NODE.THE_UPPER := EST + TEMP.THE_WITHIN - TEMP.THE_MET;
    else
      ADDL_NODE.THE_UPPER := EST + TEMP.THE_PERIOD - TEMP.THE_MET;
    end if;
    EDL_PRIORITY_QUEUES.INSERT_IN_PRIORITY_QUEUE(ADDL_NODE, ADDL_NODE.THE_UPPER, PRIORITY_QUEUE);
  end if;
  NODE_LIST.NEXT(T_SORT);
end if;
if NEW_NODE.THE_STOP > H_B_LENGTH then
  VALID_SCHEDULE := false;
end if;
SCHEDULE_INPUTS_LIST.ADD(NEW_NODE, REV_AGENDA);
NEW_NODE.THE_LOWER := 0;
NEW_NODE.THE_UPPER := 0;
end loop;
SCHEDULE_INPUTS_LIST.LIST_REVERSE(REV_AGENDA, AGENDA);
SCHEDULE_INPUTS_LIST.FREE_LIST(REV_AGENDA);
end EARLIEST_DEADLINE;

procedure EXHAUSTIVE_ENUMERATION ( TOP_SORT      : in NODE_LIST.LIST;
                                   AGENDA       : in out SCHEDULE_INPUTS_LIST.LIST;
                                   OP_COUNT      : in INTEGER;
                                   H_B_LENGTH    : in INTEGER;
                                   VALID_SCHEDULE: in out BOOLEAN) is

package int_io is new TEXT_IO.integer_io(integer);
use int_io;

```

```

TEMP                : SCHEDULE_INPUTS_LIST.LIST;
COUNT              : INTEGER := 0;

procedure TOP_SORTS (AGENDA      : in out SCHEDULE_INPUTS_LIST.LIST;
COUNT      : in INTEGER;
VALID_SCHEDULE : in out BOOLEAN;
BLOCK_LENGTH : in INTEGER) is

type VECTOR is array (1..COUNT) of INTEGER;
LOC          : VECTOR;
type SCHEDULE_ARRAY is array (1..COUNT) of SCHEDULE_INPUTS;
P_ARRAY      : SCHEDULE_ARRAY;
type TIME_RECORD is
  record
    OPERATOR      : INTEGER;
    TIME_1        : INTEGER;
    TIME_2        : INTEGER;
  end record;
type TIME_ARRAY is array (1..OP_COUNT+1) of TIME_RECORD;
START_TIME_ARRAY : TIME_ARRAY;

HOLD            : SCHEDULE_INPUTS;
TEMP            : SCHEDULE_INPUTS_LIST.LIST := AGENDA;
INDEX           : INTEGER := 1;
INDEX_1         : INTEGER := 1;
NODE_1          : INTEGER;
NODE_2          : INTEGER;
MET             : INTEGER;
POSITION        : INTEGER;
STOP_TIME       : INTEGER;
HOLD_STOP_TIME  : INTEGER;
START_TIME      : INTEGER;
i               : INTEGER := COUNT;
INITIAL_START_TIME : INTEGER;
LOWER_BOUND     : INTEGER;
ADJUSTED        : BOOLEAN := false;

begin
  while SCHEDULE_INPUTS_LIST.NON_EMPTY(TEMP) loop
    P_ARRAY(INDEX) := SCHEDULE_INPUTS_LIST.VALUE(TEMP);
    LOC(INDEX) := INDEX;
    INDEX := INDEX + 1;
    if SCHEDULE_INPUTS_LIST.VALUE(TEMP).THE_INSTANCE = 1 then
      START_TIME_ARRAY(INDEX_1).OPERATOR := SCHEDULE_INPUTS_LIST.VALUE(TEMP).THE_OPERATOR;
      START_TIME_ARRAY(INDEX_1).TIME_1 := SCHEDULE_INPUTS_LIST.VALUE(TEMP).THE_START;
      START_TIME_ARRAY(INDEX_1).TIME_2 := SCHEDULE_INPUTS_LIST.VALUE(TEMP).THE_STOP;
      INDEX_1 := INDEX_1 + 1;
    end if;
    SCHEDULE_INPUTS_LIST.NEXT(TEMP);
  end loop;
  while i > 1 loop
    NODE_1 := P_ARRAY(LOC(i)).THE_OPERATOR;
    NODE_2 := P_ARRAY(LOC(i)-1).THE_OPERATOR;
    if not FRONT_END.NEW_GRAPH.IS_PARENT(NODE_2, NODE_1) then
      HOLD := P_ARRAY(LOC(i));
      if i > 2 then
        STOP_TIME := P_ARRAY(LOC(i)-1).THE_START;
      else
        STOP_TIME := 0;
      end if;
    end if;
  end loop;
end TOP_SORTS;

```

```

end if;
P_ARRAY(LOC(i)) := P_ARRAY(LOC(i)-1);
P_ARRAY(LOC(i)-1) := HOLD;
STOP_TIME := 0;
for i in 1..COUNT loop
  if P_ARRAY(i).THE_INSTANCE = 1 then
    for j in 1..OP_COUNT+1 loop
      if P_ARRAY(i).THE_OPERATOR = START_TIME_ARRAY(j).OPERATOR then
        MET := START_TIME_ARRAY(j).TIME_2 - START_TIME_ARRAY(j).TIME_1;
        P_ARRAY(i).THE_START := STOP_TIME;
        START_TIME_ARRAY(j).TIME_1 := STOP_TIME;
        STOP_TIME := STOP_TIME + MET;
        START_TIME_ARRAY(j).TIME_2 := STOP_TIME;
        P_ARRAY(i).THE_STOP := STOP_TIME;
        exit;
      end if;
    end loop;
  else
    for l in 1..OP_COUNT+1 loop
      if P_ARRAY(i).THE_OPERATOR = START_TIME_ARRAY(l).OPERATOR then
        INITIAL_START_TIME := START_TIME_ARRAY(l).TIME_1;
        exit;
      end if;
    end loop;
    LOWER_BOUND := INITIAL_START_TIME + ((P_ARRAY(i).THE_INSTANCE-1) *
    NEW_GRAPH.OP_RETURN(P_ARRAY(i).THE_OPERATOR).THE_PERIOD);
    if LOWER_BOUND > STOP_TIME then
      START_TIME := LOWER_BOUND;
    else
      START_TIME := STOP_TIME;
    end if;
    MET := P_ARRAY(i).THE_STOP - P_ARRAY(i).THE_START;
    P_ARRAY(i).THE_START := START_TIME;
    STOP_TIME := START_TIME + MET;
    P_ARRAY(i).THE_STOP := STOP_TIME;
    P_ARRAY(i).THE_LOWER := LOWER_BOUND;
  end if;
end loop;
if P_ARRAY(COUNT).THE_STOP <= BLOCK_LENGTH then
  VALID_SCHEDULE := true;
  exit;
end if;
LOC(i) := LOC(i)-1;
i := COUNT;
else
  if LOC(i) /= i then
    HOLD := P_ARRAY(LOC(i));
    for j in LOC(i) ..i-1 loop
      P_ARRAY(j) := P_ARRAY(j+1);
    end loop;
    P_ARRAY(i) := HOLD;
    LOC(i) := i;
    STOP_TIME := 0;
    for i in 1..COUNT loop
      if P_ARRAY(i).THE_INSTANCE = 1 then
        for j in 1..OP_COUNT+1 loop
          if P_ARRAY(i).THE_OPERATOR = START_TIME_ARRAY(j).OPERATOR then
            MET := START_TIME_ARRAY(j).TIME_2 - START_TIME_ARRAY(j).TIME_1;
            P_ARRAY(i).THE_START := STOP_TIME;
            START_TIME_ARRAY(j).TIME_1 := STOP_TIME;
            STOP_TIME := STOP_TIME + MET;
          end if;
        end loop;
      end if;
    end loop;
  end if;
end if;

```

```

        START_TIME_ARRAY(j).TIME_2 := STOP_TIME;
        P_ARRAY(i).THE_STOP := STOP_TIME;
        exit;
    end if;
end loop;
else
    for l in 1..OP_COUNT+1 loop
        if P_ARRAY(i).THE_OPERATOR = START_TIME_ARRAY(l).OPERATOR then
            INITIAL_START_TIME := START_TIME_ARRAY(l).TIME_1;
            exit;
        end if;
    end loop;
    LOWER_BOUND := INITIAL_START_TIME + ((P_ARRAY(i).THE_INSTANCE-1) *
    NEW_GRAPH.OP_RETURN(P_ARRAY(i).THE_OPERATOR).THE_PERIOD);
    if LOWER_BOUND > STOP_TIME then
        START_TIME := LOWER_BOUND;
    else
        START_TIME := STOP_TIME;
    end if;
    MET := P_ARRAY(i).THE_STOP - P_ARRAY(i).THE_START;
    P_ARRAY(i).THE_START := START_TIME;
    STOP_TIME := START_TIME + MET;
    P_ARRAY(i).THE_STOP := STOP_TIME;
    P_ARRAY(i).THE_LOWER := LOWER_BOUND;
end if;
end loop;
end if;
i := i-1;
end if;
end loop;
SCHEDULE_INPUTS_LIST.FREE_LIST(AGENDA);
for l in reverse 1..COUNT loop
    SCHEDULE_INPUTS_LIST.ADD(P_ARRAY(l), AGENDA);
end loop;
end TOP_SORTS;

begin
    EARLIEST_START(TOP_SORT,AGENDA,OP_COUNT,H_B_LENGTH, VALID_SCHEDULE);
    TEMP := AGENDA;
    while SCHEDULE_INPUTS_LIST.NON_EMPTY(TEMP) loop
        COUNT := COUNT + 1;
        SCHEDULE_INPUTS_LIST.NEXT(TEMP);
    end loop;
    TOP_SORTS(AGENDA, COUNT, VALID_SCHEDULE,H_B_LENGTH);
end EXHAUSTIVE_ENUMERATION;

procedure CREATE_STATIC_SCHEDULE (OPERATOR_LIST      : in NODE_LIST.LIST;
                                  THE_SCHEDULE_INPUTS : in SCHEDULE_INPUTS_LIST.LIST;
                                  HARMONIC_BLOCK_LENGTH : in INTEGER) is
    -- creates the static schedule output and prints to "ss.a" file.
    OP_LIST      : NODE_LIST.LIST := OPERATOR_LIST;
    S            : SCHEDULE_INPUTS_LIST.LIST := THE_SCHEDULE_INPUTS;
    SCHEDULE     : TEXT_IO.FILE_TYPE;
    OUTPUT       : TEXT_IO.FILE_MODE := TEXT_IO.OUT_FILE;
    COUNTER      : INTEGER := 1;
    TEMPVAR      : OPERATOR_ID;

package VALUE_IO is new TEXT_IO.INTEGER_IO(VALUE);

```

```

use VALUE_IO;
package F_IO is new TEXT_IO.FLOAT_IO(FLOAT);
package INTEGERIO is new TEXT_IO.INTEGER_IO(INTEGER);
use INTEGERIO;

begin
  TEXT_IO.CREATE(SCHEDULE, OUTPUT, "ss.a");
  TEXT_IO.PUT_LINE(SCHEDULE, "with GLOBAL_DECLARATIONS; use GLOBAL_DECLARATIONS;");
  TEXT_IO.PUT_LINE(SCHEDULE, "with DS_DEBUG_PKG; use DS_DEBUG_PKG;");
  TEXT_IO.PUT_LINE(SCHEDULE, "with TL; use TL;");
  TEXT_IO.PUT_LINE(SCHEDULE, "with DS_PACKAGE; use DS_PACKAGE;");
  TEXT_IO.PUT(SCHEDULE, "with PRIORITY_DEFINITIONS;");
  TEXT_IO.PUT_LINE(SCHEDULE, "use PRIORITY_DEFINITIONS;");
  TEXT_IO.PUT_LINE(SCHEDULE, "with CALENDAR; use CALENDAR;");
  TEXT_IO.PUT_LINE(SCHEDULE, "with TEXT_IO; use TEXT_IO;");
  TEXT_IO.PUT_LINE(SCHEDULE, "procedure STATIC_SCHEDULE is");
  NODE_LIST.NEXT(OP_LIST); --* Bypass dummy start node
  while NODE_LIST.NON_EMPTY(OP_LIST) loop
    TEXT_IO.SET_COL(SCHEDULE, 3);
    VARSTRING.PUT(SCHEDULE, NEW_GRAPH.OP_RETURN(NODE_LIST.VALUE(OP_LIST)).THE_OPERATOR_ID);
    TEXT_IO.PUT_LINE(SCHEDULE, "_TIMING_ERROR : exception;");
    NODE_LIST.NEXT(OP_LIST);
  end loop;

  TEXT_IO.SET_COL(SCHEDULE, 3);
  TEXT_IO.PUT_LINE(SCHEDULE, "task type SCHEDULE_TYPE is");
  TEXT_IO.SET_COL(SCHEDULE, 5);
  TEXT_IO.PUT_LINE(SCHEDULE, "pragma priority (STATIC_SCHEDULE_PRIORITY);");
  TEXT_IO.SET_COL(SCHEDULE, 3);
  TEXT_IO.PUT_LINE(SCHEDULE, "end SCHEDULE_TYPE;");
  TEXT_IO.SET_COL(SCHEDULE, 3);
  TEXT_IO.PUT_LINE(SCHEDULE, "for SCHEDULE_TYPE'SORAGE_SIZE use 200_000;");
  TEXT_IO.SET_COL(SCHEDULE, 3);
  TEXT_IO.PUT_LINE(SCHEDULE, "SCHEDULE : SCHEDULE_TYPE;");
  TEXT_IO.NEW_LINE(SCHEDULE);
  TEXT_IO.SET_COL(SCHEDULE, 3);
  TEXT_IO.PUT_LINE(SCHEDULE, "task body SCHEDULE_TYPE is");
  TEXT_IO.PUT(SCHEDULE, " PERIOD : duration := duration(");
  F_IO.PUT(SCHEDULE, FLOAT(HARMONIC_BLOCK_LENGTH)/1000.0);
  TEXT_IO.PUT_LINE(SCHEDULE, ");");
  S := THE_SCHEDULE_INPUTS;
  SCHEDULE_INPUTS_LIST.NEXT(S); --* Bypass dummy start node.
  while SCHEDULE_INPUTS_LIST.NON_EMPTY(S) loop
    TEXT_IO.SET_COL(SCHEDULE, 5);
    VARSTRING.PUT(SCHEDULE,
FRONT_END.NEW_GRAPH.OP_RETURN(SCHEDULE_INPUTS_LIST.VALUE(S).THE_OPERATOR_ID);
    TEXT_IO.PUT(SCHEDULE, "_STOP_TIME");
    INTEGERIO.PUT(SCHEDULE, COUNTER, 1);
    TEXT_IO.PUT(SCHEDULE, " : duration := duration(");
    F_IO.PUT(SCHEDULE, FLOAT(SCHEDULE_INPUTS_LIST.VALUE(S).THE_STOP)/1000.0);
    TEXT_IO.PUT_LINE(SCHEDULE, ");");
    SCHEDULE_INPUTS_LIST.NEXT(S);
    COUNTER := COUNTER + 1;
  end loop;
  TEXT_IO.SET_COL(SCHEDULE, 5);
  TEXT_IO.PUT_LINE(SCHEDULE, "SLACK_TIME : duration;");
  TEXT_IO.SET_COL(SCHEDULE, 5);
  TEXT_IO.PUT_LINE(SCHEDULE, "START_OF_PERIOD : time := clock;");
  TEXT_IO.SET_COL(SCHEDULE, 5);
  TEXT_IO.PUT_LINE(SCHEDULE, "CURRENT_TIME : duration;");

```

```

TEXT_IO.PUT_LINE(SCHEDULE, "begin");
TEXT_IO.PUT_LINE(SCHEDULE, " loop");
TEXT_IO.SET_COL(SCHEDULE, 5);
TEXT_IO.PUT(SCHEDULE, "begin");

S := THE_SCHEDULE_INPUTS;
SCHEDULE_INPUTS_LIST.NEXT(S); --* Bypass dummy start node.
COUNTER := 1;
while SCHEDULE_INPUTS_LIST.NON_EMPTY(S) loop
    TEXT_IO.SET_COL(SCHEDULE, 7);
    VARSTRING.PUT(SCHEDULE,
FRONT_END.NEW_GRAPH.OP_RETURN(SCHEDULE_INPUTS_LIST.VALUE(S).THE_OPERATO
R).THE_OPERATOR_ID);
    TEXT_IO.PUT_LINE(SCHEDULE, "_DRIVER;");
    TEXT_IO.SET_COL(SCHEDULE, 7);
    TEXT_IO.PUT(SCHEDULE, "SLACK_TIME := START_OF_PERIOD + ");
    VARSTRING.PUT(SCHEDULE,
FRONT_END.NEW_GRAPH.OP_RETURN(SCHEDULE_INPUTS_LIST.VALUE(S).THE_OPERATO
R).THE_OPERATOR_ID);
    TEXT_IO.PUT(SCHEDULE, "_STOP_TIME");
    INTEGERIO.PUT(SCHEDULE, COUNTER, 1);
    TEXT_IO.PUT_LINE(SCHEDULE, " - CLOCK;");
    TEXT_IO.SET_COL(SCHEDULE, 7);
    TEXT_IO.PUT_LINE(SCHEDULE, "if SLACK_TIME >= 0.0 then");
    TEXT_IO.SET_COL(SCHEDULE, 9);
    TEXT_IO.PUT_LINE(SCHEDULE, "delay (SLACK_TIME);");
    TEXT_IO.SET_COL(SCHEDULE, 7);
    TEXT_IO.PUT_LINE(SCHEDULE, "else");
    TEXT_IO.SET_COL(SCHEDULE, 9);
    TEXT_IO.PUT(SCHEDULE, "raise ");
    VARSTRING.PUT(SCHEDULE,
FRONT_END.NEW_GRAPH.OP_RETURN(SCHEDULE_INPUTS_LIST.VALUE(S).THE_OPERATO
R).THE_OPERATOR_ID);
    TEXT_IO.PUT_LINE(SCHEDULE, "_TIMING_ERROR;");
    TEXT_IO.SET_COL(SCHEDULE, 7);
    TEXT_IO.PUT_LINE(SCHEDULE, "end if;");
    TEMPVAR:=
FRONT_END.NEW_GRAPH.OP_RETURN(SCHEDULE_INPUTS_LIST.VALUE(S).THE_OPERATO
R).THE_OPERATOR_ID;
    SCHEDULE_INPUTS_LIST.NEXT(S);
    if SCHEDULE_INPUTS_LIST.NON_EMPTY(S) then
        -- pointer is pointing to the next record after this.
        TEXT_IO.SET_COL(SCHEDULE, 7);
        TEXT_IO.PUT(SCHEDULE, "delay (START_OF_PERIOD + ");
        VARSTRING.PUT(SCHEDULE, TEMPVAR);
        TEXT_IO.PUT(SCHEDULE, "_STOP_TIME");
        INTEGERIO.PUT(SCHEDULE, COUNTER, 1);
        TEXT_IO.PUT_LINE(SCHEDULE, " - CLOCK;");
        TEXT_IO.NEW_LINE(SCHEDULE);
    end if;
    COUNTER := COUNTER + 1;
end loop;

TEXT_IO.SET_COL(SCHEDULE, 7);
TEXT_IO.PUT_LINE(SCHEDULE,
    "START_OF_PERIOD := START_OF_PERIOD + PERIOD;");
TEXT_IO.SET_COL(SCHEDULE, 7);
TEXT_IO.PUT_LINE(SCHEDULE, "delay (START_OF_PERIOD - clock);");

TEXT_IO.SET_COL(SCHEDULE, 7);
TEXT_IO.PUT_LINE(SCHEDULE, "exception");

```

```

OP_LIST := OPERATOR_LIST;
NODE_LIST.NEXT(OP_LIST); --* Bypass dummy start node
COUNTER:= COUNTER - 1;
while NODE_LIST.NON_EMPTY(OP_LIST) loop
    TEXT_IO.SET_COL(SCHEDULE, 9);
    TEXT_IO.PUT(SCHEDULE, "when ");
    VARSTRING.PUT(SCHEDULE,
NEW_GRAPH.OP_RETURN(NODE_LIST.VALUE(OP_LIST)).THE_OPERATOR_ID);
    TEXT_IO.PUT_LINE(SCHEDULE, "_TIMING_ERROR =>");
    TEXT_IO.SET_COL(SCHEDULE, 11);
    TEXT_IO.PUT(SCHEDULE, "PUT_LINE('"'timing error from operator "'");
    VARSTRING.PUT(SCHEDULE,
NEW_GRAPH.OP_RETURN(NODE_LIST.VALUE(OP_LIST)).THE_OPERATOR_ID);
    TEXT_IO.PUT_LINE(SCHEDULE, "'");
    TEXT_IO.PUT_LINE(SCHEDULE, "START_OF_PERIOD := clock;");
    NODE_LIST.NEXT(OP_LIST);
    COUNTER:= COUNTER - 1;
end loop;

TEXT_IO.SET_COL(SCHEDULE, 7);
TEXT_IO.PUT_LINE(SCHEDULE, "end;");
TEXT_IO.SET_COL(SCHEDULE, 5);
TEXT_IO.PUT_LINE(SCHEDULE, "end loop;");
TEXT_IO.SET_COL(SCHEDULE, 3);
TEXT_IO.PUT_LINE(SCHEDULE, "end SCHEDULE_TYPE;");
TEXT_IO.NEW_LINE(SCHEDULE);
TEXT_IO.PUT_LINE(SCHEDULE, "begin");
TEXT_IO.SET_COL(SCHEDULE, 3);
TEXT_IO.PUT_LINE(SCHEDULE, "null;");
TEXT_IO.PUT_LINE(SCHEDULE, "end STATIC_SCHEDULE;");

end CREATE_STATIC_SCHEDULE;

end SCHEDULER;

```

with DATA; use DATA;

package ANNEAL is

    procedure SIMULATED\_ANNEAL (PRECEDENCE\_LIST : in NODE\_LIST\_LIST;  
                                  AGENDA : in out SCHEDULE\_INPUTS\_LIST\_LIST;  
                                  H\_B\_LENGTH : in INTEGER;  
                                  VALID\_SCHEDULE : in out BOOLEAN);

end ANNEAL;

```

with TEXT_IO;
with DIAGNOSTICS;
with RANDOM;
with MATH; --* Necessary for EXP function.
with DATA; use DATA;
with FRONT_END; use FRONT_END;

```

package body ANNEAL is

```

package int_io is new TEXT_IO.integer_io(integer);--put in for debugging
use int_io;
package float_io is new TEXT_IO.float_io(float);--put in for debugging
use float_io;

```

```

-----
--* The following code is a modification of the HARMONIC BLOCK WITH PRECEDENCE
--* CONSTRAINTS scheduling algorithm developed and implemented by Kilic. It is
--* intended to develop an initial solution.

```

```

procedure CREATE_INTERVAL (THE_OPERATOR : in OPERATOR;
                           INPUT         : in out SCHEDULE_INPUTS;
                           OLD_LOWER     : in VALUE) is

```

```

    LOWER_BOUND : VALUE;

```

```

function CALC_LOWER_BOUND return VALUE is

```

```

begin
-- since CREATE_INTERVAL function is used in both SCHEDULE_INITIAL_SET and
-- SCHEDULE_REST_OF_BLOCK (OLD_LOWER /= 0) check is needed. In case of the
-- operator is scheduled somewhere in its interval and (OLD_LOWER /= 0),
-- this check guarantees that the periods will be consistent.
if (OLD_LOWER /= 0) then --* Schedule subsequent instance of task
    LOWER_BOUND := OLD_LOWER;
else --* Schedule first instance of task
    LOWER_BOUND := INPUT.THE_START;
end if;
return LOWER_BOUND;
end CALC_LOWER_BOUND;

```

```

function CALC_UPPER_BOUND return VALUE is

```

```

begin
if THE_OPERATOR.THE_WITHIN = 0 then
    return LOWER_BOUND + THE_OPERATOR.THE_PERIOD - THE_OPERATOR.THE_MET;
-- if the operator has a WITHIN constraint, the upper bound of the
-- interval is reduced.
else
    return LOWER_BOUND + THE_OPERATOR.THE_WITHIN - THE_OPERATOR.THE_MET;
end if;
end CALC_UPPER_BOUND;
begin --main CREATE_INTERVAL
    INPUT.THE_LOWER := CALC_LOWER_BOUND;
    INPUT.THE_UPPER := CALC_UPPER_BOUND;
end CREATE_INTERVAL;

```

```

-----
procedure SCHEDULE_INITIAL_SET (PRECEDENCE_LIST : in NODE_LIST.LIST;
                                THE_SCHEDULE_INPUTS : in out SCHEDULE_INPUTS_LIST.LIST;
                                HARMONIC_BLOCK_LENGTH : in INTEGER;
                                STOP_TIME : in out INTEGER) is

```

```

V                : NODE_LIST.LIST := PRECEDENCE_LIST;
START_TIME       : INTEGER := 0;
NEW_INPUT        : SCHEDULE_INPUTS;
OLD_LOWER        : VALUE := 0;
OP_NUM           : INTEGER;
TEMP             : OPERATOR;

begin --SCHEDULE_INITIAL_SET
  SCHEDULE_INPUTS_LIST.EMPTY(THE_SCHEDULE_INPUTS);
  NEW_INPUT.THE_OPERATOR := 0; --* This Code schedules
  NEW_INPUT.THE_LOWER := HARMONIC_BLOCK_LENGTH + 10; --* the first and only
  SCHEDULE_INPUTS_LIST.ADD(NEW_INPUT, THE_SCHEDULE_INPUTS); --* instance of the
  NODE_LIST.NEXT(V); --* dummy start node.
  while NODE_LIST.NON_EMPTY(V) loop
    OP_NUM := NODE_LIST.VALUE(V);
    TEMP := NEW_GRAPH.OP_RETURN(OP_NUM);
    NEW_INPUT.THE_OPERATOR := OP_NUM;
    NEW_INPUT.THE_START := START_TIME;
    STOP_TIME := START_TIME + TEMP.THE_MET;
    NEW_INPUT.THE_STOP := STOP_TIME;
    START_TIME := STOP_TIME;
    -- for every operator in SCHEDULE_INITIAL_SET, OLD_LOWER is zero. So we
    -- always send zero value to CREATE_INTERVAL.
    CREATE_INTERVAL(TEMP, NEW_INPUT, OLD_LOWER);
    SCHEDULE_INPUTS_LIST.ADD(NEW_INPUT, THE_SCHEDULE_INPUTS);
    NODE_LIST.NEXT(V);
  end loop;
end SCHEDULE_INITIAL_SET;

-----
procedure SCHEDULE_REST_OF_BLOCK(PRECEDENCE_LIST: in NODE_LIST.LIST;
  THE_SCHEDULE_INPUTS : in out SCHEDULE_INPUTS_LIST.LIST;
  HARMONIC_BLOCK_LENGTH : in INTEGER;
  STOP_TIME : in INTEGER) is

  V                : NODE_LIST.LIST := PRECEDENCE_LIST;
  TEMP             : SCHEDULE_INPUTS_LIST.LIST := THE_SCHEDULE_INPUTS;
  V_LIST,
  HEAD             : NODE_LIST.LIST;
  P                : SCHEDULE_INPUTS_LIST.LIST;
  S                : SCHEDULE_INPUTS_LIST.LIST;
  T                : SCHEDULE_INPUTS_LIST.LIST;
  START_TIME       : INTEGER := 0;
  TIME_STOP        : INTEGER := STOP_TIME;
  NEW_INPUT        : SCHEDULE_INPUTS;
  OLD_LOWER        : VALUE;
  OUTSIDE_BLOCK    : BOOLEAN := false;
  OP_NUM           : INTEGER;
  TEMP_OP          : OPERATOR;

begin
  NODE_LIST.DUPLICATE(PRECEDENCE_LIST, V_LIST);

  SCHEDULE_INPUTS_LIST.LIST_REVERSE(THE_SCHEDULE_INPUTS, P);
  T := P;

  loop
    while SCHEDULE_INPUTS_LIST.NON_EMPTY(P) loop
      --* Changed < to <= on 1 Apr 91 to correct flaw in scheduler
      OP_NUM := NODE_LIST.VALUE(V);

```

```

TEMP_OP := NEW_GRAPH.OP_RETURN(OP_NUM);
if (SCHEDULE_INPUTS_LIST.VALUE(P).THE_LOWER
  + TEMP_OP.THE_PERIOD
  + TEMP_OP.THE_MET) <= HARMONIC_BLOCK_LENGTH then
  NEW_INPUT.THE_OPERATOR := OP_NUM;
--* The following if statement determines the appropriate start time
--* of an operator.
  if SCHEDULE_INPUTS_LIST.VALUE(P).THE_LOWER
    + TEMP_OP.THE_PERIOD >= TIME_STOP then
    START_TIME := SCHEDULE_INPUTS_LIST.VALUE(P).THE_LOWER + TEMP_OP.THE_PERIOD;
  else
    START_TIME := TIME_STOP;
  end if;
  NEW_INPUT.THE_START := START_TIME;
  NEW_INPUT.THE_STOP := START_TIME + TEMP_OP.THE_MET;
  TIME_STOP := NEW_INPUT.THE_STOP;
  OLD_LOWER := SCHEDULE_INPUTS_LIST.VALUE(P).THE_LOWER + TEMP_OP.THE_PERIOD;
  CREATE_INTERVAL(TEMP_OP, NEW_INPUT, OLD_LOWER);
  NEW_INPUT.THE_INSTANCE := SCHEDULE_INPUTS_LIST.VALUE(P).THE_INSTANCE + 1;
  SCHEDULE_INPUTS_LIST.ADD(NEW_INPUT, TEMP);
  SCHEDULE_INPUTS_LIST.ADD(NEW_INPUT, S);
  NODE_LIST.NEXT(V);
  SCHEDULE_INPUTS_LIST.NEXT(P);
else
  NODE_LIST.NEXT(V);
  NODE_LIST.REMOVE(OP_NUM, V_LIST);
  SCHEDULE_INPUTS_LIST.NEXT(P);
end if;
end loop;
if SCHEDULE_INPUTS_LIST.NON_EMPTY(S) then
  SCHEDULE_INPUTS_LIST.FREE_LIST(T);
  SCHEDULE_INPUTS_LIST.LIST_REVERSE(S, P);
  SCHEDULE_INPUTS_LIST.FREE_LIST(S);
  T := P;
  V := V_LIST;
else
  exit;
end if;
end loop;
SCHEDULE_INPUTS_LIST.LIST_REVERSE(TEMP, THE_SCHEDULE_INPUTS);
SCHEDULE_INPUTS_LIST.FREE_LIST(TEMP);
end SCHEDULE_REST_OF_BLOCK;

```

---

--\* All code beyond this point is utilized by the SIMULATED ANNEALING algorithm \*--

```

procedure TEST_SCHEDULE ( AGENDA          : in SCHEDULE_INPUTS_LIST.LIST;
                          COST             : in out INTEGER;
                          BLOCK_LENGTH    : in INTEGER;
                          OUTSIDE_BLOCK   : in out BOOLEAN) is
--* This procedure finds the cost of a schedule by traversing through it.

```

```

  V          : SCHEDULE_INPUTS_LIST.LIST := AGENDA;
  PREVIOUS   : SCHEDULE_INPUTS_LIST.LIST := null;

```

```

begin
  COST := 0;
  SCHEDULE_INPUTS_LIST.NEXT(V); --Bypass Dummy Start Node
  while SCHEDULE_INPUTS_LIST.NON_EMPTY(V) loop
    if SCHEDULE_INPUTS_LIST.VALUE(V).THE_START
      < SCHEDULE_INPUTS_LIST.VALUE(V).THE_LOWER then
      COST := COST + (SCHEDULE_INPUTS_LIST.VALUE(V).THE_LOWER
        - SCHEDULE_INPUTS_LIST.VALUE(V).THE_START);
    elsif SCHEDULE_INPUTS_LIST.VALUE(V).THE_START
      > SCHEDULE_INPUTS_LIST.VALUE(V).THE_UPPER then
      COST := COST + (SCHEDULE_INPUTS_LIST.VALUE(V).THE_START
        - SCHEDULE_INPUTS_LIST.VALUE(V).THE_UPPER);
    end if;
    PREVIOUS := V;
    SCHEDULE_INPUTS_LIST.NEXT(V);
  end loop;
  if SCHEDULE_INPUTS_LIST.VALUE(PREVIOUS).THE_STOP > BLOCK_LENGTH then
    OUTSIDE_BLOCK := true; --* Schedule exceeds harmonic block length Not acceptable
  end if;
end TEST_SCHEDULE;

```

```

procedure ADJUST_SCHEDULE(TEMP_AGENDA : in out SCHEDULE_INPUTS_LIST.LIST;
  PRECEDENCE_LIST : in out NODE_LIST.LIST;
  H_B_LENGTH : in INTEGER;
  OUTSIDE_HARMONIC_BLOCK : in out BOOLEAN;
  NEW_LIST : in out BOOLEAN) is

```

--\* This procedure develops a new schedule based on another schedule

```

  HOLD,
  ADJUST_POINT : SCHEDULE_INPUTS_LIST.LIST; --* op that misses deadline
  V : SCHEDULE_INPUTS_LIST.LIST := TEMP_AGENDA;
  --* Original Schedule

```

```

  PENALTY_COST,
  MET,
  START_TIME,
  STOP_TIME : INTEGER := 0;
  NEW_INPUT : SCHEDULE_INPUTS;
  MOVED : BOOLEAN := false;
  ADJUSTED : BOOLEAN := false;
  REDO : BOOLEAN := false;

```

```

procedure ADJUST_PRECEDENCE (PRECEDENCE_LIST: in out NODE_LIST.LIST) is
--* Develop a new precedence list.

```

```

  OP_TO_BE_RESCHEDULED,
  TEMP_PARENTS,
  PARENTS,
  TEMP : NODE_LIST.LIST;
  NEW_LIST,
  ADJUSTABLE,
  ADJUSTED,
  FOUND_PARENT,
  CAN_GO_NO_FURTHER : BOOLEAN := false;
  RESCHEDULED_OP : INTEGER;
  MOVE_COUNT : INTEGER := 0;

```

```

begin
  while not NEW_LIST loop
    TEMP := PRECEDENCE_LIST;
    while NODE_LIST.NON_EMPTY(TEMP) loop --Move to tail of list

```

```

    OP_TO_BE_RESCHEDULED := TEMP;
    NODE_LIST.NEXT(TEMP);
end loop;
MOVE_COUNT := INTEGER(RANDOM.NEXT_NUMBER * FLOAT(DATA.OP_COUNT));
while MOVE_COUNT > 1 loop
    NODE_LIST.PREVIOUS(OP_TO_BE_RESCHEDULED);
    MOVE_COUNT := MOVE_COUNT - 1;
end loop;
TEMP := OP_TO_BE_RESCHEDULED;
NODE_LIST.PREVIOUS(TEMP);
while not ADJUSTED loop
    if not NODE_LIST.NON_EMPTY(TEMP) then
        exit; --* Cannot reschedule first op in list.
    end if;
    while NODE_LIST.NON_EMPTY(TEMP) loop
        if not NEW_GRAPH.IS_PARENT(NODE_LIST.VALUE(TEMP),
            NODE_LIST.VALUE(OP_TO_BE_RESCHEDULED)) then
            ADJUSTABLE := true;
            NODE_LIST.PREVIOUS(TEMP);
        else
            exit;
        end if;
    end loop;
    if ADJUSTABLE then
        RESCHEDULED_OP := NODE_LIST.VALUE(OP_TO_BE_RESCHEDULED);
        NODE_LIST.REMOVE(RESCHEDULED_OP, PRECEDENCE_LIST);
        NODE_LIST.INSERT_NEXT(RESCHEDULED_OP, TEMP);
        ADJUSTED := true;
        NEW_LIST := true;
    else
        NODE_LIST.PREVIOUS(OP_TO_BE_RESCHEDULED);
        TEMP := OP_TO_BE_RESCHEDULED;
        NODE_LIST.PREVIOUS(TEMP);
    end if;
end loop;
end loop;
end ADJUST_PRECEDENCE;

```

---

```

begin --* MAIN Adjust Schedule procedure
--* This first loop traverse thru a copy of the agenda to find the first instance of an
--* operator that misses its deadline the schedule will be adjusted from this point.
while SCHEDULE_INPUTS_LIST.NON_EMPTY(V) loop
    if SCHEDULE_INPUTS_LIST.VALUE(V).THE_START
        > SCHEDULE_INPUTS_LIST.VALUE(V).THE_UPPER then
        ADJUST_POINT := V;
        exit;
    end if;
    SCHEDULE_INPUTS_LIST.NEXT(V);
end loop;
while not ADJUSTED loop
    if not SCHEDULE_INPUTS_LIST.NON_EMPTY(V) or REDO then
--* At this point all operators meet their deadlines but the schedule exceeds the
--* harmonic block length. The initial set of ops must be adjusted
        ADJUST_PRECEDENCE(PRECEDENCE_LIST);
        SCHEDULE_INPUTS_LIST.FREE_LIST(TEMP_AGENDA);
        SCHEDULE_INITIAL_SET(PRECEDENCE_LIST, TEMP_AGENDA, H_B_LENGTH,
STOP_TIME);
    end if;
end loop;

```

```

    SCHEDULE_REST_OF_BLOCK(PRECEDENCE_LIST,TEMP_AGENDA,H_B_LENGTH,
STOP_TIME);
    NEW_LIST := true;
    ADJUSTED := true;
    else
--* The following if statement finds the point in the original AGENDA where we can begin
--* to reschedule operators. It does so in reverse order from the point that the first
--* operator missed its deadline back to the start point of the schedule. Each
--* operator's start time and child relationships are checked to see if the operator
--* that missed its deadline (ADJUST POINT) can start prior to this operator.
    SCHEDULE_INPUTS_LIST.PREVIOUS(V);
    HOLD := V;
    while SCHEDULE_INPUTS_LIST.NON_EMPTY(V) loop
        if SCHEDULE_INPUTS_LIST.VALUE(V).THE_START
        > SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_LOWER
        and not NEW_GRAPH.IS_PARENT(SCHEDULE_INPUTS_LIST.VALUE(V).THE_OPERATOR,
        SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_OPERATOR) then
            SCHEDULE_INPUTS_LIST.PREVIOUS(V);
            MOVED := true;
        else
            STOP_TIME := SCHEDULE_INPUTS_LIST.VALUE(V).THE_STOP;
            exit;
        end if;
    end loop;
    if MOVED then
        NEW_INPUT.THE_OPERATOR :=
SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_OPERATOR;
        if SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_LOWER > STOP_TIME
then
            START_TIME := SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_LOWER;
        else
            START_TIME := STOP_TIME;
        end if;
        NEW_INPUT.THE_START := START_TIME;
        MET:= SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_STOP
        - SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_START;
        STOP_TIME := START_TIME + MET;
        NEW_INPUT.THE_STOP := STOP_TIME;
        NEW_INPUT.THE_LOWER :=
SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_LOWER;
        --* These should stay the same
        NEW_INPUT.THE_INSTANCE :=
SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_INSTANCE;
        NEW_INPUT.THE_UPPER :=
SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT).THE_UPPER;
        SCHEDULE_INPUTS_LIST.INSERT_NEXT(NEW_INPUT, V);

SCHEDULE_INPUTS_LIST.REMOVE(SCHEDULE_INPUTS_LIST.VALUE(ADJUST_POINT),
TEMP_AGENDA);
    SCHEDULE_INPUTS_LIST.NEXT(V);
    ADJUSTED := true;
    while SCHEDULE_INPUTS_LIST.NON_EMPTY(V) loop
        if SCHEDULE_INPUTS_LIST.VALUE(V).THE_LOWER <= STOP_TIME or
        SCHEDULE_INPUTS_LIST.VALUE(V).THE_START < STOP_TIME then
            if SCHEDULE_INPUTS_LIST.VALUE(V).THE_START > STOP_TIME then
                exit;
            end if;
            NEW_INPUT.THE_OPERATOR := SCHEDULE_INPUTS_LIST.VALUE(V).THE_OPERATOR;
            START_TIME := STOP_TIME;
            NEW_INPUT.THE_START := START_TIME;
            MET:= SCHEDULE_INPUTS_LIST.VALUE(V).THE_STOP

```

```

        - SCHEDULE_INPUTS_LIST.VALUE(V).THE_START;
        STOP_TIME := START_TIME + MET;
        NEW_INPUT.THE_STOP := STOP_TIME;
        NEW_INPUT.THE_LOWER :=
SCHEDULE_INPUTS_LIST.VALUE(V).THE_LOWER;
        NEW_INPUT.THE_UPPER :=
SCHEDULE_INPUTS_LIST.VALUE(V).THE_UPPER;
        SCHEDULE_INPUTS_LIST.REPLACE_ITEM(NEW_INPUT, V);
        end if;
        SCHEDULE_INPUTS_LIST.NEXT(V);
    end loop;
end if;
if not ADJUSTED then
    REDO := true;
end if;
end loop;
end ADJUST_SCHEDULE;

```

```

procedure ANNEAL_PROCESS (H_B_LENGTH      : in INTEGER;
                          AGENDA           : in out SCHEDULE_INPUTS_LIST.LIST;
                          SOLUTION_FOUND   : in out BOOLEAN;
                          PENALTY_COST     : in out INTEGER;
                          PRECEDENCE_LIST  : in out NODE_LIST.LIST;
                          OUTSIDE_HARMONIC_BLOCK : in out BOOLEAN) is

```

```

    SCRATCH_AGENDA,
    BEST_AGENDA,
    TEMP_AGENDA                : SCHEDULE_INPUTS_LIST.LIST;

    TEMPERATURE                : FLOAT;
    BEST_COST,
    TEMP_COST                  : INTEGER := 0;
    TRIAL_NUM                  : INTEGER := 100;
    ACCEPT_NUM                  : INTEGER := 25;
    STOP_TIME,
    TRIAL_COUNT,
    ACCEPT_COUNT                : INTEGER := 0;
    COOLING_FACTOR              : FLOAT := 0.95;
    FREEZE                     : FLOAT := 1.0;
    NEW_PREC_LIST               : BOOLEAN := false;

```

```

function ANNEAL_FUNCTION (COST_1          : in INTEGER;
                          COST_2          : in INTEGER;
                          CURRENT_TEMPERATURE : in FLOAT) return FLOAT is

```

```

    DELTA_C                    : FLOAT;

begin
    DELTA_C := (FLOAT(COST_1 - COST_2)/CURRENT_TEMPERATURE);
    if DELTA_C <= 15.0 then
        return MATHEXP(-DELTA_C);
    else
        return 0.0;
    end if;
end ANNEAL_FUNCTION;

```

```

begin
    SCHEDULE_INPUTS_LIST.DUPLICATE(AGENDA, BEST_AGENDA);

```

```

BEST_COST := PENALTY_COST;
TEMPERATURE := 2.0 * FLOAT(PENALTY_COST);
CHEDULE_INPUTS_LIST.DUPLICATE(AGENDA, TEMP_AGENDA);
while not SOLUTION_FOUND and TEMPERATURE > FREEZE loop
  while TRIAL_COUNT < TRIAL_NUM and ACCEPT_COUNT < ACCEPT_NUM loop
    ADJUST_SCHEDULE(TEMP_AGENDA,PRECEDENCE_LIST,H_B_LENGTH,OUTSIDE_HARMONIC_BLOCK,
NEW_PREC_LIST);
    OUTSIDE_HARMONIC_BLOCK := false;
    TEST_SCHEDULE(TEMP_AGENDA,TEMP_COST,H_B_LENGTH,OUTSIDE_HARMONIC_BLOCK);
    if TEMP_COST <= PENALTY_COST or else RANDOM.NEXT_NUMBER
      < ANNEAL_FUNCTION(TEMP_COST, PENALTY_COST, TEMPERATURE) then
      if TEMP_COST < BEST_COST then
        BEST_COST := TEMP_COST;
        SCHEDULE_INPUTS_LIST.COPY_LIST(TEMP_AGENDA, BEST_AGENDA);
      end if;
      PENALTY_COST := TEMP_COST;
      SCRATCH_AGENDA := AGENDA;
      AGENDA := TEMP_AGENDA;
      TEMP_AGENDA := SCRATCH_AGENDA;
      ACCEPT_COUNT := ACCEPT_COUNT + 1;
    elsif NEW_PREC_LIST then
      SCRATCH_AGENDA := AGENDA;
      AGENDA := TEMP_AGENDA;
      TEMP_AGENDA := SCRATCH_AGENDA;
      PENALTY_COST := TEMP_COST;
      NEW_PREC_LIST := false;
      if TEMP_COST < BEST_COST then
        BEST_COST := TEMP_COST;
        SCHEDULE_INPUTS_LIST.COPY_LIST(TEMP_AGENDA, BEST_AGENDA);
      end if;
    end if;
    SCRATCH_AGENDA := null;
    TRIAL_COUNT := TRIAL_COUNT + 1;
    if PENALTY_COST <= 0 and not OUTSIDE_HARMONIC_BLOCK then
      SOLUTION_FOUND := true;
      exit;
    else
      SCHEDULE_INPUTS_LIST.COPY_LIST(AGENDA, TEMP_AGENDA);
    end if;
  end loop;
  ACCEPT_COUNT := 0;
  TRIAL_COUNT := 0;
  TEMPERATURE := TEMPERATURE * COOLING_FACTOR;
end loop;
if not SOLUTION_FOUND then
  AGENDA := BEST_AGENDA;
  PENALTY_COST := BEST_COST;
end if;

```

end ANNEAL\_PROCESS;

```

procedure SIMULATED_ANNEAL (PRECEDENCE_LIST : in NODE_LIST.LIST;
                           AGENDA          : in out SCHEDULE_INPUTS_LIST.LIST;
                           H_B_LENGTH      : in INTEGER;
                           VALID_SCHEDULE  : in out BOOLEAN) is

```

```

  PENALTY_COST,
  TEMP_COST,
  STOP_TIME
  : INTEGER := 0; --* (MAR 91)

```

```

ANNEAL                                : BOOLEAN := false;
WORKING_PRECEDENCE_LIST               : NODE_LIST.LIST;
OUTSIDE_HARMONIC_BLOCK               : BOOLEAN := false;
A_AGENDA                             : SCHEDULE_INPUTS_LIST.LIST;
BLANK                                : SCHEDULE_INPUTS;

begin
  NODE_LIST.DUPLICATE(PRECEDENCE_LIST,WORKING_PRECEDENCE_LIST);
  SCHEDULE_INITIAL_SET(PRECEDENCE_LIST,AGENDA,H_B_LENGTH,STOP_TIME);
  SCHEDULE_REST_OF_BLOCK(PRECEDENCE_LIST,AGENDA,H_B_LENGTH,STOP_TIME);
  ANNEAL := false;

TEST_SCHEDULE(AGENDA,PENALTY_COST,H_B_LENGTH,OUTSIDE_HARMONIC_BLOCK);
  if PENALTY_COST > 0 or OUTSIDE_HARMONIC_BLOCK then --* Then Annealing is required.
    OUTSIDE_HARMONIC_BLOCK := false;
    ANNEAL := true;
    RANDOM.INITIALIZE(2*DATA.OP_COUNT+1); --* Initialize Random Number Generator
    --* with an odd number.
  else
    VALID_SCHEDULE := true;
  end if;
  if ANNEAL then
    ANNEAL_PROCESS(H_B_LENGTH,AGENDA, VALID_SCHEDULE,PENALTY_COST,
      WORKING_PRECEDENCE_LIST,OUTSIDE_HARMONIC_BLOCK);
  end if;
end SIMULATED_ANNEAL;

end ANNEAL;

```

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