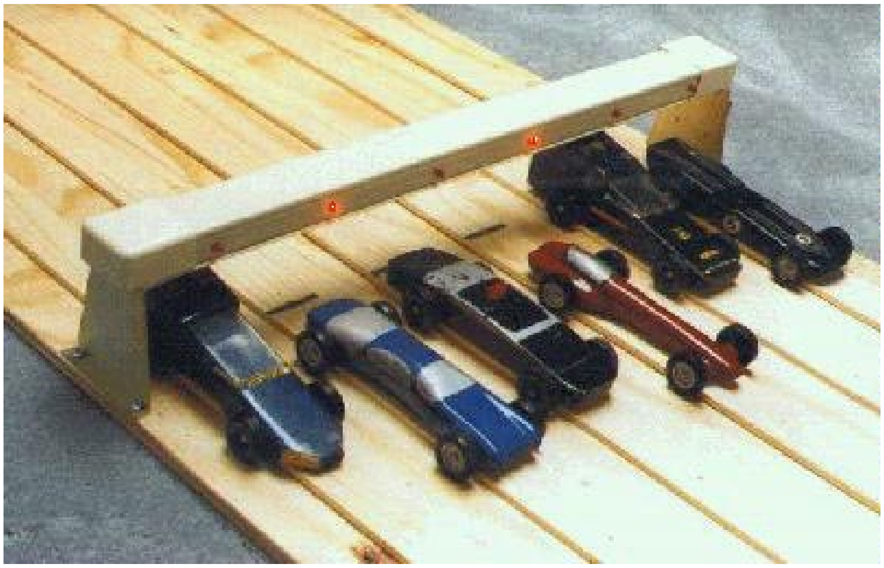
†Pinewood



Over 80 million people have participated in Cub Scout Pinewood Derbies. Pinewood is a case study of the design of a Cub Scout Pinewood Derby for one particular scout pack. The system helps manage the entire event from initial entry through final results. Many alternatives or race format, scoring, and judging are presented.

The following detailed table of contents should be examined closely by the systems engineer. It is important that the designers provide an entry for every table item. This will ensure that the important points are not overlooked.

Note that in the seven documents that follow many comments are set in italics, indented, and bounded by a box (such as this one). They are not a part of the system documents, but are comments for the reader. They contain explanations and indications of the strong and weak points of this documentation.

Individual Cub Scout packs usually hold their Pinewood Derbies at the end of January or the beginning of February; district and citywide derbies follow. You should find out when and where a Pinewood Derby will be held in your neighborhood and attend it.

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† This document is based on chapter five of *Engineering Modeling and Design,* by W.L. Chapman, A.T. Bahill, and A.W. Wymore, CRC Press, Boca Raton, 1992.

Contents

1 DOCUMENT 1: PROBLEM SITUATION

> *The Problem Situation Document is the executive summary. It explains the problem that needs to be solved It is written in plain language and is intended for management.*

1.1 The Top Level System Function

The top level system function is to conduct a cub scout Pinewood Derby that maximizes scout enjoyment and minimizes hard feelings.

1.2 History of the Problem and the Present System

Since the 1950s, over 80 million cub scouts have built cars and raced them in Pinewood Derbies. Pack 212 in Tucson, Arizona, has conducted derbies since 1977. Problems that have developed in past Pinewood Derbies include:

1. scouts and parents wasting large amounts of time,
2. irate parents,
3. questions about the fairness of races,
4. other people touching the scouts' cars,
5. adverse weather conditions,
6. scouts unable to tell which cars were called to race or in which lane the cars were to run,
7. scouts unable to tell which cars won, and
8. scouts unable to figure out which cars were winning the derby.

The cub scouts build cars from a Pinewood Derby Kit to prescribed requirements. Systems engineers will design a derby to alleviate the existing adverse factors. This project is known as Pinewood.

1.3 The Customer

1.3.1 Owners

The system will be owned by Cub Scout Pack 212, Catalina Council, Boy Scouts of America.

1.3.2 Bill payers: The client

The budget for the system will be provided by Dr. A. Terry Bahill.

1.3.3 Users

The system will be used by the cub scouts of Pack 212, their parents, and the Pinewood Derby Committee.

1.3.4 Operators

The system will be operated by the members of the Pinewood Derby Committee (judges, inspectors, track managers, etc.) of Pack 212.

1.3.5 Beneficiaries

The cub scouts, their parents, the organizers, and spectators are the beneficiaries of the system.

1.3.6 Victims

Those who might feel the system adversely affected them are:

1. those cub scouts who lose,
2. cub scouts whose cars are broken,
3. disgruntled parents,
4. those who must clean up the area after the event, and
5. committee members who take verbal abuse from irate parents.

1.3.7 Technical representatives to systems engineering

The sole technical representative of this system is the system designer Dr. Bahill of the University of Arizona.

1.4 Technical Personnel and Facilities

1.4.1 Life Cycle Phase 1: Requirements development

Dr. Bahill is the technical consultant for the basic system throughout Phase 1. All requirements data will be supplied by Dr. Bahill. Supplies and tools will be provided by Dr. Bahill. Computer equipment for document generation will be provided by the system designers.

1.4.2 Life Cycle Phase 2: Concept development

The system designers will perform the concept development and will be available throughout Phase 2. Information resources obtained from previous derbies will be provided by Dr. Bahill. Computer resources for simulations will be provided by the system designers. Bill Chapman will be the systems engineer.

1.4.3 Life Cycle Phase 3: Full-scale engineering development

The full-scale engineering task will be performed by Dr. Bahill and Bill Karnavas. A three lane racetrack will be provided by the cub scout pack. Computers and timing hardware will be provided by Dr. Bahill.

1.4.4 Lif Cycle Phase 4: System development

The system development will be performed by Dr. Bahill and Bill Karnavas.

1.4.5 Life Cycle Phase 5: System test and integration

System test and integration will be performed by Dr. Bahill and Bill Karnavas.

1.4.6 Life Cycle Phase 6: Operations support and modification

Following successful system test and integration, operations support and modification will be performed by the Pinewood Derby Committee.

1.4.7 Life Cycle Phase 7: Retirement and replacement

At the end of the race day, the system will be disassembled and the equipment will be stored. Next year, a replacement system will be designed and built.

1.5 System Environment

1.5.1 Social impact

The primary social impact of the new system is to provide a better overall derby, which will be more organized, more efficient, and more enjoyable. For the children who race the cars, competition is de-emphasized and racing is emphasized. By this we mean that the format or structure of the event should allow scouts to participate in a large number of races, thus keeping their attention focused on the races. The scouts learn that their own actions, rather than luck, control who wins and loses.

1.5.2 Economic impact

The new system will improve the utilization of the economic resources. Although the new system may not require more resources, it is estimated to cost approximately $300.

1.5.3 Environmental impact

The local environment may be affected by debris from the crowd or by graphite deposits left by the scouts (the scouts use graphite during the races). This will have to be cleaned up following the event. The Pinewood Derby Committee or maintenance personnel will restore the environment to an acceptable state. Other potential problems are noise and parking congestion during the event.

1.5.4 Interoperability

The system must be compatible with the environment and the established components of the derby, such as the pinewood cars and the racing track. Furthermore, the system must be in compliance with existing Boy Scouts of America Pinewood Derby specifications.

1.6 Systems Engineering Management Plan

The system designers will describe the project design within the seven systems engineering documents:

1. Problem Situation Document,
2. Operational Need Document,
3. System Requirements Document,
4. System Requirements Validation Document,
5. Concept Exploration Document,
6. System Functional Analysis Document, and
7. Physical Synthesis Document.

These documents will be continually updated as the design progresses using the SEDSO software package (see Chapter 7 of Chapman, Bahill, and Wymore, 1992 for details on SEDSO). Furthermore, the Pinewood Derby Committee will be responsible for the project from the end of the system test and integration phase to the end of the life cycle.

2 DOCUMENT 2: OPERATIONAL NEED

> *The Operational Need Document is a detailed description of the problem in plain language. It is intended for management, the customer, and systems engineers.*

2.1 Deficiency

In the past, the emphasis for this derby was placed on winning, rather than racing. Also, hard feelings were created by wasted time and what the parents and the scouts perceived to be incorrect or unfair judging. The new system will change the emphasis to racing, reduce the number of irate parents, and increase the number of happy kids.

2.2 Input/Output and Functional Requirement

2.2.1 Time scale

The system will use a time scale with a resolution of tenths of milliseconds. The life expectancy of the system will be six hours.

2.2.2 Inputs

The system has eight inputs:

1. name of the owner of the current Pinewood Derby car entering the system,
2. division the owner is in,
3. den the owner is a member of,
4. car's speed ability,
5. car's compliance with derby rules (i.e., pass or no pass),
6. time of day,
7. scheduled judging time for each event, and
8. scheduled racing order for each race.

The divisions are Webelos, Bears, Wolves, Tiger Cubs, and Family. No two owners may use the same name. The dens have separate unique names or numbers. The scouts belong to both a den and a division. The Family cars will not have a den designation. The scheduled racing order will depend on the format of the racing technique, though it will be determined in advance and provided to the system.

> *Family cars are built by fathers, mothers, or siblings obeying the same rules as the scouts. The original purpose of the Family car division was to cajole the fathers into leaving the scouts' cars alone by building cars of their own. This worked quite well, the kids' cars being built by the kids. Subsequently, the Family car division developed an added facet of presenting truly innovative and fancy designs. Some cars were built for speed; some were built for originality, such as a three-wheeled, inchworm-shaped car; and some were built to reflect family occupations—UPS trucks, window glass delivery trucks, etc.*

2.2.3 Input trajectories

The system input trajectories will be restricted to the order of divisional racing: Webelos, Bears, Wolves, Tiger Cubs, and Family.

2.2.4 Outputs

To ease the descriptions of our scheduling heuristic, we will now introduce a standard terminology for this paper. We will refer to each set of cars running down the track at the same time as a *heat.* Occasionally a heat will colliquilaly be called a *race.* A *round* will consist of the number of heats necessary for every car in the division to run once. A set number of rounds will constitute a *divisional race*. Finally, several divisional races will constitute a *derby.* Thus for 15 cars to run six times each, the divisional race will consist of six rounds of five heats each. Typically, the divisions are aggregated by age, with four or five divisions being common in a Cub Scout pack.

The outputs of the system are indicators of:

1. the first, second, and third place finisher of each heat,
2. the name, division, and den of the first, second, and third place finishers in each division event,
3. the first, second, and third place winners of the Pack Championship and the Family car races and the winner of the Classy Chassis Competition for each division,
4. the first, second, and third place winners of each den and a list of the other den entrants,
5. scouts who are either happy or not,
6. parents who are either irate or not, and
7. qualifying or disqualifying of cars.

2.2.5 Output trajectories

The output trajectories shall be restricted as follows:

1. The determination of the division winners will precede the Pack Championship race, and the Family car category will conclude the derby events.
2. No heat can end in a tie.
3. The final Classy Chassis determinations will occur after all the events are completed.

2.2.6 Matching function

The required matching between input trajectories and output trajectories are as follows:

1. The Webelos winner will be a car from the Webelos car division.
2. The Bears winner will be a car from the Bears car division.
3. The Wolves winner will be a car from the Wolves car division.
4. The Tiger Cubs winner will be a car from the Tiger Cubs division.
5. One Classy Chassis winner will be selected from the Family cars and one will also be selected from the Webelo, Bear, and Wolf division nominees.
6. The Pack Champions will be from the Webelos, Bears, or Wolves division.
7. The Family cars winner will be from the Family car division.

2.3 Technology Requirement

2.3.1 Available money

The time spent by the volunteers, Dr. Bahill and Bill Karnavas, is considered free. Dr. Bahill says that $50 is not an unreasonable amount of out-of-pocket money to spend. The pack will pay gym rental fees, if needed. This will usually cost $25 to $100.

2.3.2 Available time

The project must be completed before the scheduled date of the derby, which is the first Sunday in February for Pack 212.

2.3.3 Available components

Available components are:

1. an IBM AT computer,
2. timing equipment and software,
3. a stopwatch,
4. committee personnel and other volunteers,
5. a three-lane racetrack,
6. awards and prizes,
7. weighing scales and rulers,
8. tables and chairs, as necessary, and
9. other materials that can be obtained "off-the-shelf," as needed and permitted by the budget.

2.3.4 Available techniques

Of the many different racing techniques that can be considered, we will use the following:

1. single-elimination,
2. double-elimination, and
3. round robin formats with the following scoring techniques:
   - 3.1 mean times,
   - 3.2. fastest times, and
   - 3.3. point assignments.

Many timing techniques are available for determining the order in which the cars cross the finish line. A list of potential techniques includes:

1. optical sensors,
2. bar code readers,
3. mechanical switches, and
4. human observation.

2.3.5 Required interfaces

The proposed system is required to interface with Pack 212's existing three lane racetrack and Pinewood Derby cars.

2.3.6 Standards, specifications, and other restrictions

The design, implementation, and operation of the system must follow the Boy Scouts of America Pinewood Derby rules and regulations, as described in Exhibit 1.

EXHIBIT 1

Typical Pinewood Derby Rules

Cars must be built using an Official Cub Scout Pinewood Derby Kit; however, weights, paint, decals, decoration, and graphite may be added. Other wheels or axles are not permitted, as we do not want the scouts to buy expensive components. The cars should be built by the scouts using commonly available tools. Thus, wheels may be sanded smooth, as described in the Pinewood Derby Kit, but they may not be turned on a lathe to produce knife edges. Likewise, axles may be smoothed, but they cannot be plated. All parts of the car must be firmly attached. The car must have proper clearance underneath; weights may not be hung under the car. Nothing can project beyond the front of the car. All cars must be built in the year of the derby. The cars should be built by the scouts. Fathers, mothers, brothers, and others may build their own cars and race them in the Family car division races. On race day, each scout should bring his car, graphite, and a tool for reducing the weight of the car if it exceeds five ounces. In addition, cars must also comply with the following council rules:

1. After inspection on race day nothing can be done to the cars. Graphite may not be added to the wheels after inspection. In particular, neither scouts nor parents can add graphite to the wheels between races.
2. Width shall not exceed 2.75 inches.
3. Length shall not exceed 7 inches.
4. Weight shall not exceed 5 ounces.
5. Axles, wheels, and body shall be from materials provided in the kit.
6. Wheel bearings, washers, and bushings are prohibited.
7. Wheels and axles may be lubricated with graphite, but oil may not be used.
8. Springs are not allowed.
9. The car must be free-wheeling, and there can be no starting devices.
10. No loose materials are allowed in or on the car.
11. The wheelbase must not be altered from that in the kit.

Some districts allows scouts to use expensive, precision machined wheels bought from mail-order hobby houses. If our distict allows such wheels, our Cubmaster will buy such knife-edged wheels for our scouts to use in the district competition.

Helpful hints from Dr. Bahill: In decreasing order of importance, the things that make a Pinewood Derby car go fast are:

1. graphite—make sure there is lots of graphite between the wheels and axles;
2. weight—make the car as close to five ounces as possible;
3. smoothness of wheels and axles—sand your wheels and polish your axles;
4. weight distribution—the center of mass should be toward the back of the car, e.g. an inch or so in front of the rear axle;
5. mounting of wheels—put your axles in straight, however it is not necessary that all four wheels touch the ground; and
6. Aerodynamics—at these low speeds wind resistance has no effect.

Concurrent engineering requires that all decisions be made with the participation of all relevant personnel, such as sales and marketing, finance, manufacturing, engineering, quality, human factors, and purchasing. In the following requirements we list the originator at the end.

2.4 Input/Output Performance Requirement

1. *Average Races per Car:* The average number of races per car. There is no defined upper limit. In 1990, the number of races per scout was six so this is the baseline. This requirement was devised using Sales and Marketing data.

In these requirements, we suggest the divisions of a large company that might be responsible for suggesting each requirement. For the Pinewood Derby this may seem a little contrived, but it does illustrate how concurrent engineering (explained in Chapter 7 of Chapman, Bayhill, and Wymore, 1992) works for larger systems.

2. *Number of Ties:* The total number of times that races had to be rerun in the entire derby because of ties. An upper limit of 15 ties has been set with a baseline value of 0.5. This requirement was set by Systems Engineering.
3. *Happiness:* The happiness of the scouts and parents resulting from the derby. This is a combination of the following seven measures:
   - 3.1 *Percent Happy Scouts:* The percentage of scouts that leave the race with a generally happy feeling. A happy feeling may be the result of a child having a good race, having a good rapport with other scouts and parents, or a combination of these factors. It should be maximized to meet the top level system function. The upper limit is 100%, and 95% is the baseline. This requirement was suggested by Sales and Marketing and the customer.
   - 3.2. *Number Irate Parents:* The total number of parents that are dissatisfied with the judging of the races or any other aspect of the race. The upper limit is 10 and the baseline value is 1. These criteria were determined by the customer and Human Factors data.
   - 3.3. *Number of Broken Cars:* The number of cars that were broken by the system itself. The upper limit is 3, and the baseline value is 1.0, since we really do not want any cars broken. This is a customer requirement.
   - 3.4. *Others Touching Scout's Car:* The number of other people who touch the scout's car during a race. The upper limit is 7 and the baseline value is 2. This requirement was specified by the customer.
   - 3.5. *Number of Repeat Races:* The number of cars that race another particular car more than once. A smaller number of repeat races will increase the perception of fairness and lower the discontent of the scouts. This requirement was made by Human Factors and Systems Engineering.

3.6. *Number of Lane Repeats:* The number of cars that do not race the same number of times in each lane. A smaller number of lane repeats will increase the perception of fairness and lower scout discontent. This requirement was determined by Human Factors and Systems Engineering.

3.7. *Difference Between Fast and Slow:* The difference between the number of heats for the fastest car and the number of heats for the slowest car. This requirement was determined by Systems Engineering.

Notice how we have grouped related subitems together into one figure of merit, Happiness. It is important to group related items so that individual items do not gain too much importance. We try to keep the number of items at any level between 3 and 7, so comparisons can be made easily.

4. *Availability:* The system will be available if it interfaces with the current track system and is manufactured on time and to specification. This requirement was determined by Systems Engineering.
5. *Reliability:* The system will be reliable if it behaves at least as well as the existing system and if it can operate in case of electrical power failure. This requirement was determined by Reliability Engineering.

Some systems engineers do a risk analysis after the most favorable alternatives are selected. We chose to merely incorporate the risk parameters into the requirements. For example, the risk of a total power failure on the day of the derby was incorporated into the Reliability Input/Output Performance Requirement.

2.5 Utilization of Resources Requirement

1. *Acquisition Time:* The number of days the project was completed before the first Sunday in February. The sooner the system is completed before this time the better. This requirement was determined by the customer and Purchasing.
2. *Acquisition Cost:* The total cost of creating the system. The absolute maximum is $300, and the baseline value is $150. This requirement was determined by the customer and Purchasing.
3. *Total Event Time:* Total time it takes to judge all cars and to run all races. In 1990, the derby took 3.5 hours to complete; so this is our baseline. This requirement was suggested by the customer.

It is not always clear when a figure of merit should be grouped with Input/Output Performance or Utilization of Resources. For the Pinewood Derby, it seems that Total Event Time could go in either category.

4. *Number of Electrical Circuits:* The number of 120 VAC electrical circuits needed to run the event. The baseline value is 1, with an optimum score of 0 circuits. This requirement was determined by Manufacturing.
5. *Number of Adults:* The total number of adults needed to run the derby. This requirement was created by Manufacturing.

2.6 Tradeoff Requirement

Pinewood's tradeoff analysis gives greater weight to the performance requirements (90%) than to the resource requirements (10%) because the parents want their kids to be happy and they are willing to pay for it. This requirement was created by Management.

2.7 System Test Requirement

The performance of the system designed by the system engineers will be determined using two tests. These requirements were created by the System Test Organization.

1. Test 1 will determine system performance using 23 cub scouts from each division.
2. Test 2 will determine if the race judging components are fair. Two cars with similar speeds will be used for this. Dr. Bahill and Bill Karnavas will be the judges.

The system will be acceptable if:

1. all requirements from this document are satisfied,
2. the system allows for adverse weather conditions,
3. at most 1500 square feet of space are used, and
4. restroom facilities are available for participants.

The system will be in compliance if the upper and lower bounds set for each figure of merit are met. The system will have failed if:

1. there is a loss of electrical power and power is needed,
2. adverse weather prevents the derby from proceeding,
3. mistakes in judging occur, or
4. one lane is faster than another.

These will be determined by the Grand Marshall during the actual event.

2.8 Rationale for Operational Need

The data and specifications were provided by Dr. Bahill and Bill Karnavas.

Below are listed some things we actually do for each derby we run but that were omitted from this documentation either because we forgot to include it or because we thought it would needlessly complicate the documentation.

(1) Find out how many scouts are in each division. Obtain historical data for time per race for each division, as shown in Exhibit 2. Produce a timetable to minimize wasted time. With electronic timing, we found that we could schedule a heat every 45 seconds. Races can be run even faster for older kids and adults. Also, later races can be run faster because the track needs no further adjustment and because the parents have learned their jobs. Small races with 12 cars or less do not require impounding of cars between races and thus can be run faster.

(2) Publish car construction rules for the pack two months before the event.

(3) Meet with the Pinewood Derby Committee and explain each person's job.

(4) Provide a listing of who won the various prizes within one week after the derby.

EXHIBIT 2

Statistical Summary of the 1991 Pack 212 Pinewood Derby

Pack 212 1991 Pinewood Derby

Division	Number of Scouts	Percentage of Scouts Participating	Number of Races	Duration of Divisional Race (minutes)	Time Used per Heat (minutes)
Webelos	23	62	48	35	0.73
Bears	16	84	36	23	0.64
Wolves	10	77	24	15	0.63
Tiger Cubs	7	87		10	0.56
Pack Championship	9		18	10	0.56
Family Cars	10		24	15	0.63
Totals	66		168		

We used an electronic timer and ran a round robin derby with each car racing six times, twice in each lane. From this summary, we see that with electronic timing one heat every 45 seconds is a reasonable schedule. The first division will be the slowest because of the time taken to cross check the computer and straighten and wax the track. With small numbers of cars per division—that is, 12 or fewer—impounding the cars between heats is not desirable, since more races can be run in the same period of time by not impounding them. These statistics are very similar to those of the previous year.

3 DOCUMENT 3: SYSTEM REQUIREMENTS

> *The Systems Requirements Document is a succinct mathematical description or model of the Input/Output Requirements, Functional Requirements, Technology Requirements, Test Requirements, and the tradeoffs between them as described in Document 2. Its audience is systems engineers.*

3.1 The System Requirement

The System Design Problem entails stating the following requirements.

1. Input/Output and Functional Requirement,
2. Technology Requirement,
3. Input/Output Performance Requirement,
4. Utilization of Resources Requirement,
5. Tradeoff Requirement,
6. System Test Requirement.

Each of these requirements will be mathematically stated in the following sections.

3.2 Input/Output and Functional Requirement

> *The set theoretic notation used in this section is explained fully in Wymore (1993). This section can be skipped if the notation bothers the reader.*

3.2.1 Time scale

TRPO is the time scale of Pinewood expressed in tenths of a millisecond. The life expectancy of the system is six hours. This becomes 6 hours x 60 minutes/hour x 60 seconds/minute x 10,000 = 216,000,000 seconds.

TRP0 = IJS[0–216000000]

> *This time scale does not presuppose that electronic timing will be used. It was chosen to be fast enough to work with all alternatives. Slower models would certainly be valid.*

3.2.2 Inputs

IRP0 represents the set of system inputs for Pinewood. There are four input ports:

IRP0 = IR1P0 x IR2P0 x IR3P0 x IR4P0

where IR1PO is a set of sets of all possible car entries and is broken down as follows:

IR1P0 = Car in = {Owner, Den, Division, Speed, Characteristic}

where:

Owner = {Words(Alphau)}

> *"Alphau" is a function that returns any letter or number. "Words" is a function that puts the alphanumerics into a word.*

Den = {Words(Alphau)}
Division = {Webelos, Bears, Wolves, Tiger Cubs, Family}
Speed = IJS[1–100]
Characteristic = {Pass, Fail}

Speed is a relative measure used for simulation. We do not know how fast the cars are, but they enter the system with some inherent speed capacity. Likewise, Characteristic represents the car's ability to ultimately Pass or Fail the inspection. This part of the modeling is simplistic, since we are not interested in an in-depth model of this portion of the system.

IR2P0 is the time of day provided to the system.

IR2P0 = IJS[0, 2160000000].

IR3P0 is the scheduled judging times.

IR3P0 = {Division, Time}

where:

Division = {Webelos, Bears, Wolves, Tiger Cubs, Family}
Time = IJS[0–216000000].

IR4P0 is the scheduled racing order.

IR4P0 = {(Index, lane 1, lane 2, lane 3)^Num}

where:

Index = IJS[0–Num] /*Index is the race number on the schedule*/
Lane 1 = Car in /*The car in lane 1*/
Lane 2 = Car in /*The car in lane 2*/
Lane 3 = Car in /*The car in lane 3*/
Num = 1000 /*The max number of possible races*/

3.2.3 Input trajectories

ITRP0 is the set of input trajectories for Pinewood, the set of all possible inputs (IRP0) over the time scale (TRP0). Formally,

ITRP0 = {f: f ∈ FNS(TRP0, IRP0);
f(t) = ((p11(t), p12(t), p13(t), p14(t), p15(t)), p2(t), p3(t), p4(t)),
tj ∈ TRP0, j = {1, 2, 3, 4, 5};
if f(t1) = ((p11, p12, Webelos, p14, p15), p2, p3, p4) and
f(t2) = ((p11, p12, Bears, p14, p15), p2, p3, p4) and
f(t3) = ((p11, p12, Wolves, p14, p15), p2, p3, p4) and

f(t4) = ((p11, p12, Tiger Cubs, p14, p15), p2, p3, p4) and
f(t5) = ((p11, p12, Family, p14, p15), p2, p3, p4) then
t1 < t2 < t3 < t4 < t5}.

where, for example, p12 is the second element of the first port and, similarly for all the others of f(t), where f(t) is the resultant input trajectory at time t.

3.2.4 Outputs

ORP0 represents the system outputs for Pinewood.

ORP0 = OR1P0 x 0R2P0 /*See figure 15*/

where OR1P0 is a set of sets of cars as follows:

OR1P0 = Cars = {Owner, Den, Division, Time in, Place, Event, Qual, Scout, Parent}

where

Owner = {Words(Alphau)}
Den = {Words(Alphau)}
Division = {Webelos, Bears, Wolves, Tiger Cubs, Family}
Time in = IJS[0-216000000],
Place = {First, Second, Third, Null}
Event = {Race, Pack Championship, Classy Chassis}
Qual = {Qualified, Disqualified}
Scout = {Happy, Not happy}
Parent = {Irate, Not irate}.

These outputs indicate conditions of the cars, the scouts, and the parents. Qual is the output that indicates whether the car is, or is not, qualified to race.

OR2P0 is a set of sets of cars as follows:

OR2P0 = Cars = {Owner, Den, Division, Time in, Place, Event, Qual, Scout, Parent}

where Cars is defined as above.

3.2.5 Output trajectories

OTRP0 is the set of all output trajectories for Pinewood. OTRP0 is the set of all possible outputs (ORP0) over the time scale (TRP0). Formally,

OTRP0 = {f: f $\in$ FNS(TRP0, ORP0), and
for t $\in$ TRP0 and
for OR1P0 = (q1, q2, q3, q4, q5, q6, q7, q8, q9),
if q3 = Webelos then t1 = t;
else if q3 = Bears then t2 = t;
else if q3 = Wolves then t3 = t;
else if q3 = Tiger Cubs then t4 = t;

else if q3 = Family then t5 = t; and
t1 < t2 < t3 < t4 < t5}

where q3 represents the third element of the output set OR1P0, which is the racing division, and t1 is the time when the Webelos race begins.

3.2.6 Matching function

MRP0 is the matching function for Pinewood.

MRP0 = {(f,g): f ∈ ITRP0; g ∈ OTRP0, and
for f=(t1, (p11, p12, p13, p14, p15), p2, p3, p4) ∈ ITRP0, and
for g=(t2, (q1, q2, q3, q4, q5, q6, q7, q8, q9) ∈ OTRP0 then
if q3 = Webelos then t2a = t2;
else if q3 = Bears then t2b = t2;
else if q3 = Wolves then t2c = t2;
else if q3 = Tiger Cubs then t2d = t2;
else if q3 = Family then t2e = t2; and
if p13 = Webelos then t1a = t1;
else if p13 = Bears then t1b = t1;
else if p13 = Wolves then t1c = t1;
else if p13 = Tiger Cubs then t1d = t1;
else if p13 = Family then t1e = t1;
then t1a < t2a and t1b < t2b and t1c < t2c
and t1d < t2d and t1e < t2e}

where, for example, q3 represents the third element of the output set OR1P0, which is the racing division; p13 is the third element of the first element of the input trajectory, which is the car's division; and t1a is the time when the Webelos race begins and t2a is the time the divisional race ends.

3.3 Technology Requirement

Section 3.3 is very similar to Section 2.3. For material for which mathematical models are not appropriate, the sections of Documents 2 and 3 will be similar, but we do not eliminate one or the other because each document must be self-contained

3.3.1 Available money

Dr. Bahill says that $50 in out-of-pocket expenses is not an unreasonable amount to spend. Gym rentals will cost approximately $25 to $100. If the Pack cannot afford this cost by the time of the event, then the race must be held elsewhere, possibly outside in someone's yard.

3.3.2 Available time

Though the time spent by Dr. Bahill and Bill Karnavas is a resource that should not be squandered, their time before, during, and after the derby is considered free.

3.3.3 Available components

The following components are available:

1. an IBM AT computer,
2. timing equipment and software,
3. a stopwatch,
4. committee personnel and other volunteers,
5. the three-lane racetrack,
6. awards and prizes,
7. weighing scales and rulers,
8. tables and chairs, as necessary, and
9. other materials that can be obtained "off-the-shelf," as needed and permitted by budget.

3.3.4 Available techniques

Perferred racing techniques include:

1. single-elimination,
2. double-elimination, and
3. round robin formats with the following scoring techniques:
   3.1.mean times,
   3.2.fastest times, and
   3.3.point assignments.

Candidate timing techniques include:

1. optical sensors,
2. bar code readers,
3. mechanical switches, and
4. human observation.

3.3.5 Required interfaces

The proposed system is required to interface with Pack 212's existing three lane racetrack and derby car sizes.

3.3.6 Form, fit, and other restrictions

These considerations include the size of the existing racetrack and the space needed to house all the participants in the event along with all inspection and timing stations. Estimated minimum floor space is 1500 square feet. The event should be held indoors to prevent adverse effects from the weather; otherwise, arrangements for holding the event in good weather should be made.

3.3.7 Standards and specifications

The Pinewood Derby system must comply with all rules and regulations of the Boy Scouts of America pertaining to Pinewood Derbies. Also, safety practices and procedures should be followed, and any building rules and codes must be obeyed.

3.4 Input/Output Performance Requirement

3.4.1 Definition of Performance Figures of Merit

The overall performance figure of merit is denoted IF0P0 and is computed as follows:

IF0P0 = ISFlP0 ∗ IWlP0 + ISF2P0 ∗ IW2P0 + . . . + ISF*n*P0 * IW*n*P0

where *n* is the total number of I/O Performance Figures of Merit and

ISF*i*P0 = IS*i*P0(IF*i*P0(FSD)) for *i* = 1 to *n*

as explained in the following section.

3.4.2 Lower, upper, baseline, and scoring parameters

In this section, the following naming convention is: The initial letter “I” indicated that the name is for an Input/Outupt Performance Requirement. The terminal P0 indicates that the name involves Problem 0 of the Pinewood Derby.

IF*i*P0	=	the i^{th} figure of merit measured per the test plan,
IB*i*P0	=	the baseline value for the i^{th} figure of merit,
IFX*i*P0	=	Measured value for the i^{th} figure of merit,
ILTH*i*P0	=	lower threshold for the figure of merit,
IR*i*P0	=	ranking of importance from 1 to 10,
ISF*i*P0	=	score for the i^{th} figure of merit,
IS*i*P0	=	scoring function for the i^{th} figure of merit,
IUTH*i*P0	=	upper threshold for the i^{th} figure of merit,
IW*i*P0	=	weight for the i^{th} figure of merit, and
SSF	=	standard scoring function.

Next we give the parameters necessary to evaluate the figures of merit using the scoring functions of Figure 4.2.

1. *Average Races per Car*

Score	IS1P0 = SSF (ILTH1P0, IB1P0, IUTH1P0, ISL1P0)
Lower Threshold	ILTH1P0 = 1
Baseline	IB1P0 = 4
Upper Threshold	IUTH1P0 = 100
Slope	ISL1P0 = 0.333

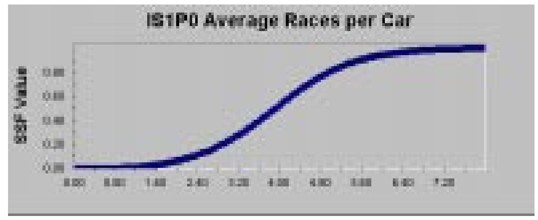

Figure 1 Scoring Function

2. *Number of Ties*

Score	IS2P0 = SSF (ILTH2P0, IB2P0, IUTH2P0, ISL2P0)
Lower Threshold	ILTH2P0 = 0
Baseline	IB2P0 = 0.5
Upper Threshold	IUTH2P0 = 5
Slope	ISL2P0 = -2

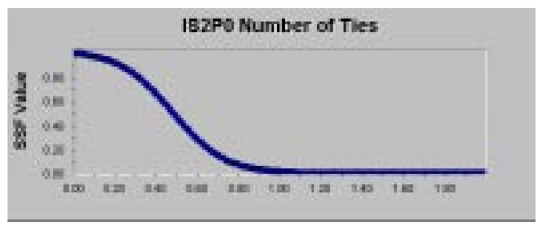

Figure 2 Scoring Function

3. *Happiness*

Score	IS3P0 = SSF (ILTH3P0, IB3P0, IUTH3P0, ISL3P0)
Lower Threshold	ILTH3P0 = 0
Baseline	IB3P0 = 0.5
Upper Threshold	IUTH3P0 = 1
Slope	ISL3P0 = 2

Figure 3 Scoring Function

3.1. *Percent Happy Scouts*

Score	IS3.1P0 = SSF (ILTH3.1P0, IB3.1P0, IUTH3.1P0, ISL3.1P0)
Lower Threshold	ILTH3.1P0 = 0
Baseline	IB3.1P0 = 90
Upper Threshold	IUTH3.P0 = 100
Slope	ISL3.1P0 = 0.1

Figure 4 Scoring Function

3.2. *Number of Irate Parents*

Score IS3.2P0 = SSF (ILTH3.2P0, IB3.2P0, IUTH3.2P0, ISL3.2P0)

Lower Threshold ILTH3.2P0 = 0

Baseline IB3.2P0 = 1

Upper Threshold IUTH3.2P0 = 10

Slope ISL3.2P0 = -1

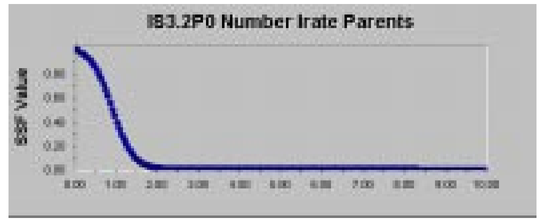

Figure 5 Scoring Function

3.3. *Number of Broken Cars*

Score IS3.3P0 = SSF (ILTH3.3P0, IB3.3P0, IUTH3.3P0, ISL3.3P0)

Lower Threshold ILTH3.3P0 = 0

Baseline IB3.3P0 = 1

Upper Threshold IUTH3.3P0 = 3

Slope ISL3.3P0 = -1

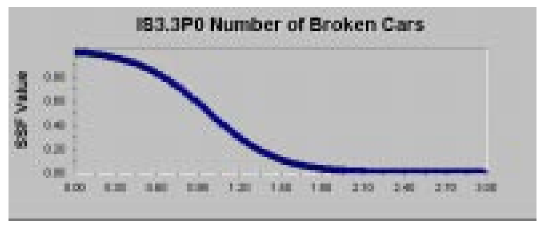

Figure 6 Scoring Function

3.4. *Others Touching Scout's Car*

Score IS3.4P0 = SSF (ILTH3.4P0, IB3.4P0, IUTH3.4P0, ISL3.4P0)

Lower Threshold ILTH3.4P0 = 0

Baseline IB3.4P0 = 2

Upper Threshold IUTH3.4P0 = 7

Slope ISL3.4P0 = -0.5

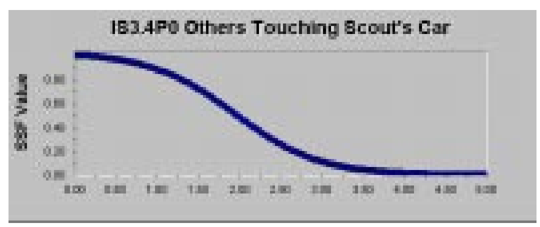

Figure 7 Scoring Function

3.5. *Number of Repeat Races*

Score IS3.5P0 = SSF (ILTH3.5P0, IB3.5P0, IUTH3.5P0, ISL3.5P0)

Lower Threshold ILTH3.5P0 = 0

Baseline IB3.5P0 = 2

Upper Threshold IUTH3.5P0 = 100

Slope ISL3.5P0 = -2

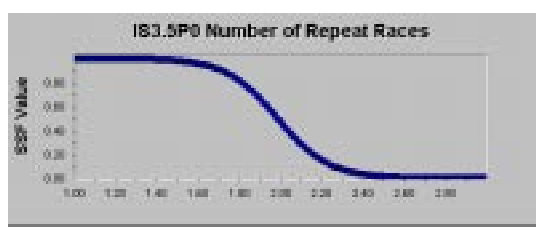

Figure 8 Scoring Function

3.6. *Number of Lane Repeats*

Score IS3.6P0 = SSF (ILTH3.6P0, IB3.6P0, IUTH3.6P0, ISL3.6P0)

Lower Threshold ILTH3.6P0 = 0

Baseline IB3.6P0 = 3

Upper Threshold IUTH3.6P0 = 100

Slope ISL3.6P0 = -3

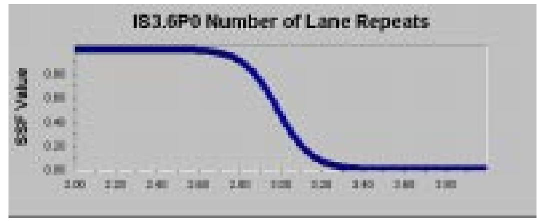

Figure 9 Scoring Function

3.7. *Difference Between Fast and Slow*

Score IS3.7P0 = SSF (ILTH3.7P0, IB3.7P0, IUTH3.7P0, ISL3.7P0)

Lower Threshold ILTH3.7P0 = 0

Baseline IB3.7P0 = 2

Upper Threshold IUTH3.7P0 = 10

Slope ISL3.7P0 = -3

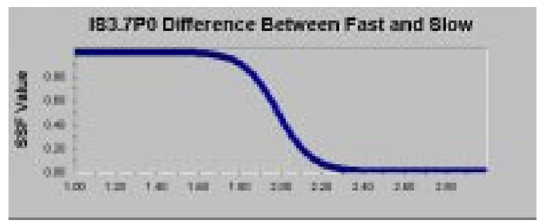

Figure 10 Scoring Function

4. *Availability*

Score IS4P0 = SSF (ILTH4P0, IB4P0, IUTH4P0, ISL4P0)

Lower Threshold ILTH4P0 = 0

Baseline IB4P0 = 0.5

Upper Threshold IUTH4P0 = 1

Slope ISL4P0 = 2

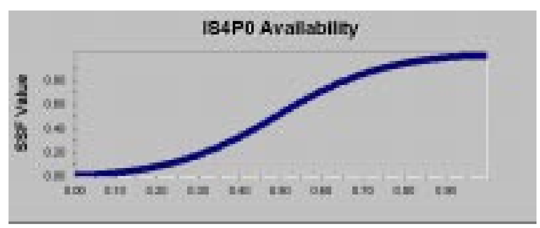

Figure 11 Scoring Function

5. *Reliability*

Score IS5P0 = SSF (ILTH5P0, IB5P0, IUTH5P0, ISL5P0)

Lower Threshold ILTH5P0 = 0

Baseline IB5P0 = 0.5

Upper Threshold IUTH5P0 = 1

Slope ISL5P0 = 2

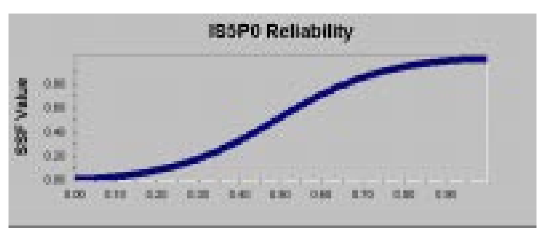

Figure 12 Scoring Function

3.4.3 Weighting criteria

The following importance values, on a scale from 1 to 10, were assigned to each performance figure of merit. The resultant weight, IW*i*P0, was computed by summing all the importance values and dividing each entry by this total.

Figure of Merit	Value	IW*i*P0
1. Average Races per Car	5	0.147
2. Number of Ties	3	0.088
3. Happiness	10	0.294

	Value	Weight
3.1. Percent Happy Scouts	10	0.238
3.2. Number Irate Parents	6	0.143
3.3. Number of Broken Cars	7	0.167
3.4. Others Touching Scout's Car	4	0.095
3.5. Number of Repeat Races	6	0.143
3.6. Number of Lane Repeats	5	0.119
3.7. Difference Between Fast and Slow	4	0.095

4. Availability	8	0.235
5. Reliability	8	0.235

Notice the grouping of the subitems under Happiness. The net result of this is the significant reduction in importance of these factors. The total score that can be achieved by Happiness is 1.0 times the weight. Each item under this heading is weighted so that the category Happiness achieves a score of 1.0 when all those items are at their optimum value. Grouping is necessary to make sense of many related items and can keep them from becoming too important, but its limitations must be recognized.

3.5 Utilization of Resources Requirement

3.5.1 Definition of Resource Figures of Merit

The overall Utilization of Resources Figure of Merit is denoted UF0P0 and is computed by

$$UF0P0 = USF1P0 * UW1P0 + USF2P0 * UW2P0 + \ldots + USFnP0 * UWnP0$$

where n is the total number of Utilization of Resources Figures of Merit and

$$USFiP0 = USiP0(IFiP0(FSD)) \text{ for } i = 1 \text{ to } n$$

as will be shown in the next section.

3.5.2 Lower, upper, baseline, and scoring parameters

In this section, the following naming convention for variables is used: The initial letter "U" indicates that the name is for a Utilization of Resources Requirement. The terminal P0 indicates that the name involves Problem 0 of the Pinewood Derby.

UF*i*P0	=	the i^{th} Utilization of Resources figure of merit.
UB*i*P0	=	the baseline value for the i^{th} figure of merit.
ULTH*i*P0	=	lower threshold for the i^{th} figure of merit.
USF*i*P0	=	score for the i^{th} figure of merit.
US*i*P0	=	scoring function for the i^{th} figure of merit.
USL*i*P0	=	slope for the i^{th} figure of merit.
UUTH*i*P0	=	upper threshold for the i^{th} figure of merit.
UW*i*P0	=	weight of the i^{th} figure of merit.
SSF	=	standard scoring function.

1. *Acquisition Time (in hours)*

Score US1P0 = SSF (ULTH1P0, UB1P0, UUTH1P0, USL1P0)

Lower Threshold	ULTH1P0 = 0
Baseline	UB1P0 = 40
Upper Threshold	UUTH1P0 = 400
Slope	USL1P0 = -0.05

Figure 13 Scoring Function

2. *Acquisition Cost (in dollars)*

Score US2P0 = SSF (ULTH2P0, UB2P0, UUTH2P0, USL2P0)

Lower Threshold	ULTH2P0 = -100
Lower Baseline	UB2P0 = 0
Lower Slope	UUTH2P0 = 0.033
Optimum	USL2P0 = 50
Upper Baseline	UUB2P0 = 100
Upper Threshold	UUTH2P0 = 300
Upper Slope	UUSL2P0 = -0.033

Figure 14 Scoring Function

3. *Total Event Time (in hours)*

Score US3P0 = SSF(ULTH3P0, ULB3P0, ULSL3P0, UOPT3P0, UUB3P0, UUTH3P0, UUSL3P0)

Lower Threshold	ULTH3P0 = 0
Lower Baseline	ULB3P0 = 2
Lower Slope	ULSL3P0 = 0.67
Optimum	UOPT3P0 = 3.5
Upper Baseline	UUB3P0 = 4.5
Upper Threshold	UUTH3P0 = 8
Slope	UUSL3P0=-1

We used a biphasic, hill-shaped scoring function for this figure of merit because we thought the event should last about 3.5 hours. In the months before the race, the scouts in the pack spent about 1000 boy-hours building their cars. For such an investment in time they want an event that lasts a significant amount of time. Anything less than one hour would trivialize their efforts. On the other hand, if the event took more than 5 hours the adults would be exhausted.

4. *Number of Electrical Circuits*

Score US4P0 = SSF (ULTH4P0,UB4P0,UUTH4P0,USL4P0)

Lower Threshold	ULTH4P0 = 0
Baseline	UB4P0 = 1
Upper Threshold	UUTH4P0 = 6
Slope	USL4P0= -1

5. *Number of Adults*

Score US5P0 = SSF (ULTH5P0,UB5P0,UUTH5P0,USL5P0)

Lower Threshold	ULTH5P0 = 1
Baseline	UB5P0 = 5
Upper Threshold	UUTH5P0 = 15
Slope	USL5P0= -0.25

3.5.3 Weighting criteria

The following importance values, on a scale from 1 to 10, were assigned to each Utilization of Resources Figure of Merit. Each resultant weight, UW*i*P0, was computed by summing all the importance values and dividing each entry by this total.

Figure of Merit	**Value**	**UW*i*P0**
1. Acquisition Time	10	0.323
2. Acquisition Cost	6	0.194
3. Total Event Time	8	0.258
4. Numberof Electrical Circuits	3	0.097
5. Number of Adults	4	0.129

3.6 Tradeoff Requirement

The Tradeoff Requirement is computed by the formula

$$TF0P0 = TWlP0 * IFX0P0 + TW2P0 * UFX0P0$$

where TWlP0 is the weight of the Overall I/O Performance Index and TW2P0 is the weight of the overall Utilization of Resources Index. IFX0P0 (FSD) indicates the overall score for the feasible I/O Performance Requirement. UFX0P0 indicates the overall score for the feasible U/R Requirement.

For our initial design we will use the following weights:

$$TWlP0 = 0.9$$

$$TW2P0 = 0.1$$

3.7 System Test Requirement

3.7.1 Test plan

3.7.1.1 Explanation of test plan. The test plan will be based on data submitted for simulation before an actual system is developed. Since there is no time or money for an actual system test before deployment, we will base our selection on the results of our simulation using the test trajectories. The test trajectories are based on actual data collected during the 1991 Pinewood Derby.

The system will be acceptable if:

1. all requirements from this document are satisfied,
2. the system allows for adverse weather conditions,
3. no more than 1500 square feet are used,
4. the system is completed by the first Sunday in February, and
5. restroom facilities are available for participants.

The system will be in compliance if the upper and lower bounds set for each figure of merit are met.

The figures of merit are measured as described under each test trajectory for each of the tests where appropriate. The results are summed and entered in concept selection data sheets.

These are the product failure modes:

1. Electrical failure (if the final system uses electricity) including
   1.1. total loss of electric power and
   1.2. computer failure (if the final system uses computers).
2. Adverse weather conditions preventing the Derby from being completed.
3. Mistakes in judging race finishes or recording results.
4. Human mistakes in
   4.1. weighing the cars,
   4.2. allowing car modifications after inspection,
   4.3. getting the cars in the correct lanes,
   4.4. resetting the finish line switches (if they are used), and
   4.5. wasting time.
5. Track imperfections that cause one lane to be faster than another.

The Grand Marshall will determine if any of these product failure modes are entered during the Derby.

3.7.1.2 Test Trajectory 1. Test Trajectory 1 will determine the system performance through the use of the data for 23 cub scouts from each division. The actual data from the 1991 Pinewood Derby, shown in Exhibit 3, will be used as input trajectories in a computer simulation to estimate racing results.

3.7.1.3 Test Trajectory 2. Test Trajectory 2 will determine if the race judging components are fair. Several cars with similar speeds will be used. Dr. Bahill and Bill Karnavas will be the judges. Forty-six heats will be run (in round robin format with 23 entries), and in each a winner or a tie is declared. Ties will be counted and used as a performance figure of merit.

3.7.2 Input/output performance tests

1. *Average Races per Car:* This will be calculated by dividing the sum of the number of races for each car by the total number of cars that raced based on Test Trajectories 1 and 2.
2. *Number of Ties:* The number of ties are observed during the event either visually (human) or automatically (computer sensing device) based on Test Trajectory 2.
3. *Happiness:* This is a computed measure based on Figures of Merit 3.1 through 3.7.
   3.1. *Percent Happy Scouts:* This figure of merit is calculated by dividing the number of happy scouts leaving the event by the total number of scouts attending. A happy scout is defined as one that leaves the event looking happy, contented, or pleased. Since this determination is subjective, the final decision will be made by the Race Marshall. It will be based partly on the results of Test Trajectory 1.

3.2. *Number of Irate Parents:* This figure of merit will be determined by the committee volunteers during the event. An irate parent is defined as one that disputes the result of a heat or some other judging decision or who makes rude or inappropriate remarks to judges. It will be based on the results of Test Trajectories 1 and 2. Since this is subjective, the final output will be decided by Grand Marshall.

EXHIBIT 3

Raw Data from the Webelos Division of the Pack 212 1991 Pinewood Derby

Round	Heat	Lane	Letter	Time	Place
1	1	1	A	2.5813	First
1	1	2	B	2.6603	Third
1	1	3	C	2.6200	Second
1	2	1	D	2.5779	First
1	2	2	E	Did not Finish	
1	2	3	F	2.7185	Second
1	3	1	G	2.6301	First
1	3	2	H	2.7010	Second
1	3	3	I	3.3249	Third
1	4	1	J	2.6370	First
1	4	2	K	2.8017	Second
1	4	3	L	2.8209	Third
1	5	1	M	2.9979	Third
1	5	2	N	2.6052	First
1	5	3	0	2.6454	Second
1	6	1	P	2.8248	Third
1	6	2	Q	2.5749	First
1	6	3	R	2.6750	Second
1	7	1	S	2.5837	First
1	7	2	T	2.5898	Second
1	7	3	U	2.6382	Third
1	8	1	V	3.0123	Second
1	8	2	W	2.7434	First
2	1	1	L	2.8310	Second
2	1	2	P	2.9599	Third

2	1	3	F	2.7036	First
2	2	1	B	2.6450	Second
2	2	2	M	3.2100	Third
2	2	3	Q	2.5768	First
2	3	1	H	2.7083	Second
2	3	2	W	2.7709	Third
2	3	3	A	2.5892	First
2	4	1	T	2.5720	First
2	4	2	C	2.6224	Second
2	4	3	V	2.8033	Third
2	5	1	S	2.5739	First
2	5	2	D	2.6139	Second
2	6	3	I	2.9690	Third
2	6	1	E	2.5982	First
2	6	2	N	2.6105	Second
2	7	3	G	2.6037	First
2	7	1	J	2.7318	Third
2	7	2	U	2.6614	Second
2	8	3	R	2.6370	Second
2	8	1	K	2.7612	Third
2	8	2	O	2.5880	First
3	1	1	L	2.9174	Second
3	1	2	G	2.6172	First
3	2	3	W	2.7918	Third
3	2	1	N	2.6160	Second
3	2	2	Q	2.5635	First
3	3	3	M	3.0267	Third
3	3	1	J	2.7044	Second
3	3	2	H	2.6813	First
3	4	3	A	2.5632	First
3	4	1	F	2.6709	Second
3	4	2	I	2.9112	Third

3	5	3	R	2.6446	Second
3	5	1	S	2.6641	Third
3	5	2	B	2.6279	First
3	6	3	C	2.5735	First
3	6	1	O	2.6450	Second
3	6	2	P	2.8474	Third
3	7	3	K	2.7667	Third
3	7	1	T	2.6426	Second
3	7	2	D	2.5989	First
3	8	3	E	2.5822	First
3	8	1	U	2.6755	Second
3	8	2	V	2.8769	Third
4	1	1	N	2.6405	First
4	1	2	S	2.6503	Second
4	1	3	P	2.8917	Third
4	2	1	F	2.6738	Second
4	2	2	B	2.6522	First
4	2	3	W	2.7659	Third
4	3	1	Q	2.5961	First
4	3	2	O	2.6072	Second
4	3	3	G	2.6481	Third
4	4	1	J	2.7152	Third
4	4	2	R	2.6936	Second
4	4	3	T	2.6397	First
4	5	1	U	2.6858	First
4	5	2	H	3.1447	Second
4	6	3	V	2.8496	Third
4	6	1	A	2.6222	First
4	6	2	D	2.6275	Second
4	7	3	I	2.9596	Third
4	7	1	L	2.9526	Third
4	7	2	C	2.6647	First

4	8	3	E	2.5839	First
4	8	1	M	3.2985	Third
4	8	2	K	2.7837	Second
5	1	1	W	2.7738	Third
5	1	2	C	2.6280	Second
5	1	3	E	2.5887	First
5	2	1	F	2.6618	Second
5	2	2	Q	2.6184	First
5	2	3	J	2.7273	Third
5	3	1	U	2.6384	First
5	3	2	P	2.9492	Third
5	3	3	B	2.6701	Second
5	4	1	I	2.9798	Second
5	4	2	K	2.7707	First
5	5	3	D	2.5896	First
5	5	1	G	2.6432	Second
5	5	2	M	3.0676	Third
5	6	3	T	2.5643	First
5	6	1	A	2.5925	Second
5	6	2	L	2.8194	Third
5	7	3	H	2.8914	Third
5	7	1	R	2.6579	Second
5	7	2	N	2.6097	First
5	8	3	O	2.5995	First
5	8	1	V	2.8129	Third
5	8	2	S	2.6071	Second
6	1	1	K	2.7295	Second
6	1	2	U	2.6894	First
6	1	3	W	2.8001	Third
6	2	1	L	2.9437	Second
6	2	2	V	2.8436	First
6	2	3	M	2.9730	Third

6	3	1	N	2.6021	Second
6	3	2	A	2.5825	First
6	4	3	B	2.6655	Second
6	4	1	D	2.6212	First
6	4	2	J	2.6748	Third
6	5	3	O	2.6255	Second
6	5	1	F	2.7286	Third
6	5	2	T	2.6215	First
6	6	3	C	2.6036	First
6	6	1	G	2.6718	Third
6	6	2	R	2.6418	Second
6	7	3	P	2.9009	Third
6	7	1	H	2.7924	Second
6	7	2	E	2.5737	First
6	8	3	Q	2.5610	First
6	8	1	I	2.9521	Third
6	8	2	S	2.5989	Second

3.3. *Number of Broken Cars:* The committee volunteers keep a count of all the broken cars. The final output will be decided by the Grand Marshall.

3.4. *Others Touching Scout's Car:* This is a count of the number of people who touch the scout's cars throughout a race, as observed by the Grand Marshall.

3.5. *Number of Repeat Races:* This is based on the simulation results from Test Trajectory 1.

3.6. *Number of Lane Repeats:* This is based on the simulation results from Test Trajectory 1.

3.7. *Difference Between Fast and Slow:* This is based on the simulation results from Test Trajectory 1. It is the difference between the number of heats for the fastest car and the number of heats for the slowest car.

4. *Availability:* This is determined through observation by the committee members at the beginning of the Pinewood Derby. If the system works properly initially, then a figure of merit of 1 is recorded; if the system works for most events but fails for some, 0.8 is recorded; if the system barely works at start-up, then 0.2 is recorded; otherwise, 0 is recorded.

5. *Reliability:* This figure of merit will be determined through observation by the committee members throughout the race. If the system at any time shows signs of not properly conducting races or recording races, it shall be deemed unreliable and a score of 0.8 is recorded. If the system fails often, a score of 0.2 is recorded. If the system fails to work at least half the time, a score of 0 is recorded. If the system always works, a score of 1.0 is recorded.

3.7.3 Utilization of resources tests

1. *Acquisition Time:* This figure of merit represents the number of hours it takes to complete the project, as observed by Dr. Bahill. The minimum value is 0 and the maximum is 400.
2. *Acquisition Cost:* This figure of merit is an approximation by Dr. Bahill of the cost of designing and implementing the system.
3. *Total Event Time:* The total event time will be calculated by subtracting the start time from the end time.
4. *Number of Electrical Circuits:* The system designers will estimate the total number of 120 VAC, 15 A, circuits the system will require.
5. *Number of Adults:* Dr. Bahill will count the number of adults needed.

3.8 Rationale for Operational Need

Data for this document were provided by Dr. Bahill, Bill Karnavas, and the Cub Master. Harry Williams has been the Cub Master for Pack 212 for the past decade. Dr. Bahill and Bill Chapman interviewed him at his home on September 17, 1990. The items listed below summarize his comments.

- The main purpose of the derby is to entertain the scouts; the competition is what makes it fun. We feel that the cars should be raced at least three times to make it worth the effort of creating the vehicle.
- We like to know the results of divisional races during the races. If the format is too technical, we can't understand it. Results can be posted by computer display or handwritten notes on a corkboard.
- The round robin format was used in 1989 and 1990. It is fairer and the scouts get to race their cars more often, though we better understand the double-elimination tournament, which is the technique most packs use. The problem with a double-elimination tournament is that a scout might get to race only twice and he may not race in what he thinks is the best lane.
- The main parental complaint was about weighing the cars. A car's weight limit is 5 ounces, but some weigh in slightly over 5 ounces. The parents say that the pack's scale must be wrong, since they already weighed below the limit at home.
- There is a perception of unfairness in judging when human judges are used, but this perception decreases a lot with computer timing.
- We can get as many adults as we need to manage the derby. Last year we used eight.
- We had only 600 square feet of space to run the races last year; crowd control was a problem. More room would help the scouts to see the races and prevent confusion and damage to their cars. We need parking space for at least 30 automobiles.
- Bleachers would enable everyone to see the races.
- An upper limit of six hours for the entire derby is reasonable.
- We think 50 linear feet of storage space is optimal for cars between races.
- A major disappointment for a scout is when his car does not make it to the bottom of the track because of design flaws. Other boys laugh and his feelings get hurt. We don't know what can be done to avoid this.

4 DOCUMENT 4: SYSTEM REQUIREMENTS VALIDATION

In the System Requirements Validation Document we:
(1) examine the mathematical description of the requirements presented in Document 3 to check for consistency and completeness,
(2) demonstrate that a real world solution can be built, and
(3) show that a real world solution can be tested to prove that it satisfies the requirements.

If the client has requested a perpetual motion machine or a system that reduces entropy, this is the time to stop the project and save money.

4.1 Input/Output and Functional Design

After examining the required inputs and outputs for the Pinewood Derby, it is obvious to us that all of the requirements had been satisfied (although not optimized) in prior years. All of the information needed for this examination was easily obtained. Therefore, we are satisfied that the system's inputs and outputs are feasible.

4.2 Technology for the Buildable System Design

An examination of the Technology Requirement shows nothing that inhibits the functioning of the system. Derbies in the past easily fit within these requirements.

4.3 Input/Output Performance Requirement

All the requirements in this category have been satisfied in past derbies. The most restrictive is the limiting of the number of ties to an upper threshold of five. That number is based on 23 entries in the event. Two closely matched cars may present a problem if the judging resolution is poor. Available technology includes computerized monitoring of the finish line. This will provide a resolution of 0.0001 second, which is accurate enough to prevent ties. Therefore, this requirement can be met.

4.4 Utilization of Resources Requirement

The requirements of this section also have been met in prior derbies. The most restrictive requirement is the upper limit of $300 on acquisition cost. The timing mechanism needed to ensure that only few ties occur could be expensive, but we have found that using a borrowed computer for processing and purchasing switches for installation at the bottom of the track can be done for less than $300.

4.5 Test Requirement

No problems are foreseen in meeting the acceptability, compliance, or observability requirements of this section.

5 DOCUMENT 5: CONCEPT EXPLORATION

The Concept Exploration Document is used to study several different system designs via approximation, simulation, or prototypes, or via a combination of these techniques. The best design alternative is suggested by the data. This document will be rewritten many times as more information becomes available.

5.1 System Design Concepts

5.1.1 System Design Concept 1

System Design Concept 1 specifies a single-elimination tournament. The winner of each heat will advance to the next heat. One loss will eliminate a participant from the tournament.

5.1.2 System Design Concept 2

System Design Concept 2 specifies a double-elimination tournament. Each participant is allowed one loss without elimination, that is, one finish short of first place. First place finishers go on to race only first place finishers; those with one loss race others with one loss. The overall first place winner is the only participant not to be eliminated. The overall second place winner is the car that lost its last heat against the first place finisher, and the third place winner is the second to last car to lose two heats.

5.1.3 System Design Concept 3

System Design Concept 3 specifies a round robin tournament with mean-time scoring to determine overall winners. The round robin is scheduled so that every contestant races at least once in each lane and against as diverse a number of entries as possible. This should help prevent problems with lane bias, and it will add to the number of races for each contestant. Suitable schedules for such round robin tournaments are given in Section 5.8 of this chapter. In the mean-time scoring system, the race times of each contestant for all his heats are averaged; the participant with the lowest mean time is the first place finisher, the second-lowest is the second place finisher, and the third-lowest is the third place finisher.

The median time might be better than the mean time because sometimes a race can be a disaster, with the car falling off the track or a very slow finish of three to four times the car's average time. This kind of poor finish very heavily influences the average time, putting such a contestant essentially out of the running. The median is also easier to calculate than the mean.

5.1.4 System Design Concept 4

System Design Concept 4 specifies a round robin tournament with best-time scoring to determine overall winners. The round robin will be scheduled so that every contestant races at least once in each lane and against as diverse a number of entries as possible. This should help prevent problems with lane bias, and it will add to the number of races for each contestant. In the best-time scoring system, the fastest time of each contestant in each heat is recorded. The lowest time is the first place finisher, the second lowest is the second place finsher, and the third-lowest is the third place finisher.

5.1.5 System Design Concept 5

System Design Concept 5 specifies a round robin tournament with point assignment scoring to determine overall winners. The round robin will be scheduled so that every contestant races at least once in each lane and against as diverse a number of entries as possible. This should help prevent problems with lane bias, and it will add to the number of races for each contestant. In the point assignment scoring system, a first place finish in a heat will be assigned three points; a second place finish, two points; and a third place finish, one point. The contestant with the highest total score is the overall first place finisher, the second highest score is the second place finisher, and the third highest score is the third place finisher.

The advantage of Concept 5 over Concepts 3 and 4 is that exact times from each heat are not necessary, only a determination of who came in first, second, and third. Thus, this concept can be easily implemented using low temporal resolution judging, such as that provided by humans.

5.1.6 System Design Concept 6

System Design Concept 6 specifies that human judges will determine race results. The resolving ability of a human judge is approximately 0.01 second (or 1 inch).

5.1.7 System Design Concept 7

System Design Concept 7 specifies that electronic circuits will determine race results. A switch in each lane is triggered as a car passes the finish line. The resolution of the electronic judging system is 0.0001 second.

The seven concepts above are not independent concepts. They provide alternatives for two independent subproblems—five alternatives for the racing format and two alternatives for judging technique. One alternative must be selected from each category. In general, some system designs will list only one subproblem and others will list many.

5.2 Figures of Merit

The figures of merit are calculated using the test plan described in Document 3 and based on the systems described in Documents 6 and 7. The values obtained for these figures of merit are entered here, then the scores are computed using the standard scoring functions defined in Document 3. The formulas

$$\mathrm{IF0P0(FSD}i\mathrm{) = IWlP0} * \mathrm{ISFlP0} + \ldots + \mathrm{IW}m\mathrm{P0} * \mathrm{ISF}m\mathrm{P0}$$

$$\mathrm{UF0P0(FSD}i\mathrm{) = UWlP0} * \mathrm{USFlP0} + \ldots + \mathrm{UW}n\mathrm{P0} * \mathrm{USF}n\mathrm{P0}$$

are used to compute the overall figures of merit for each design, where *m* is the number of I/O Performance Figures of Merit and *n* is the number of resource figures of merit, and

$$\mathrm{ISFlP0 = ISlP0(IFXlP0(FSD}i\mathrm{))}$$

$$\mathrm{USFlP0 = USlP0(UFXlP0(FSD}i\mathrm{))}$$

where *i* is the concept design number.

The tables on the following pages show the estimates given for the figures of merit. The column titled IFX*i*P0 (where *i* is the figure of merit number) is the figure of merit measured per the test plan. The column labeled ISF*i*P0 is the calculated score after entering the figure of merit into the standard scoring function defined in Document 3. The column IW*i*P0 is the weight factor given in Document 3 for the respective figure of merit. The overall scores, IF0P0 and UF0P0, are determined from the weights and scores.

When there are sub-requirements, a cascade process is followed. First, the value of the figure of merit is obtained; for example, in the table in Section 2.1.1 we expected five irate parents, so the value 5 is entered in the intersection of the row labeled "3.2. Number Irate Parents" and the IFX*i*P0 column. This value is next processed through its scoring function, in this example yielding a score of 0.0. This score is multiplied by its weight, 0.142857. The weighted scores for the seven sub-requirements 3.1 to 3.7 are calculated and then added together. This total is the figure of merit value (the IFX*i*P0 column) for the requirement "3. Happiness" (0.398 in this example). Now we perform the second step of passing this value through its scoring function to get its score of 0.306; this score is then multiplied by its weight, 0.294118. Finally, the weighted scores of all five requirements are summed to give the overall performance figure of merit of 0.656 for the approximation data for this concept.

Three different methods for determining the figures of merit are given: approximation, simulation, and prototype. These methods reflect the different types of data available for determining figures of merit throughout the initial design. Approximation values are based on estimates made by the systems engineer based on experience and historical data. Simulation data are obtained using computer models built to simulate the prototype. Prototype data are calculated from previous derbies.

In the tables below, the figure of merit Number of Ties is treated differently for Concepts 1 to 5 than for Concepts 6 and 7. The number of ties is a function of the judging technique, not of race format. Therefore, values of 0 were entered for the figure of merit for Concepts 1 to 5, whereas actual numbers were used for Concepts 6 and 7. Given this philosophy, perhaps it would have been better to call the figure of merit "Percentage of Races Called a Tie.”

5.2.1 Figures of merit for Concept 1

Concept 1 specifies a single-elimination tournament. Tables for the approximation and simulation methods follow.

5.2.1.1 Approximation figures of merit for Concept 1

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD1)	ISF*i*P0 (FSD1)	IW*i*P0
1 Average Races per Car	2	0.051	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.398	0.306	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	50	0	0.238
3.2 Number Irate Parents	5	0	0.143
3.3 Number of Broken Cars	1.2	0.310	0.167
3.4 Others Touching Scout's Car	1	0.889	0.095
3.5 Number of Repeat Races	0	1	0.143
3.6 Number of Lane Repeats	1	1	0.119
3.7 Difference Between Fast and Slow	5	0	0.095

REQUIREMENTS	IFX*i*P0 (FSD1)	ISF*i*P0 (FSD1)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD1) = 0.656

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD1)	USF*i*P0(FSD1)	UW*i*P0
1 Acquisition Time	10	0.97	0.323
2 Acquisition Cost	10	0.79	0.194
3 Total EventTime	2	0.5	0.258
4 Numberof Electrical Circuits	0	1	0.097
5 Number of Adults	4	0.732	0.129

UFOP0(FSD1) = 0.786

5.2.1.2 Simulation figures of merit for Concept 1

I/O FIGURES OF MERIT

REQUIREMENTS	**IFX*i*P0 (FSD1)**	**ISF*i*P0 (FSD1)**	**Iw*i*P0**
1 Average Races per Car	1.4	0.01	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.37	0.260	0.294

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	50	0	0.238
3.2 Number Irate Parents	5	0	0.143
3.3 Number of Broken Cars	1	0.5	0.167
3.4 Others Touching Scout's Car	1	0.889	0.095
3.5 Number of Repeat Races	0	1	0.143
3.6 Number of Lane Repeats	3	0.5	0.119
3.7 Difference Between Fast and Slow	4	0	0.095

REQUIREMENTS	**IFX*i*P0 (FSD1)**	**ISF*i*P0 (FSD1)**	**Iw*i*P0**
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IF0P0(FSD1) = 0.637

U/R FIGURES OF MERIT

REQUIREMENTS	**UFX*i*P0(FSD1)**	**USF*i*P0(FSD1)**	**UW*i*P0**
1 Acquisition Time	10	0.97	0.323
2 Acquisition Cost	10	0.79	0.194
3 Total Event Time	2	0.5	0.258
4 Number of Electrical Circuits	0	1	0.097
5 Number of Adults	4	0.732	0.129

UF0P0(FSD1) = 0.786

5.2.2 Figures of merit for Concept 2

Concept 2 specifies a double-elimination tournament. Tables for the approximation, simulation, and prototype methods follow.

5.2.2.1 Approximation figures of merit for Concept 2

I/O FIGURES OF MERIT

REQUIREMENTS	**IFX*i*P0 (FSD2)**	**ISF*i*P0 (FSD2)**	**Iw*i*P0**
1 Average Races per Car	3	0.206	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.377	0.271	0.294

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	85	0.119	0.238
3.2 Number Irate Parents	4	0	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	1	0.889	0.095
3.5 Number of Repeat Races	1	1	0.143
3.6 Number of Lane Repeats	2	1	0.119
3.7 Difference Between Fast and Slow	4	0	0.095

REQUIREMENTS	**IFX*i*P0 (FSD2)**	**ISF*i*P0 (FSD2)**	**Iw*i*P0**
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD2) = 0.669

U/R FIGURES OF MERIT

REQUIREMENTS	**UFX*i*P0(FSD2)**	**USF*i*P0(FSD2)**	**UW*i*P0**
1 Acquisition Time	10	0.97	0.323
2 Acquisition Cost	20	0.937	0.194
3 Total Event Time	5	0.119	0.258
4 Number of Electrical Circuits	0	1	0.097
5 Number of Adults	6	0.269	0.129

UFOP0(FSD2) = 0.656

5.2.2.2 Simulation figures of merit for Concept 2

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD2)	ISF*i*P0 (FSD2)	IW*i*P0
1 Average Races per Car	3.7	0.401	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.241	0.103	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	90	0.5	0.238
3.2 Number Irate Parents	4	0	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	2	0.5	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	8	0	0.119
3.7 Difference Between Fast and Slow	3	0	0.095

4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD2) = 0.648

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD2)	USF*i*P0(FSD2)	Uw*i*P0
1 Acquisition Time	10	0.97	0.323
2 Acquisition Cost	20	0.937	0.194
3 Total Event Time	5	0.119	0.258
4 Number of Electrical Circuits	0	1	0.097
5 Number of Adults	6	0.269	0.129

UFOP0(FSD2) = 0.656

2.2.3 Prototype figures of merit for Concept 2

(from the 1988 Derby)

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD2)	ISF*i*P0 (FSD2)	IW*i*P0
1 Average Races per Car	3.7	0.401	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.138	0.036	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	80	0.015	0.238
3.2 Number Irate Parents	7	0	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	5	0.002	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	8	0.5	0.119
3.7 Difference Between Fast and Slow	3	0	0.095

REQUIREMENTS	IFX*i*P0 (FSD2)	ISF*i*P0 (FSD2)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD2) = 0.628

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD2)	USF*i*P0(FSD2)	UW*i*P0
1 Acquisition Time	15	0.937	0.323
2 Acquisition Cost	35	0.994	0.194
3 Total EventTime	5	0.119	0.258
4 Numberof Electrical Circuits	0	1	0.097
5 Number of Adults	6	0.269	0.129

UFOP0(FSD2) = 0.842

5.2.3 Figures of merit for Concept 3

Concept 3 specifies a round robin tournament with mean-time scoring. Tables for the approximation and simulation methods follow.

5.2.3.1 Approximation figures of merit for Concept 3

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD3)	ISF*i*P0 (FSD3)	IW*i*P0
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.514	0.528	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	95	0.889	0.238
3.2 Number Irate Parents	2	0.018	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD3)	ISF*i*P0 (FSD3)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD3) = 0.852

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD3)	USF*i*P0(FSD3)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	70	0.986	0.194
3 Total EventTime	6	0.002	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD3) = 0.577

5.2.3.2 Simulation figures of merit for Concept 3

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD3)	ISF*i*P0 (FSD3)	IW*i*P0
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	0	0.088
3 Happiness	0.514	0.528	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	95	0.889	0.238
3.2 Number Irate Parents	2	0.018	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD3)	ISF*i*P0 (FSD3)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD3) = 0.852

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD3)	USF*i*P0(FSD3)	UW*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	70	0.986	0.194
3 Total EventTime	6	0.002	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD3) = 0.577

5.2.4 Figures of merit for Concept 4

Concept 4 specifies a round robin tournament with best-time scoring. Tables for the approximation, simulation, and prototype methods follow.

5.2.4.1 Approximation figures of merit for Concept 4

I/O FIGURES OF MERIT

REQUIREMENTS	**IFX*i*P0 (FSD4)**	**ISF*i*P0 (FSD4)**	**IW*i*P0**
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.535	0.570	0.294
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	98	0.979	0.238
3.2 Number Irate Parents	2	0.018	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

IFOP0(FSD4) = 0.864

U/R FIGURES OF MERIT

REQUIREMENTS	**UFX*i*P0(FSD4)**	**USF*i*P0(FSD4)**	**UW*i*P0**
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	70	0.986	0.194
3 Total EventTime	6	0.002	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD4) = 0.577

5.2.4.2 Simulation figures of merit for Concept 4

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD4)	ISF*i*P0 (FSD4)	IW*i*P0
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	0	0.088
3 Happiness	0.535	0.570	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	98	0.979	0.238
3.2 Number Irate Parents	2	0.018	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD4)	ISF*i*P0 (FSD4)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD4) = 0.864

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD4)	USF*i*P0(FSD4)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	70	0.986	0.194
3 Total EventTime	6	0.002	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD4) = 0.577

5.2.4.3 Prototype figures of merit for Concept 4
(from the 1991 Derby)

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD4)	ISF*i*P0 (FSD4)	IW*i*P0
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.680	0.812	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	96	0.970	0.238
3.2 Number Irate Parents	0	0.018	0.143
3.3 Number of Broken Cars	0	0.015	0.167
3.4 Others Touching Scout's Car	2	0.889	0.095
3.5 Number of Repeat Races	0	1	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD4) = 0.847

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD4)	USF*i*P0(FSD4)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	100	0.986	0.194
3 Total EventTime	3.5	0.002	0.258
4 Numberof Electrical Circuits	2	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD4) = 0.577

5.2.5 Figures of merit for Concept 5

Concept 5 specifies a round robin tournament with point-assignment scoring. Tables for the approximation, simulation, and prototype methods follow.

5.2.5.1 Approximation figures of merit for Concept 5

<u>I/O FIGURES OF MERIT</u>

REQUIREMENTS	**IFX*i*P0 (FSD5)**	**ISF*i*P0 (FSD5)**	**IW*i*P0**
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.421	0.347	0.294
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	90	0.5	0.238
3.2 Number Irate Parents	2	0.018	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

IFOP0(FSD5) = 0.798

<u>U/R FIGURES OF MERIT</u>

REQUIREMENTS	**UFX*i*P0(FSD5)**	**USF*i*P0(FSD5)**	**Uw*i*P0**
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	70	0.986	0.194
3 Total EventTime	6	0.002	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD5) = 0.577

5.2.5.2 Simulation figures for Concept 5

I/O FIGURES OF MERIT

REQUIREMENTS	**IFX*i*P0 (FSD5)**	**ISF*i*P0 (FSD5)**	**IW*i*P0**
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.467	0.434	0.294

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	92	0.691	0.238
3.2 Number Irate Parents	2	0.018	0.143
3.3 Number of Broken Cars	2	0.015	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD5) =0.824

U/R FIGURES OF MERIT

REQUIREMENTS	**UFX*i*P0(FSD5)**	**USF*i*P0(FSD5)**	**Uw*i*P0**
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	70	0.986	0.194
3 Total EventTime	6	0.002	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD5) = 0.577

5.2.5.3 Prototype figures of merit for Concept 5 (from the 1990 Derby)

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD5)	ISF*i*P0 (FSD5)	IW*i*P0
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.666	0.434	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	90	0.5	0.238
3.2 Number Irate Parents	1	0.5	0.143
3.3 Number of Broken Cars	0	1	0.167
3.4 Others Touching Scout's Car	3	0.118	0.095
3.5 Number of Repeat Races	1	1	0.143
3.6 Number of Lane Repeats	4	0.5	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD5)	ISF*i*P0 (FSD5)	IW*i*P0
4 Availability			0.235
5 Reliability			0.235

IFOP0(FSD5) = 0.804

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD5)	USF*i*P0(FSD5)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	250	0	0.194
3 Total EventTime	4	0.889	0.258
4 Numberof Electrical Circuits	1	0.5	0.097
5 Number of Adults	7	0.118	0.129

UFOP0(FSD5) = 0.615

For the tables for Concepts 6 and 7, we inserted zeros for the Average Races per Car figure of merit because this figure of merit had no direct relationship with the judging technique. Perhaps we should have done this for other figures of merit, such as Number of Broken Cars and Number of Lane Repeats. We should have done a better job in defining the figures of merit, identifying some for choosing the racing format and others for selecting the judging technique

5.2.6 Figures of merit for Concept 6

Concept 6 specifies the use of human judges. Tables for the approximation, simulation, and prototype methods follow.

5.2.6.1 Approximation figures of merit for Concept 6

I/O FIGURES OF MERIT

REQUIREMENTS	**IFX*i*P0 (FSD6)**	**ISF*i*P0 (FSD6)**	**IW*i*P0**
1 Average Races per Car	0	0	0.147
2 Numberof Ties	3	0	0.088
3 Happiness	0.472	0.444	0.294

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	90	0.5	0.238
3.2 Number Irate Parents	10	0	0.143
3.3 Number of Broken Cars	1.5	0.118	0.167
3.4 Others Touching Scout's Car	2	0.5	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	**IFX*i*P0 (FSD6)**	**ISF*i*P0 (FSD6)**	**IW*i*P0**
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD6) = 0.601

U/R FIGURES OF MERIT

REQUIREMENTS	**UFX*i*P0(FSD6)**	**USF*i*P0(FSD6)**	**Uw*i*P0**
1 Acquisition Time	10	0.97	0.323
2 Acquisition Cost	10	0.79	0.194
3 Total EventTime	4	0.889	0.258
4 Numberof Electrical Circuits	0	1	0.097
5 Number of Adults	8	0.046	0.129

UFOP0(FSD6) = 0.798

5.2.6.2 Simulation figures for Concept 6

I/O FIGURES OF MERIT

REQUIREMENTS	**IFX*i*P0 (FSD6)**	**ISF*i*P0 (FSD6)**	**IW*i*P0**
1 Average Races per Car	0	0	0.147
2 Numberof Ties	5	0	0.088
3 Happiness	0.326	0.196	0.294

	Value	**Score**	**Weight**
3.1 Percent Happy Scouts	85	0.119	0.238
3.2 Number Irate Parents	10	0	0.143
3.3 Number of Broken Cars	1	0.5	0.167
3.4 Others Touching Scout's Car	5	0.002	0.095
3.5 Number of Repeat Races	5	0	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD6) = 0.528

U/R FIGURES OF MERIT

REQUIREMENTS	**UFX*i*P0(FSD6)**	**USF*i*P0(FSD6)**	**Uw*i*P0**
1 Acquisition Time	10	0.970	0.323
2 Acquisition Cost	10	0.79	0.194
3 Total EventTime	4.2	0.771	0.258
4 Numberof Electrical Circuits	0	1	0.097
5 Number of Adults	8	0.046	0.129

UFOP0(FSD6) = 0.767

5.2.6.3 Prototype figures of merit for Concept 6
(form the 1989 Derby)

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD6)	ISF*i*P0 (FSD6)	IW*i*P0
1 Average Races per Car	0	0	0.147
2 Numberof Ties	12	0	0.088
3 Happiness	0.36	0.24	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	85	0.119	0.238
3.2 Number Irate Parents	6	0	0.143
3.3 Number of Broken Cars	1	0.5	0.167
3.4 Others Touching Scout's Car	4	0.022	0.095
3.5 Number of Repeat Races	2	0	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD6) = 0.541

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD6)	USF*i*P0(FSD6)	Uw*i*P0
1 Acquisition Time	10	0.970	0.323
2 Acquisition Cost	100	0.5	0.194
3 Total EventTime	5	0.889	0.258
4 Numberof Electrical Circuits	0	1	0.097
5 Number of Adults	8	0.046	0.129

UFOP0(FSD6) = 0.761

5.2.7 Figures of merit for Concept 7

Concept 7 specifies the use of electronic judging. Tables for the approximation, simulation, and prototype methods follow.

5.2.7.1 Approximation figures of merit for Concept 7

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
1 Average Races per Car	0	0	0.147
2 Numberof Ties	1	0.018	0.088
3 Happiness	0.721	0.86	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	98	0.979	0.238
3.2 Number Irate Parents	1	0.5	0.143
3.3 Number of Broken Cars	1	0.5	0.167
3.4 Others Touching Scout's Car	2	0.5	0.095
3.5 Number of Repeat Races	2	0.5	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD7) = 0.725

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD7)	USF*i*P0(FSD7)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	100	0.5	0.194
3 Total EventTime	4	0.889	0.258
4 Numberof Electrical Circuits	2	0.018	0.097
5 Number of Adults	6	0.269	0.129

UFOP0(FSD7) = 0.685

5.2.7.2 Simulation figures of merit for Concept 7

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
1 Average Races per Car	0	0	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.793	0.924	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	98	0.979	0.238
3.2 Number Irate Parents	1	0.5	0.143
3.3 Number of Broken Cars	1	0.5	0.167
3.4 Others Touching Scout's Car	2	0.5	0.095
3.5 Number of Repeat Races	0	1	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD7) = 0.831

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD7)	USF*i*P0(FSD7)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	100	0.5	0.194
3 Total EventTime	4	0.889	0.258
4 Numberof Electrical Circuits	2	0.018	0.097
5 Number of Adults	6	0.269	0.129

UFOP0(FSD7) = 0.586

5.2.7.3 Prototype figures of merit for Concept 7

(from the 1990 and 1991 Derbies)

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
1 Average Races per Car	0	0	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.752	0.85	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	93	0.6	0.239
3.2 Number Irate Parents	0.5	0.88	0.143
3.3 Number of Broken Cars	0	1	0.167
3.4 Others Touching Scout's Car	2.5	0.38	0.095
3.5 Number of Repeat Races	0.5	0.88	0.143
3.6 Number of Lane Repeats	2	0.5	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	0.9	0.959	0.235

IFOP0(FSD7) = 0.798

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD7)	USF*i*P0(FSD7)	Uw*i*P0
1 Acquisition Time	2	0.998	0.323
2 Acquisition Cost	175	0.018	0.194
3 Total EventTime	3.75	0.97	0.258
4 Numberof Electrical Circuits	1.5	0.119	0.097
5 Number of Adults	6.5	0.182	0.129

UFOP0(FSD7) = 0.611

5.2.8 Figures of merit for Concepts 4 and 7 combined

Concept 4 specifies a round robin tournament with best-time scoring, and Concept 7 specifies the use of electronic judging. A table for the prototype method follows.

5.2.8.1 Prototype figures of merit for Concepts 4 and 7 combined

(from the 1992 Derby, with 46 cars observed)

I/O FIGURES OF MERIT

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
1 Average Races per Car	6	0.935	0.147
2 Numberof Ties	0	1	0.088
3 Happiness	0.771	0.907	0.294

	Value	Score	Weight
3.1 Percent Happy Scouts	92.6	0.74	0.238
3.2 Number Irate Parents	0	1	0.143
3.3 Number of Broken Cars	0	1	0.167
3.4 Others Touching Scout's Car	1.47	0.744	0.095
3.5 Number of Repeat Races	10	0	0.143
3.6 Number of Lane Repeats	0	1	0.119
3.7 Difference Between Fast and Slow	0	1	0.095

REQUIREMENTS	IFX*i*P0 (FSD7)	ISF*i*P0 (FSD7)	IW*i*P0
4 Availability	1	1	0.235
5 Reliability	1	1	0.235

IFOP0(FSD7) = 0.946

U/R FIGURES OF MERIT

REQUIREMENTS	UFX*i*P0(FSD7)	USF*i*P0(FSD7)	Uw*i*P0
1 Acquisition Time	10	0.97	0.323
2 Acquisition Cost	72	0.98	0.194
3 Total EventTime	3.5	1	0.258
4 Numberof Electrical Circuits	3	0	0.097
5 Number of Adults	8	0.046	0.129

UFOP0(FSD7) = 0.767

5.3 Tradeoff Analysis

Figures of merit, which are also called measures of effectiveness and attributes and criteria, provide quantitative evidence of the goodness of a design. Typical figures of merit include cost, performance, schedule deviation, weight, reliability, availability, estimated risk, and percent change in requirements.

Figures of merit should be independent and should show compensation. For example, suppose people are to be selected using two figures of merit: years of school completed and annual salary. The resulting recommendation would not be robust, because the two figures of merit are highly dependent. In mathematical terminology, figures of merit should be orthogonal.

To illustrate the concept of compensation, let us imagine astronauts on a long space mission. First consider figures of merit that are good substitutes for each other (in the multicriterion literature this would be called perfect compensation). Suppose the astronauts are to grow their own food. They have two figures of merit: the amount of rice grown and the amount of beans grown. They may want to maximize their yield. For purposes of survival, a lot of rice and few beans is just as good as a lot of beans and little rice. Therefore, we can tradeoff beans for rice. These figures of merit show perfect compensation (such an example from the Systems Engineering literature is preference requirements).

But now suppose the astronauts have a system that produces oxygen and water. A value of zero for either oxygen or water would produce a tradeoff value of zero. A system that produced a huge amount of water but no oxygen might have the highest score due solely to its water producing capabilities. It is clear, however, that such a system would not support life. These figures of merit show no compensation (such an example from the System Engineering literature is mandatory requirements).

The systems engineers life would be a lot simpler if the figures of merit are worded so that ‘more is better.’ For example, instead of using Total Life Cycle Cost use the reciprocal of total life cycle cost. Alternatively, you can use scoring functions (to be discussed later) to invert a negative statement.

A tradeoff analysis allows the systems engineer to tradeoff (give more importance to some criteria and less importance to others) the criteria in order to find the preferred alternative. After the figures of merit are collected and the scores computed, the Overall Performance Figure of Merit and the Overall Utilization of Resources Figure of Merit are used to compute the tradeoff scores for each category of figures of merit. Comparisons are made for the approximation, simulation, and prototype data. The symbology IFOP0 (FSD1) indicates this is the Overall Input/Output Performance Figure of Merit for Problem 0 of Pinewood for the Functional System Design Concept 1.

5.3.1 Approximation tradeoff analysis

The scores for the Input/Output Performance Requirement and the Utilization of Resources Requirement are summarized here with the Tradeoff Requirement.

5.3.1.1 Tradeoff scores

Concept 1: Single-elimination tournament

TWlP0	*	IF0P0(FSD1)	+	TW2P0	*	UF0P0(FSD1)	=	TF0P0(FSD1)
0.9	*	0.656	+	0.1	*	0.786	=	0.668

Concept 2: Double-elimination tournament

TWlP0	*	IF0P0(FSD2)	+	TW2P0	*	UF0F0(FSD2)	=	TF0P0(FSD2)
0.9	*	0.669	+	0.1	*	0.656	=	0.669

Concept 3: Round robin tournament, mean-time scoring

TWlP0	*	IF0P0(FSD3)	+	TW2P0	*	UF0F0(FSD3)	=	TF0P0(FSD3)
0.9	*	0.852	+	0.1	*	0.577	=	0.825

Concept 4: Round robin tournament, best-time scoring

TWlP0	*	IF0P0(FSD4)	+	TW2P0	*	UF0F0(FSD4)	=	TF0P0(FSD4)
0.9	*	0.864	+	0.1	*	0.577	=	0.835

Concept 5: Round robin tournament, point-assignment scoring

TWlP0	*	IF0P0(FSD5)	+	TW2P0	*	UF0F0(FSD5)	=	TF0P0(FSD5)
0.9	*	0.798	+	0.1	*	0.577	=	0.776

Concept 6: Human judges

TWlP0	*	IF0P0(FSD6)	+	TW2P0	*	UF0F0(FSD6)	=	TF0P0(FSD6)
0.9	*	0.601	+	0.1	*	0.798	=	0.621

Concept 7: Electronic judging

TWlP0	*	IF0P0(FSD7)	+	TW2P0	*	UF0F0(FSD7)	=	TF0P0(FSD7)
0.9	*	0.725	+	0.1	*	0.685	=	0.721

5.3.1.2 Approximation alternatives: The preferred alternative from the race formats (Concepts 1 through 5) and the preferred alternative from the judging (Concepts 6 and 7) will be combined into the overall optimal system design alternative. This is possible because these two sets of alternatives are independent of each other.

The preferred race format is Concept 4, the round robin tournament using best-time scoring. The preferred judging alternative is Concept 7, the electronic system. These are based on guesses for the figures of merit and are used as the preferred concepts to begin focusing on.

> *Notice an anomaly in our scoring system. Concept 1, the single elimination tournament got the same score as Concept 2, the double elimination tournament. The Percent Happy Scouts was 50% for the first and 85% for the second, but the overall contribution of the scoring function was 0.0 and 0.119, respectively, times the weight of 0.238. We should have used this information to modify the scoring so that Percent Happy Scouts was emphasized more.*

5.3.2 Simulation tradeoff analysis

5.3.2.1 Tradeoff scores

Concept 1: Single-elimination tournament

TWlP0	∗	IF0P0(FSD1)	+	TW2P0	∗	UF0P0(FSD1)	=	TF0P0(FSD1)
0.9	∗	0.637	+	0.1	∗	0.786	=	0.650

Concept 2: Double-elimination tournament

TWlP0	∗	IF0P0(FSD2)	+	TW2P0	∗	UF0F0(FSD2)	=	TF0P0(FSD2)
0.9	∗	0.648	+	0.1	∗	0.656	=	0.650

Concept 3: Round robin tournament, mean-time scoring

TWlP0	∗	IF0P0(FSD3)	+	TW2P0	∗	UF0F0(FSD3)	=	TF0P0(FSD3)
0.9	∗	0.852	+	0.1	∗	0.577	=	0.825

Concept 4: Round robin tournament, best-time scoring

TWlP0	∗	IF0P0(FSD4)	+	TW2P0	∗	UF0F0(FSD4)	=	TF0P0(FSD4)
0.9	∗	0.864	+	0.1	∗	0.577	=	0.835

Concept 5: Round robin tournament, point-assignment scoring

TWlP0	∗	IF0P0(FSD5)	+	TW2P0	∗	UF0F0(FSD5)	=	TF0P0(FSD5)
0.9	∗	0.824	+	0.1	∗	0.577	=	0.799

Concept 6: Human judges

TWlP0	∗	IF0P0(FSD6)	+	TW2P0	∗	UF0F0(FSD6)	=	TF0P0(FSD6)
0.9	∗	0.528	+	0.1	∗	0.767	=	0.552

Concept 7: Electronic judging

TWlP0	∗	IF0P0(FSD7)	+	TW2P0	∗	UF0F0(FSD7)	=	TF0P0(FSD7)
0.9	∗	0.831	+	0.1	∗	0.586	=	0.807

5.3.2.2 Simulation alternatives. The simulations were done on an IBM AT computer using Test Trajectory 1 for Concepts 1 through 5. Data for the races were based on 1991 actual races and were not varied (see Exhibit 3). The figures of merit Percent Happy Scouts and Number Irate Parents were estimated.

Simulations for Concepts 6 and 7 were done by randomizing data using Test Trajectory 1. The data for a round robin format were used, and the data were varied using a normal data distribution (see Exhibit 4). An estimate for lane bias was created based on the actual data from 1991 (see Exhibit 5). Using these estimates, it was found that 12.9% of the races did not result in the fastest car winning. Most of this was the result of lane bias. Simulation estimated human judging errors were made in 5.2% of the races, with half of those from ties and half from calling the second place finisher the winner. The computer simulation, with a resolution to 0.0001 second, never made an error.

The preferred format is Concept 4, the round robin tournament using best-time scoring. The preferred judging method is Concept 7, the electronic system.

EXHIBIT 4

Statistical Data for Simulations

Car	Average	Standard Deviation
A	2.5885	0.0194
B	2.6534	0.0158
C	2.6187	0.0300
D	2.6048	0.0193
E	2.5853	0.0090
F	2.6930	0.0278
G	2.6357	0.0241
H	2.8200	0.1773
I	3.0161	0.1531
J	2.6984	0.0363
K	2.7689	0.0241
L	2.8808	0.0637
M	3.0956	0.1300
N	2.6140	0.0138
O	2.6184	0.0241
P	2.8957	0.0536
Q	2.5818	0.0218
R	2.6583	0.0221
S	2.6130	0.0364
T	2.6050	0.0343
U	2.6593	0.0236
V	2.8664	0.0762
W	2.7743	0.0200

These data were assumed to be normally distributed. Each car was given a randomized finish time that was based on the average and standard deviation.

[†]EXHIBIT 5

Estimate of Lane Bias

Lane Number	Average	Standard Deviation	Number of Cars	% of Lowest
1	2.7028	0.1436	46	1.0000
2	2.7357	0.1614	45	1.0122
3	2.7216	0.1616	46	1.0070
All	2.7203	0.1555	137	

These data came from races in the Webelos division. The data from another race (Bears division) showed similar results. Therefore, it was decided to include the lane bias as a percent increase over the true time of the car.

A confidence interval can be computed based on these measurements. The computations are shown below.

$$P\left(-1.96 \leq \frac{2.7203 - \mu_T}{0.1436/\sqrt{45}} \leq 1.96\right)$$

The 95% confidence interval for the total of all lanes is then

$$C(2.6942 \leq \mu_T \leq 2.74226) = 0.95$$

Which means that there is a 95% chance the mean is between these numbers. For lane 1,

$$C(2.6608 \leq \mu_T \leq 2.7448) = 0.95$$

For lane 2,

$$C(2.6880 \leq \mu_T \leq 2.7834) = 0.95$$

For lane 3,

$$C(2.6744 \leq \mu_T \leq 2.7688) = 0.95$$

Examining the means of each lane, we see that no firm statement can be made regarding a lane bias, at least not with at 95% certainty. All the regions overlap, indicating they could all have the same time beyond some statistical variation. Indeed, by returning to the normal table we see that the data leave only a 70% confidence interval, which is not much confidence at all!

[†] Material in this exhibit is based on tools not presented in the text. It may be skipped without loss of continuity.

5.3.3 Prototype tradeoff analysis

5.3.3.1 Tradeoff scores

Concept 2: Double-elimination tournament

TWlP0	*	IF0P0(FSD2)	+	TW2P0	*	UF0F0(FSD2)	=	TF0P0(FSD2)
0.9	*	0.628	+	0.1	*	0.842	=	0.649

Concept 4: Round robin tournament, best-time scoring

TWlP0	*	IF0P0(FSD4)	+	TW2P0	*	UF0F0(FSD4)	=	TF0P0(FSD4)
0.9	*	0.847	+	0.1	*	0.577	=	0.820

Concept 5: Round robin tournament, point-assignment scoring

TWlP0	*	IF0P0(FSD5)	+	TW2P0	*	UF0F0(FSD5)	=	TF0P0(FSD5)
0.9	*	0.804	+	0.1	*	0.615	=	0.785

Concept 6: Human judges

TWlP0	*	IF0P0(FSD6)	+	TW2P0	*	UF0F0(FSD6)	=	TF0P0(FSD6)
0.9	*	0.541	+	0.1	*	0.761	=	0.563

Concept 7: Electronic judging

TWlP0	*	IF0P0(FSD7)	+	TW2P0	*	UF0F0(FSD7)	=	TF0P0(FSD7)
0.9	*	0.798	+	0.1	*	0.611	=	0.779

5.3.3.2 Prototype alternatives. Only prototypes from Concepts 2, 4, 5, 6, and 7 were built. Data for all of these concepts were available from prior years, thus historical data became our prototype. However, we have little confidence that the data presented were indeed collected as they were supposed to be. Dr. Bahill and Bill Karnavas have assured us that the quality of the data we received was acceptable. The only real surprise was the lack of reliability of the electronic scoring, which gave us a score of only 0.8. The reason for this was a brief system failure (a software error) during the race.

The preferred race format is Concept 4, the round robin using best-time scoring. The preferred judging method is Concept 7, the electronic system.

Our tradeoff analyses produced the same conclusions for the approximation, simulation, and prototype data: The round robin tournament with best-time scoring is the preferred race format and electronic judging is better than human judging. It would be unfortunate if the three sets of data yielded different conclusions, because they would require expensive revisions.

5.4 Sensitivity Analysis, Prototype Data

The system is sensitive to the tradeoff weightings. For example, changing weights of the Tradeoff Requirement can easily sway the answer, current tradeoff puts heavy emphasis on the I/O performance of the system (0.90) and not on the utilization of resources (0.10). Changing the degree emphasis can change the results, as summarized below using a 0.50/0.50 weighting and then a 0.30/0.70 weighting.

Weights: 0.90/0.10		Weights: 0.50/0.50		Weights: 0.30/0.70	
Concept	Score	Concept	Score	Concept	Score
2	0.649←	2	0.735←	2	0.778←
4	0.820	4	0.712	4	0.658
5	0.785	5	0.709	5	0.672
6	0.563	6	0.651	6	0.695←
7	0.779←	7	0.704←	7	0.667

In the 0.90/0.10 tradeoff, the preferred race format is Concept 4, the round robin using best-time scoring. The preferred judging method is Concept 7, the electronic system.

In the 0.50/0.50 tradeoff, the double-elimination format beats the round robin. This is because less time is spent in generating schedules and fewer adults are needed.

In the 0.30/0.70 tradeoff, the double-elimination format is the best, as is the human judging alternative. Electronic judging loses because of its higher cost and greater use of time.

This indicates that if a scout pack is strapped for resources, the preferred approach is double-elimination with human judges. Otherwise, a round robin format with electronic judging is the preferred system.

B. Karnavas has done an extensive sensitivity analysis of this system (Karnavas, Sanchez, Bahill, 1993). He found that only two parameters (out of 92) could change the recommended alternatives. The first was the tradeoff weighting, as discussed above. The second was the slope of the scoring function for the figure of merit Percent Happy Scouts.

If this was increased from 0.1 to 0.3, Concept 3 (round robin, mean time) would be preferable to Concept 4 (round robin, best time).

This sensitivity study shows our design is insensitive to variations in almost all of the parameters. It is a robust design. We are pleased with this result.

5.5 Rationale for Alternatives, Models, and Methods

An important part of systems engineering is encouraging an exploration of all possible alternatives. For the Pinewood Derby we briefly considered the following concepts:

1. Do not race; have a judge pick the winners based solely on appearance.
2. Race, but do not pick winners.
3. Have the audience vote on the winners by whatever criteria they choose.
4. Have every car race only once, with the fastest time winning.
5. Run handicap races. Measure times in initial heats, then let the slower cars add weight.
6. Build a track with other than the traditional three lanes.
7. Run round robin races, but arrange the schedules so that fast cars race fast cars and slow cars race slow cars.
8. Run a triple-elimination tournament.

We surveyed many techniques for deciding the winner of each race. The following five techniques received detailed analysis:

1. *Human observation.* This is the oldest and most common technique. Human judges are good at detecting the correct winner if the cars finish one or more inches apart (a 0.01s difference). In closer races, humans often make mistakes or announce ties, which necessitates a subsequent rerun of the heat.

2. *Photography*. A Polaroid camera could be mounted above the finish line to photograph the finish of each heat. This would cost 75¢ per heat and require one to two minutes for the photograph to develop. If the shutter were pressed at the wrong time, no cars would be in the field of view. This system was considered too slow, costly, and cumbersome.

3. *Bar code readers.* Paper bar codes could be glued to the bottom of each car, and bar code readers could be installed under the track at the finish line. This technique would not only tell which lane won, but also which car was in that lane. Merely stating that Lane 1 won could produce mistakes if, as often happens, Car A was supposed to be in Lane 1, but Car B was actually put there. The bar code readers we used cost $1000, and one would be needed for each lane. This alternative was considered too expensive.

4. *Optical sensors.* We used optical sensors mounted in the track at the start and finish lines to determine the winner of each heat. The optical sensors were attached to electronic stopwatches that were accurate to 0.01s. We found that this was not more accurate than human judges. This system worked well until the temperature dropped 30°F, and the batteries lost their ability to deliver power. It has been said that such systems give false results in the presence of flash photography, although we did not experience this problem.

5. *Mechanical switches.* We installed mechanical switches in each lane at the start and finish lines. The disadvantages of such switches are that they bounce, and sometimes they fail to make good contact. However, we found ways to overcome these problems. The advantage of this mechanical switch timing system was that we could buy a complete system for $150. The mechanical switches were connected to an IBM compatible personal computer. The system was accurate to 0.0001s. We had no ties using this system. The computer was also used for scheduling and analyzing results.

For simplicity in the rest of this case study, the selection of the judging technique (Concepts 6 and 7) will not be considered a part of the system we are designing. We will only consider the consequences of 0.01s and 0.0001s resolutions.

6 DOCUMENT 6: SYSTEM FUNCTIONAL ANALYSIS

The System Functional Analysis Document decomposes the 1/0 Requirements into a functional system design. Its intended audience is systems engineers.

6.1 System Functional Analysis of Concept 1

6.1.1 Top level system functional analysis of Concept 1

System Concept 1 is a single-elimination tournament. The entire system has been modeled based on the current design. The major components of this model are shown in Figure 15. The major subfunctions are:

1. Inspect
2. Impound
3. Racing
4. Judging
5. Results

The system model shown in Figure 15 is the baseline that all other concepts will alter. The modeling of the System Subfunction 5 (Results) is altered for this concept.

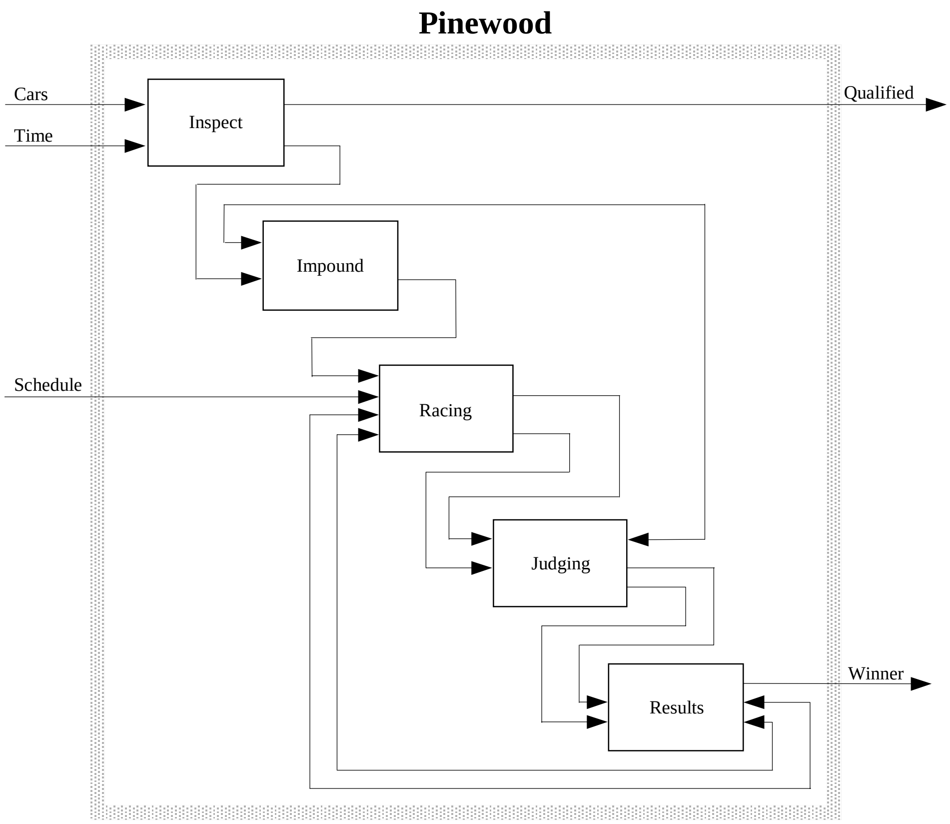

Figure 15 Major Components of Pinewood Model

6.1.2 Subfunction decomposition

6.1.2.1 Subfunction 1. Subfunction 1 is Inspect. Cars enter the system at this point. They are inspected for conformance to the rules of the Pinewood Derby. If they pass, they proceed to the Impound area. If they fail, they leave the system with a disqualified tag.

6.1.2.2 Subfunction 2. Subfunction 2 is the Impound function. Cars are placed in this holding area after they pass inspection and while they wait for a race. They exit this area only on a request from the Racing component.

6.1.2.3 Subfunction 3. Subfunction 3 is the Racing component. The Racing component will perform the following functions:

1. If a new race then
   Get cars from the Impound area per the schedule and schedule index,
   else if a tie then
   Get cars from the Judging component based on the schedule and schedule index.
2. Set the cars at the starting blocks,
3. Start the race,
4. Send the cars back to the Judging component,
5. Output the new schedule index.

The schedule index is increased by one after each race. See Exhibit 6 for an example of a single-elimination tournament schedule. This schedule is input to the racing component and defines the scheduling of races. Cars are removed from the Impound component and placed in the appropriate lanes based on the schedule. The incrementing index tracks the races throughout the derby.

EXHIBIT 6

Single-Elimination Tournament: 23 Cars (A Through W.)

Heat #	Lane 1	Lane2	Lane3	Comment
1	A	B	C	
2	D	E	F	
3	G	H	I	
4	J	K	L	
5	M	N	O	
6	P	Q	R	
7	S	T	U	
8	V	W		
9	F1	F2	F3	
10	F4	F5	F6	
11	F7	F8		
12	F9	F10	Fll	1st is first place

Note: F1 means the first place finisher of the first heat; F2 means the first place finisher of the second heat; and so on.

6.1.2.4 Subfunction 4. Subfunction 4 is the Judging component. The output of each heat is sent to this component. The results of each heat are decided as follows:

1. First place awarded to the car that crosses the finish line first.
2. Second place awarded to the car that crosses the finish line second.
3. Third place awarded to the car that crosses the finish line last.
4. A tie occurs if the first and second cars finish at the same time.
5. A nil occurs if the car does not cross the finish line.

The Judging component outputs the cars to the Impound area if there was no tie. If there was a tie, the cars are sent back to Racing component, and a judging flag is set to 1. If no judging is occurring, the flag is 0. If a valid race has occurred, then the judging flag is set to 1. The results of the heat for each car are sent to the Results component.

6.1.2.5 Subfunction 5. Subfunction 5 is the Results function. The results of each heat are sent here from the Judging component. Results are tallied per heat. Results of every heat are output to outside of the system (the spectators and scouts), showing the current place of each car.

> *In this particular example, the five subfunctions coincide with the five physical components of the system. This is not always the case; for example, a computer may handle hundreds of different functions on one processor.*

6.1.3 Complete subfunction model

6.1.3.1 Terminology

Z1' = (SZ1', IZ1', OZ1' NZ1', RZ1')

Where

Z1'	=	model of the Results component of the system,
SZ1'	=	states of the system,
IZ1'	=	inputs to the system,
OZ1'	=	outputs of the system,
NZ1'	=	next state function, and
RZ1'	=	readout function.

6.1.3.2 States

SZ1' = {Wait, Fix Schedule #i j k, Tally #i j k p1 p2 p3}

This lists all the states where # is the index number; i j k represents the valid car names in Lanes 1, 2, and 3, respectively; and p1 p2 p3 are the places for Lanes 1, 2, and 3, respectively.

6.1.3.3 Inputs

IZ1' = I1Z1' x I2Z1'

I1Z1' = {#,i, j, k, place 1, place 2, place 3} where

= IJS[0,39] /*the schedule index*/

i = ALPHA /*valid car label in lane 1*/

j = ALPHA / *valid car label in lane 2*/

k = ALPHA /*valid car label in lane 3*/

place1 = {1st, 2nd, 3rd, Nil} /*finish place for car i*/

place2 = {1st, 2nd, 3rd, Nil} /*finish place for car j*/

place3 = {1st, 2nd, 3rd, Nil} /*finish place for car k*/

I2Z1' = {(index, lane 1, lane 2, lane 3)^num}

/*this represents the schedule in the form of Exhibit 6. The*/

/*variable num represents the length of the schedule*/

6.1.3.4 Outputs

0Z1' = 01Z1' x 02Z1' x 03Z1'

01Z1' = {index, i, j, k, place 1, place 2, place 3}

/*This represents the Tally sheet as shown in Exhibit 8*/

02Z1' = IJS[1, INFINITY) /*This is the schedule index number*/

03Z2' = {(index, lane 1, lane 2, lane 3)^num}

/*This represents the new schedule in the form of Exhibit 6. The*/

/*variable num represents the length of the schedule.*/

6.1.3.5 Next state function

NZ1 ' = {((Wait, ((0, x, x, x, x, x, x),any)), Wait),

((Wait, ((#, i, j, k, place 1, place 2, place 3), any)), Fix Schedule #i j k),

((Fix Schedule #i j k, ((#, i, j, k, place 1, place 2, place 3), any)), Tally #i j k p1 p2 p3), ((Tally #i j k p1 p2 p3, ((#, i, j, k, place 1, place 2, place 3), any)), Wait)}

where the next states, Fix Schedule #i j k and Tally #i j k p1 p2 p3, correspond with the inputs #, i, j, k, place 1, place 2, place 3 from Port 1. For example an input of (8, C, F, J, 2nd, 3rd,1st) would yield a next state of Fix Schedule 8 C F J or of Tally 8 C F J 2nd 3rd 1st.

6.1.3.6 Readout function

RZ1 ' = {(Wait, ((0, nil^6), 0, (0, 0, 0, 0)^num)),

(Fix Schedule #i j k, ((nil^6), nil, (#, i, j, k))),

(Tally #i j k p1 p2 p3, ((#, i, j, k, p1, p2, p3), #+1, (nil^4)^num))}

6.2 System Functional Analysis of Concept 2

6.2.1 Top level system functional analysis of Concept 2

System Concept 2 is a double-elimination tournament. The entire system has been modeled on the current design. The major components of this model are the same as for Concept 1 and are shown in Figure 15. The modeling of the Results component from the baseline system is altered for this concept.

6.2.2 Subfunction decomposition

The system's subfunctions are decomposed the same as in Concept 1, except the schedule is different. Exhibit 7 is an example of a double-elimination tournament schedule. This schedule is provided to the Racing component and defines the scheduling of races.

EXHIBIT 7

Double-Elimination Tournament: 23 Cars (A through W)

Heat #	Lane 1	Lane2	Lane3	Comment
1	A	B	C	
2	D	E	F	
3	G	H	I	
4	J	K	L	
5	M	N	O	
6	P	Q	R	
7	S	T	U	
8	V	W		
9	F1	F2	F3	
10	F4	F5	F6	0 losses, 2nd race
11	F7	F8		0 losses, 2nd race
12	S1	S2	T7	1 loss,2nd race
13	S3	S4	T6	1 loss, 2nd race
14	S5	T4	T3	1 loss,2nd race
15	S6	S7	T5	1 loss,2nd race
16	S8	T2	T1	1 loss,2nd race
17	S9	T10	S11	1 loss, 3rd race
18	S10	T9	F12	1 loss, 3rd race
19	F13	F14		1 loss, 3rd race
20	F16	F15		1 loss,3rd race
21	F9	F10	F11	0 losses, 3rd race, 1st is winner
22	S21	F17	F18	1 loss, 4th race
23	T21	F19	F20	1 loss,4th race
24	F22	F23		1st is second, 2nd is third

Note: F1 is the first place finisher of the first heat, F2 is the first place finisher of the second heat, and so on. S1 is the second place finisher of the first heat, and T1 is the third place finisher of the first heat.

6.2.3 Complete subfunction model

6.2.3.1 Terminology

Z2' = (SZ2', IZ2', OZ2', NZ2', RZ2')

where

Z2'	=	model of the Racing component of Concept 2,
SZ2'	=	states of the system,
IZ2'	=	inputs to the system,
OZ2'	=	outputs of the system
NZ2'	=	next state function, and
RZ2'	=	readout function.

This model is identical to that for Z1'.

6.3 System Functional Analysis of Concept 3

6.3.1 Top level system functional analysis of Concept 3

System Concept 3 is a round robin format with mean-time scoring for the Results component. The entire system has been modeled on the current design. The major components of this model are the same as in Concept 1 and are shown in Figure 15. The modeling of the system Results component is altered for this concept.

6.3.2 Subfunction decomposition

The system is decomposed the same as in Concept 1, except the schedule is different. See Section 8 of this chapter for examples of round robin tournament schedules. For this concept, the mean time of each heat is calculated and stored in the Results subfunction. The result of each heat is provided by the Judging component. The division winners are determined by the best mean score of each heat.

6.3.3 Complete subfunction model

6.3.3.1 Terminology

Z3' = (SZ3', IZ3', OZ3', NZ3', RZ3')

where

Z3'	=	model of the Racing system,
SZ3'	=	states of the system,
IZ3'	=	inputs to the system,
OZ3'	=	Outputs of the system,
NZ3'	=	next state function, and
RZ3'	=	Readout function.

6.3.3.2 States

SZ3' = {Wait, Fix Schedule #i j k, Tally #i j k p1 p2 p3}

6.3.3.3 Inputs

IZ3' = I1Z3' x I2Z3' x I3Z3'

I1Z3' = {#, i, j, k, place 1, place 2, place 3} where

= IJSCO, 39] /*the schedule index*/

i = ALPHA /*valid car label in lane 1*/

j = ALPHA / *valid car label in lane 2*/

k = ALPHA /*valid car label in lane 3*/

EXHIBIT 8

Part of a Tally Sheet

Webelos

Pack 212 Pinewood Derby Tally Sheet

Car Label	Scout's Name	Den	Round Number 1	2	3	4	5	6	Result	Den Winners	Division Winners
A											
B											
C											
D											
E											
F											
G											
• • •											
DD											
EE											
FF											
GG											
HH											
II											
JJ											

Place1 = IJS[O,INFINITY)
/*finish place for car i*/
Place2 = IJS[O,INFINITY)
/*finish place for car j*/
Place3 = IJS[O,INFINITY)
/*finish place for car k*/

I2Z3' = {(index,lane1,lane2,lane3)^num}

/*this represents the schedule in the form of Exhibit 6. The variable num*/

/*represents the length of the schedule*/

6.3.3.4 Outputs

OZ3 ' = 01 Z3 ' x 02Z3 ' x 03Z3 '

01Z3' = {index, i, j, k, place 1, place 2, place 3}

/*This represents the Tally sheet as shown in Exhibit 8*/

02Z3' = IJS[1, INFINITY)

/*This is the schedule index number*/

03Z3 ' = {(index, lane1, lane2, lane3)^num}

/*This represents the new schedule in the form of those shown in Section 8.*/

/*The variable num represents the length of the schedule.*/

6.3.3.5 Next state function

NZ3' = {((Wait, ((0, x, x, x, x, x, x), any)), Wait),

((Wait, ((#, i, j ,k, place 1, place 2, place 3), any)), Fix Schedule #i j k),

((Fix Schedule #i j k, ((#, i, j, k, place 1, place 2, place 3), any)), Tally #i j k p1-p2-p3),

((Tally #i j k p1 p2 p3, ((#, i, j, k, place 1, place 2, place 3), any)), Wait)}

where the next states Fix Schedule #i j k and Tally #i j k p1 p2 p3 correspond with the inputs #, i, j, k, place 1, place 2, place 3, from Port l. For example, an input of (8, C, F, J, 40, 43, 35) means the eighth race per the schedule using Cars C, F, and J resulted in times of 40, 43, and 35, respectively. This would yield a next state of Fix Schedule 8 C F J to update the schedule and then Tally 8 C F J 40-43-35 to update the tally sheets.

6.3.3.6 Readout function

RZ3' = {(Wait, ((0, nil^6), 0,(0, 0, 0, 0)^num)),
(Fix Schedule #i j k, ((nil^6), nil, (#, i, j, k))),
(Tally #i j k p1-p2-p3, ((#, i, j, k, p1, p2, p3),
#+1, (nil^4)^num))}

6.4 System Functional Analysis of Concept 4

6.4.1 Top level system functional analysis of Concept 4

System Concept 4 is a round robin format, the winner being determined by the fastest race time. The entire system has been modeled on the current design. The major components of this model are identical to Concept 3 except for the Results section.

6.4.2 Subfunction decomposition

The functional decomposition is the same as Concept 3 except for the Results subfunction. For this concept, the best time in each heat is calculated and stored in the Results component. The result of each heat is as provided by the Judging component. The division winners are those having the best time in all the heats.

6.4.3 Complete subfunction model

6.4.3.1 Terminology

Z4' = (SZ4', IZ4', OZ4', NZ4', RZ4')

where

Z4'	=	model of the system,
SZ4'	=	states of the system,
IZ4'	=	inputs to the system,
0Z4'	=	Outputs of the system,
NZ4'	=	next state function, and
RZ4'	=	Readout function

Z4' is identical to Z3' except for the scoring method used.

6.5 System Functional Analysis of Concept 5

6.5.1 Top level system functional analysis of Concept 5

System Concept 5 is a round robin format with point-assignment scoring. The entire system has been modeled on the current design. The major components of this model are identical to Concept 3 except that system components Racing and Results are altered for this concept.

6.5.2 Subfunction decomposition

6.5.2.1 Subfunction 1. Subfunction 1 is the Inspect function. This is the same as for Concept 3.

6.5.2.2 Subfunction 2. Subfunction 2 is the Impound function. This is same as for Concept 3.

6.5.2.3 Subfunction 3. Subfunction 3 is the Racing component. The Racing component will perform the following functions:

1. If a new heat then
   Get cars from the Impound area per the schedule and schedule index,
   else if a tie then
   Get cars from the Judging component for the schedule and schedule index.
2. Set the cars at the starting blocks,
3. Start the heat,
4. Send the cars back to the Judging component,
5. Output the new schedule index.

The schedule index is increased by one each time. See Section 8 for examples of round robin tournament schedules. One of these schedules is input to the Racing component and defines the scheduling of races. Cars are removed from the Impound component and placed in the appropriate lanes based on the schedule. The incrementing index tracks the races throughout the derby.

6.5.2.4 Subfunction 4. Subfunction 4 is the Judging component. This component is the same as for Concept 3.

6.5.2.5 Subfunction 5. Subfunction 5 is the Results function. The results of each heat are sent here from the Judging component. Race results are tallied per heat, the pack, and the division. Results are output external to the system (the spectators and scouts), clearly showing the current place of each car.

For this concept, each heat score is calculated and stored based on 3 points for first, 2 points for second, 1 point for third, and 0 points for a no-show or a heat not completed. The result of each heat is as provided by the Judging component. The division winners are determined by the best average score of each heat.

6.5.3 Complete subfunction model

6.5.3.1 Terminology

Z5' = (SZ5', IZ5', OZ5', NZ5', RZ5')

where

Z5'	=	model of the Racing component,
SZ5'	=	states of the system,
IZ5'	=	inputs to the system,
OZ5'	=	outputs of the system,
NZ5'	=	next state function, and
RZ5'	=	readout function.

System Z5' is identical to system Z3' except for the scoring method.

6.6 System Functional Analysis of Concept 6

6.6.1 Top level system functional analysis of Concept 6

System Concept 6 uses a human judge to decide winners of races. The entire system has been modeled on the current design. The major components of this model are the same as in Concept 1, as shown in Figure 15. The modeling of the system component Judging is altered for this concept.

6.6.2 Subfunction decomposition

The system decomposition is the same for this model as that for Concept 1, except for the Judging component. The judges will decide which car has won only when the difference in their finish times is greater than 0.01s. Otherwise, a tie will be declared.

6.6.3 Complete subfunction model

6.6.3.1 Terminology

Z6' = (SZ6', IZ6', OZ6', NZ6', RZ6')

where

Z6'	=	model of the Judging system,
SZ6'	=	states of the system,
IZ6'	=	inputs to the system,
OZ6'	=	outputs of the system,
NZ6'	=	next state function, and
RZ6'	=	readout function.

6.6.3.2 States

SZ6' = {Start, Lane 1 First, Lane 2 First, Lane 3 First, Lane 1 2 3 i j k, Lane 1 3 2 i j k, Lane 2 1 3 i j k, Lane 2 3 1 i j k, Lane 3 1 2 i j k, Lane 3 2 1 i j k, Tie}

where i j k represents the valid names of cars in lanes 1, 2, and 3, respectively.

6.6.3.3 Inputs

IZ6' = {(car, t)^3}   /*where car is any valid name of a car in the derby or is Nil,*/
/*and t is the time the car reached the finish line*/

6.6.3.4 Outputs

OZ6' = 01Z6' x 02Z6'

01Z6'	=	{cars^3}	/*where cars represents any valid name of a car*/ /*in the derby, or is Nil*/
02Z6'	=	{-1,0,1}	/*where -1 represents a tie, and 0 is no race, and*/ /*1 is a valid race*/
03Z6'	=	{(car,place)^3}	/*where car is a valid car entry and place is First,*/ /*Second, Third, Tie, or Nil*/
04Z6'	=	{cars^3}	/*where cars represents any valid name of a car*/ /*in the derby, or is Nil*/

6.6.3.5 Next state function

```
NZ6' = {((Start, f1), Next State 1),
        ((Lane 1 First, f2), Next State 2),
        ((Lane 2 First, f3), Next State 3),
        ((Lane 3 First, f4), Next State 4),
        ((Lane 1 2 3 i j k, any), Start),
        ((Lane 1 3 2 i j k, any), Start),
        ((Lane 2 1 3 i j k, any), Start),
        ((Lane 2 3 1 i j k, any), Start),
        ((Lane 3 1 2 i j k, any), Start),
        ((Lane 3 2 1 i j k, any), Start),
        ((Tie, any), Start)}
```

where

```
/*f1 determines who is first*/
f1 = (let ((p11, p12), (p21, p22), (p31, p32))=IZ6';
        if (p12 > p22+resolve and p12 > p32+resolve) then
                Next State 1 = Lane 1 First
        else if (p22 > p12+resolve and p22 > p32+ resolve) then
                Next State 1 = Lane 2 First
        else if (p32 > p12+resolve and p32 > p22+ resolve) then
                Next State 1 = Lane 3 First
```

```
        else if (p11=Nil and p21=Nil and P31=Nil) then
                Next State 1 = Start
        else
                Next State 1 = Tie;)
/*f2 determines who is second and third if 1 is first*/
f2 = (let ((p11, p12), (p21, p22), (p31, p32))=IZ6';
        if (p22 > p32+resolve) then
                Next State 2 = Lane 1 2 3 i j k
        else
                Next State 2 = Lane 1 3 2 i j k;)
/*f3 determines who is second and third if 2 is first*/
f3 = (let ((p11, p12), (p21, p22), (p31, p32))=IZ6';
        if (p12 > p32 + resolve) then
                Next State 3 = Lane 2 1 3 i j k
        else
                Next State 3 = Lane 2 3 1 i j k;)
/*f4 determines who is second and third if 3 is first*/
f4 = (let ((p11, p12), (p21, p22), (p31, p32))=IZ6';
        if (p12 > p22 + resolve) then
                Next State 4 = Lane 3 1 2 i j k
        else
                Next State 4 = Lane 3 2 1 i j k;)
```

where resolve = 0.01s for human judges, and i j k corresponds to pl1, p21, and p31, respectively.

6.6.3.6 Readout function

```
RZ6' = {(Start, ((Nil)^3, 0, (Nil, Nil)^3)), (Nil)^3),
    (Lane 1 First, ((Nil)^3, 0, (Nil, Nil)^3), (Nil)^3),
    (Lane 2 First, ((Nil)^3, 0, (Nil, Nil)^3), (Nil)^3),
    (Lane 3 First, ((Nil)^3, 0, (Nil, Nil)^3), (Nil)^3),
    (Lane 1 2 3 i j k, ((Nil)^3, 1, ((p11, First),
    (p21, Second), (p31, Third)), (i, j, k)),
    (Lane 1 3 2 I j k, ((Nil)^3, 1, ((p11, First),
    (p21, Third), (p31, Second)), (i, j, k)),
    (Lane 2 1 3 i j k, ((Nil)^3, 1, ((p11, Second),
    (p21, First), (p31, Third)), (i, j, k)),
```

(Lane 2 3 1 i j k, ((Nil)^3, 1, ((p11, Third),
(p21, First), (p31, Second)), (i, j, k)),
(Lane 3 1 2 i j k, ((Nil)^3, 1, ((p11, Second),
(p21, Third), (p31, First)), (i, j, k)),
(Lane 3 2 1 i j k, ((Nil)^3, 1, ((p11, Third),
(p21, Second), (p31, First)), (i, j, k)),
(Tie i j k, (i j k, -1, (Nil, Nil)^3), (Nil)^3)}

where we let ((p11, p12), (p21, p22), (p31, p32)) = IZ6'.

6.7 System Functional Analysis of Concept 7

6.7.1 Top level system functional analysis of Concept 7

System Concept 7 uses an electronic system to judge the winners of races. The entire system has been modeled on the current design. The major components of this model are the same as for Concept 5. The modeling of the Judging system component is altered for this concept.

6.7.2 Subfunction decomposition

The subfunction decomposition is identical to that for Concept 6 except that the Judging component is altered. The resolution (Resolve in the model) is 0.0001 s. If the difference in time between cars passing the finish line are less than the resolution, there is a tie; otherwise, a winner is declared.

7 DOCUMENT 7: SYSTEM PHYSICAL SYNTHESIS

The System Physical Synthesis Document develops and explains the relationships between the models of the previous documents and the physical components that will comprise the final system. It is created in conjunction with Document 6.

7.1 Physical Synthesis of Concept 1

7.1.1 Top level system design of Concept 1

System Concept 1 is for a single-elimination tournament. Concepts 1 through 5 differ only in the Results component of the functional design. The original system will continue unaltered with the exception of this change. The physical decomposition will be as follows:

1. A judging system (determined by Concepts 6 and 7).
2. A paper schedule of races will be provided.
3. A paper tally sheet will be provided.

7.1.2 Subunit physical synthesis

7.1.2.1 Subunit 1. At the end of each heat, the first, second, and third place winners will be determined. The names of the cars in the heat and the results are combined for one input. The other inputs are the schedule and heat index. The place the participants finish in will be recorded in the Results column of the heat schedule and in the tally sheet, as shown in Exhibit 8. The winner of each heat will be designated as F#, where # is the index number.

The second place finisher will be S#, and the third place finisher, T#. The schedule is updated to indicate these results. The tally sheet will be updated with the results of this heat, and the results will also be made available to the participants.

7.1.2.2 Subunit 2. A paper schedule of heats will be provided. A sample of this schedule for a single-elimination tournament is given in Exhibit 6.

7.1.2.3 Subunit 3. A Tally sheet will be used for this heat as per Exhibit 8.

7.2 Physical Synthesis of Concept 2

7.2.1 Top level system design of Concept 2

System Concept 2 is for a double-elimination tournament. This affected only the Results component of the functional design. The original system will continue unaltered with the exception of this change.

The physical decomposition will be the same as for Concept 1, except the schedule is different. See Exhibit 7 for an example.

7.3 Physical synthesis of Concept 3

7.3.1 Top level system design of Concept 3

System Concept 3 is for a round robin tournament with mean-time scoring. This affected only the Results component of the functional design. The original system will continue unaltered with the exception of this change.

7.3.2 Subunit physical synthesis

7.3.2.1 Subunit 1. At the end of each heat, the first, second, and third place winners will be determined. The names of the cars in the heat and the results are combined for one input.

The other inputs are the schedule and heat index. The actual finish times will be recorded in the Results column of the heat schedule and in the tally sheet, as shown in Exhibit 8. The winner of each heat will be designated as F#, where # is the index number. The second place finisher will be S#, and the third place finisher, T#. The schedule is updated to indicate these results. The tally sheet will be updated with the results of this heat, and the results will also be made available to the participants. The winner of all heats will be determined at the end of all heats. At that time, an average of all race times will be calculated. In this unit, only the times are recorded.

7.3.2.2 Subunit 2. A paper schedule of heats will be provided. Sample schedules for a round robin tournament are given in Section 8.

7.3.2.3 Subunit 3. A Tally sheet will be used for this heat as per Exhibit 8.

7.4 Physical Synthesis of Concept 4

7.4.1 Top level system design of Concept 4

System Concept 4 is for a round robin tournament with best-time scoring. This system is functionally identical to Concept 3 except for the Results component of the functional design.

7.4.2 Subunit physical synthesis

7.4.2.1 Subunit 1. At the end of each heat, the first, second, and third place winners will be determined. The names of the cars in the heat and the results are combined for one input. The other inputs are the schedule and heat index. The actual finish times will be recorded in the Results column of the heat schedule and in the tally sheet, as shown in Exhibit 8. The winner of each heat will be designated as F#, where # is the index number. The second place finisher will be S#, and the third place finisher, T#. The schedule will be updated to indicate these results. The tally sheet will be updated with the results of this heat and the results will also be made available to the participants. The winner of all heats will be determined at the end of all heats. At that time, the best time of all the heats for each participant will be calculated. In this unit, only the times will be recorded.

7.4.2.2 Subunit 2. This subunit is identical to Subunit 2 of Concept 3.

7.4.2.3 Subunit 3. This subunit is identical to Subunit 3 of Concept 3.

7.5 Physical Synthesis of Concept 5

7.5.1 Top level system design of Concept 5

System Concept 5 is for a round robin tournament with point-assignment scoring. This system is functionally identical to Concept 3 except for the Results component of the functional design.

7.5.2 Subunit physical synthesis

7.5.2.1 Subunit 1. At the end of each heat, the first, second, and third place winners will be determined. The names of the cars in the heat and the result are combined for one input. The other inputs are the schedule and heat index. The actual finish times will be recorded in the results column of the heat schedule and in the tally sheet, as shown in Exhibit 8. The winner of each heat will be designated as F#, where # is the index number. The second place finisher will be S#, and the third place finisher, T#. The schedule will be updated to indicate these results. The tally sheet will be updated with the results of this heat and the results will also be made available to the participants. The winner of all heats will be determined at the end of all heats. The winner of a race receives 1 point, second place receives 2 points, and third place receives 3 points. At the completion of all races the winners are the ones with the lowest overall sum of points.

7.5.2.2 Subunit 2. This subunit is identical to Subunit 2 of Concept 3.

7.5.2.3 Subunit 3. This subunit is identical to Subunit 3 of Concept 3.

7.6 Physical Synthesis of Concept 6

7.6.1 Top level system design of Concept 6

System Concept 6 specifies a human judge to determine winners. This affects only the Judging component of the functional design. The original system will continue unaltered with the exception of this change.

The physical decomposition will be as follows:

1. Two people will be used: Judge 1 and Judge 2.
2. A paper schedule of heats will be provided.

7.6.2 Subunit physical synthesis

7.6.2.1 Subunit 1. The primary jobs of Judge 1 and Judge 2 are to determine the winners. An additional job is to control the crowd. The Finish Line Judge (Judge 1) will watch the finish line and (1) ensure that the cars are in the proper lanes and (2) reset the finish line switches and tell the starter when they are ready for the next heat. The Finish Line Facilitator (Judge 2) will keep the scouts away from the finish line. After the Finish Line Judge has observed the race and reset the switches, the Finish Line Facilitator will pick up the cars and hand them to the scouts or, if the scout owner is not there, put them on a pillow.

At the end of each race, Judge 1 calls out the first, second, and third place lane numbers. In other words, if the fastest car was in Lane 2, the second place car was in Lane 1, and the slowest car was in Lane 3, the judge would call out, "Two, one, three."

7.6.2.2 Subunit 2. Paper schedules of heats will be used as for Concepts 1, 2, and 3.

7.7 Physical Synthesis Of Concept 7

7.7.1 Top level system design of Concept 7

System Concept 7 specifies an electronic system to determine winners. This affects only the Judging component of the functional design. The original system will continue unaltered with the exception of this change.

The physical decomposition will be as follows:

1. Two people will be used: a Finish Line Judge and a Computer "Guru."
2. A paper schedule of heats will be provided.
3. Sensors are connected to the end of the racetrack and interfaced to a personal computer with appropriate software.

7.7.2 Subunit physical synthesis

7.7.2.1 Subunit 1. The race will be computerized. The jobs of the Finish Line Judge are to control the crowds, reset the finish line switches, verify that the computer is working correctly, and be prepared to step in and run the race manually in the case of power failure. The Finish Line Judge will watch the finish line and (1) ensure that the cars are in the proper lanes, (2) reset the finish line sensors and tell the starter when they are ready for the next heat, and (3) keep the scouts away from the finish line. The Finish Line Judge will then pick up the cars and hand them to the scouts or, if the scout owner is not there, put them on a pillow. The Computer Guru will be available to troubleshoot in case of computer malfunction.

7.7.2.2 Subunit 2. A paper schedule of heats, as shown in the exhibits for Concepts 1, 2, and 3, will be used.

7.7.2.3 Subunit 3. Sensors that detect the passage of the cars will be installed at the end of the racetrack. These will be interfaced to a computer with software that can determine race time. The judge must reset these sensors after each heat. The sensors are capable of determining the race times to a resolution of 0.0001s.

8 ROUND ROBIN SCHEDULES FOR A PINEWOOD DERBY

Document 8: The System Model. Models will be developed for most alternative concepts explored in Document 5. The model for the preferred alternatives will be expanded and used to help manage the system throughout its entire life cycle. For this Pinewood Derby study the only models we present are the schedules for the races.

In the following section we present round robin schedules for various sized derbies. These schedules can also be used as tally sheets. Each car is identified with a letter, e.g. A, B, C, . . . L. The objective was to allow each scout to race more often and race throughout the whole event. We decided to use six rounds because that would give each car two runs in each lane and still keep the whole event reasonably short. Switching from an elimination tournament to a round robin produced tow side benefits: the scouts raced more of their friends; and lane biases were ameliorated because each car ran in each lane the same number of times.

This schedule looks simple, but it took us eight years to derive it. Let’s see why. Originally we asked for schedules where each car raced in each of six rounds, each car raced twice in each lane, and no cars raced each other more than once. We used many programs and many computers (including six uninterrupted weeks searching on an AT&T 3B2), but we could not find a perfect schedule. Five different experts in scheduling theory were consulted. All said they could find a solution. In fact, they all claimed to have already solved a similar problem at some point in their careers. They were asked to provide the solution to this problem, but none did. Subsequently, we discovered that there is no schedule that meets the above requirements for 12 cars.

To see why, let us first examine the requirement that no car race another car more than once for a 12 car derby. Consider first car A.

In the first round, let car A race cars B and C.
In the second round, let car A race cars D and E.
In the third round, let car A race cars F and G.
In the fourth round, let car A race cars H and I.
In the fifth round, let car A race cars J and K.
In the sixth round, let car A race cars L and Who?

There is no one left for car A to race. Therefore, it is impossible to schedule a 12 car round robin where no car races another car more than once. Although it is harder to prove, it is also impossible to have ever car race every other car.

When we were making schedules, we did not know that a 12 car schedule was impossible; we only knew that we could not find it. But we had to have some schedule, because the Pinewood Derby was going to be held and we had to run it. So we relaxed our requirements in order to get an acceptable, but not perfect, solution to the problem.

A lesson can be learned from this case study. During the design process, when it becomes clear that an easy solution is not at hand, the best approach is to relax the requirements and obtain any suboptimal solution. Brainstorming to achieve a breakthrough which produces a perfect schedule will require lots of time with possibly no deliverable product. The best approach is to obtain a deliverable first, then iterate the design to get a better solution. If something is infeasible by the statement of the problem, then a solution can only be found by changing the problem statement, not by investigating many possible solutions.

We now understand this scheduling problem better, se we can state the requirements better. As the cars arrive, each is assigned a letter, e.g. A, B, C, . . . L. If there are only 10 cars in a divisional race, then a 12 car schedule is used, but no cars are labeled K or L. For a 12 car round robin there are six mandatory requirements:

1. each car shall race in each of six rounds,
2. each car shall run twice in each lane,
3. there shall be three cars in each race,
4. no cars should race each other more than twice,
5. even if cars K and L are missing, no car will ever race without at least one opponent, and
6. every car shall race every other car, except cars K and L shall not race each other.

The first round should be almost alphabetical order so that the scouts have some control over whom they race. The following schedule satisfies these requirements.

12 Car Round Robin Schedule

	Lane 1 Car	Lane 2 Car	Lane 3 Car
Round 1:			
Race 1	A	B	C
Race 2	D	E	F
Race 3	G	H	K
Race 4	I	J	L
Round 2:			
Race 1	C	L	E
Race 2	B	H	J
Race 3	F	G	I
Race 4	K	D	A
Round 3:			
Race 1	K	I	C
Race 2	G	E	B
Race 3	J	F	A
Race 4	H	L	D
Round 4:			
Race 1	B	D	I
Race 2	L	A	E
Race 3	J	K	G
Race 4	H	C	F
Round 5:			
Race 1	C	J	D
Race 2	F	B	K
Race 3	E	I	H
Race 4	A	G	L
Round 6:			
Race 1	E	K	J
Race 2	L	F	B
Race 3	D	C	G
Race 4	I	A	H

We also provide a schedule for a 15 car, six round divisional race. As the cars arrive, each is assigned a letter, e.g. A, B, C, . . .O. If there are only 13 cars in a divisional race, then the 15 car schedule is to be used, but no cars will be labeled N or O. There are six mandatory requirements:

1. each car shall race in each of six rounds,
2. each car shall run twice in each lane,
3. three cars shall be scheduled in each race,
4. no cars should race each other more than twice
5. even if cars N and O are missing, no car will ever race without at least one opponent, and
6. cars N and O shall not race each other.

The first round should be almost alphabetical so that the scouts have some control over whom they race.

15 Car Round Robin Schedule

	Lane 1 Car	Lane 2 Car	Lane 3 Car
Round 1:			
Race 1	A	B	C
Race 2	D	E	F
Race 3	G	H	I
Race 4	J	K	N
Race 5	M	L	O
Round 2:			
Race 1	H	A	E
Race 2	B	O	G
Race 3	K	L	C
Race 4	I	F	J
Race 5	N	M	D
Round 3:			
Race 1	L	F	H
Race 2	G	D	J
Race 3	C	E	N
Race 4	A	I	O
Race 5	K	M	B
Round 4:			
Race 1	D	C	I
Race 2	F	N	A
Race 3	E	G	M
Race 4	J	B	L
Race 5	H	O	K
Round 5:			
Race 1	N	G	L
Race 2	O	C	F
Race 3	E	I	K
Race 4	M	J	A
Race 5	B	D	H
Round 6:			
Race 1	L	A	D
Race 2	O	J	E
Race 3	I	N	B
Race 4	F	K	G
Race 5	C	H	M

The 12 and 15 car schedules were difficult to generate. Most of our scheduling techniques failed to find such schedules. The schedules for the 12 and 15 car derbies were generated by David Van Voorhees using genetic algorithms. Schedules for round robin races with 18 or more cars were derived by Bill Karnavas. The requirements for schedules for 18 or more cars are the same as for 15 cars.

9 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
Round 1						
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Round 2						
Race 1	A		D		G	
Race 2	B		E		H	
Race 3	C		F		I	
Round 3						
Race 1	B		F		G	
Race 2	D		C		H	
Race 3	E		I		A	
Round 4						
Race 1	C		G		E	
Race 2	F		H		A	
Race 3	I		D		B	
Round 5						
Race 1	E		B		C	
Race 2	G		A		F	
Race 3	H		I		D	
Round 6						
Race 1	F		C		D	
Race 2	H		A		E	
Race 3	I		G		B	

18 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
Round 1						
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Round 2						
Race 1	E		N		I	
Race 2	R		O		A	
Race 3	H		B		K	
Race 4	C		J		P	
Race 5	Q		F		G	
Race 6	L		D		M	
Round 3						
Race 1	B		L		N	
Race 2	O		P		D	
Race 3	E		G		C	
Race 4	M		F		R	
Race 5	H		J		A	
Race 6	I		K		Q	
Round 4						
Race 1	P		E		B	
Race 2	I		A		L	
Race 3	N		Q		D	
Race 4	F		O		H	
Race 5	R		C		K	
Race 6	G		M		J	
Round 5						
Race 1	A		G		N	
Race 2	J		I		F	
Race 3	D		R		B	
Race 4	L		P		H	
Race 5	O		C		Q	
Race 6	K		M		E	
Round 6						
Race 1	Q		L		E	
Race 2	B		I		O	
Race 3	C		H		M	
Race 4	N		R		J	
Race 5	F		A		P	
Race 6	K		D		G	

21 Car Round robin Schedule

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
Round 1						
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Round 2						
Race 1	I		Q		J	
Race 2	F		O		H	
Race 3	M		P		S	
Race 4	R		T		C	
Race 5	U		A		D	
Race 6	K		E		B	
Race 7	G		L		N	
Round 3						
Race 1	U		F		I	
Race 2	D		E		G	
Race 3	T		J		E	
Race 4	A		H		R	
Race 5	K		S		N	
Race 6	O		L		P	
Race 7	B		M		Q	
Round 4						
Race 1	L		U		B	
Race 2	I		C		E	
Race 3	N		P		T	
Race 4	D		J		O	
Race 5	S		A		Q	
Race 6	R		F		G	
Race 7	H		K		M	

21 Car Round robin Schedule *continued*

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
			Round 5			
Race 1	T		M		L	
Race 2	B		R		D	
Race 3	Q		U		K	
Race 4	N		C		F	
Race 5	E		G		P	
Race 6	H		S		J	
Race 7	O		I		A	
			Round 6			
Race 1	C		O		U	
Race 2	J		N		A	
Race 3	P		I		K	
Race 4	L		D		H	
Race 5	E		R		M	
Race 6	F		B		S	
Race 7	Q		G		T	

24 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Race 8	V		W		X	
	Round 2					
Race 1	L		P		F	
Race 2	B		M		Q	
Race 3	H		W		A	
Race 4	T		C		V	
Race 5	S		D		X	
Race 6	I		E		N	
Race 7	G		J		U	
Race 8	R		K		O	
	Round 3					
Race 1	X		L		G	
Race 2	W		N		Q	
Race 3	M		J		H	
Race 4	A		F		I	
Race 5	R		S		B	
Race 6	C		I		P	
Race 7	K		T		D	
Race 8	E		U		V	
	Round 4					
Race 1	N		S		P	
Race 2	F		B		W	
Race 3	Q		O		G	
Race 4	J		R		T	
Race 5	U		X		H	
Race 6	V		A		D	
Race 7	I		L		C	
Race 8	E		M		K	

24 Car Round robin Schedule *continued*

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 5					
Race 1	W		C		E	
Race 2	F		Q		J	
Race 3	U		P		B	
Race 4	X		I		K	
Race 5	D		G		M	
Race 6	T		A		L	
Race 7	H		R		N	
Race 8	O		V		S	
	Round 6					
Race 1	K		U		W	
Race 2	K		V		M	
Race 3	N		X		A	
Race 4	B		D		J	
Race 5	O		F		T	
Race 6	C		G		R	
Race 7	P		H		E	
Race 8	Q		I		S	

27 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
Round 1						
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Race 8	V		W		X	
Race 9	Y		Z		AA	
Round 2						
Race 1	L		R		S	
Race 2	M		A		Y	
Race 3	U		I		W	
Race 4	J		Z		X	
Race 5	B		T		V	
Race 6	H		AA		C	
Race 7	Q		D		G	
Race 8	E		O		K	
Race 9	F		N		P	
Round 3						
Race 1	N		R		I	
Race 2	Z		A		W	
Race 3	C		U		V	
Race 4	B		X		K	
Race 5	F		Q		AA	
Race 6	L		Y		T	
Race 7	D		P		H	
Race 8	O		G		J	
Race 9	S		E		M	
Round 4						
Race 1	G		M		F	
Race 2	R		O		T	
Race 3	P		V		Y	
Race 4	H		J		Q	
Race 5	A		S		D	
Race 6	I		X		L	
Race 7	K		C		Z	
Race 8	W		AA		B	
Race 9	N		U		E	

27 Car Round robin Schedule *continued*

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
			Round 5			
Race 1	X		S		G	
Race 2	T		P		Z	
Race 3	I		Y		J	
Race 4	Q		W		N	
Race 5	AA		D		M	
Race 6	C		F		O	
Race 7	E		B		H	
Race 8	R		K		U	
Race 9	V		L		A	
			Round 6			
Race 1	U		J		A	
Race 2	K		M		P	
Race 3	O		V		Q	
Race 4	T		C		D	
Race 5	W		L		N	
Race 6	X		H		R	
Race 7	Y		F		B	
Race 8	Z		G		E	
Race 9	AA		I		S	

30 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Race 8	V		W		X	
Race 9	Y		Z		AA	
Race 10	BB		CC		DD	
	Round 2					
Race 1	W		CC		A	
Race 2	Y		C		X	
Race 3	Z		B		BB	
Race 4	K		F		Q	
Race 5	DD		L		AA	
Race 6	U		D		R	
Race 7	E		M		H	
Race 8	G		S		V	
Race 9	P		N		J	
Race 10	I		O		T	
	Round 3					
Race 1	U		M		B	
Race 2	CC		S		H	
Race 3	N		V		C	
Race 4	BB		O		J	
Race 5	Q		W		T	
Race 6	I		D		DD	
Race 7	X		K		R	
Race 8	L		P		Y	
Race 9	Z		A		E	
Race 10	F		AA		G	

30 Car Round robin Schedule *continued*

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
Round 4						
Race 1	Q		Y		BB	
Race 2	D		V		P	
Race 3	W		G		B	
Race 4	L		H		U	
Race 5	J		Z		CC	
Race 6	X		T		M	
Race 7	R		E		N	
Race 8	O		K		S	
Race 9	C		AA		I	
Race 10	F		DD		A	
Round 5						
Race 1	C		R		L	
Race 2	K		A		G	
Race 3	H		J		F	
Race 4	S		I		W	
Race 5	E		P		CC	
Race 6	M		T		V	
Race 7	AA		U		N	
Race 8	O		X		Z	
Race 9	T		BB		D	
Race 10	B		DD		Q	
Round 6						
Race 1	N		Q		S	
Race 2	AA		X		D	
Race 3	R		BB		M	
Race 4	H		C		O	
Race 5	V		F		Z	
Race 6	T		G		P	
Race 7	CC		I		K	
Race 8	DD		U		W	
Race 9	A		J		Y	
Race 10	B		L		E	

33 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Race 8	V		W		X	
Race 9	Y		Z		AA	
Race 10	BB		CC		DD	
Race 11	EE		FF		GG	
	Round 2					
Race 1	N		V		Y	
Race 2	O		A		DD	
Race 3	Z		K		BB	
Race 4	L		FF		CC	
Race 5	B		U		AA	
Race 6	J		EE		C	
Race 7	W		GG		D	
Race 8	X		R		G	
Race 9	E		H		M	
Race 10	Q		F		S	
Race 11	I		P		T	
	Round 3					
Race 1	C		Z		CC	
Race 2	D		DD		L	
Race 3	G		S		GG	
Race 4	M		BB		W	
Race 5	AA		T		FF	
Race 6	O		I		B	
Race 7	U		X		Y	
Race 8	N		P		A	
Race 9	H		F		EE	
Race 10	Q		E		J	
Race 11	V		R		K	

33 Car Round robin Schedule *continued*

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
Round 4						
Race 1	FF		O		U	
Race 2	T		BB		EE	
Race 3	H		J		R	
Race 4	A		W		E	
Race 5	K		AA		M	
Race 6	L		G		B	
Race 7	CC		I		X	
Race 8	S		Y		P	
Race 9	C		N		Q	
Race 10	Z		V		D	
Race 11	DD		GG		F	
Round 5						
Race 1	W		J		FF	
Race 2	U		CC		Q	
Race 3	K		O		E	
Race 4	F		L		N	
Race 5	Y		A		T	
Race 6	GG		X		H	
Race 7	P		B		Z	
Race 8	AA		EE		G	
Race 9	I		C		S	
Race 10	R		D		BB	
Race 11	DD		M		V	
Round 6						
Race 1	GG		L		A	
Race 2	BB		G		J	
Race 3	R		C		I	
Race 4	T		D		N	
Race 5	X		S		Z	
Race 6	B		Q		V	
Race 7	CC		Y		W	
Race 8	EE		M		I	
Race 9	FF		DD		H	
Race 10	E		AA		P	
Race 11	F		U		K	

36 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Race 8	V		W		X	
Race 9	Y		Z		AA	
Race 10	BB		CC		DD	
Race 11	EE		FF		GG	
Race 12	HH		II		JJ	
	Round 2					
Race 1	P		X		Y	
Race 2	Q		A		GG	
Race 3	BB		L		EE	
Race 4	M		HH		FF	
Race 5	B		W		AA	
Race 6	K		CC		II	
Race 7	Z		DD		D	
Race 8	JJ		T		H	
Race 9	C		I		E	
Race 10	S		F		N	
Race 11	G		J		O	
Race 12	R		U		V	
	Round 3					
Race 1	Z		BB		V	
Race 2	I		D		HH	
Race 3	X		U		J	
Race 4	O		P		CC	
Race 5	T		Y		E	
Race 6	GG		AA		DD	
Race 7	K		N		JJ	
Race 8	H		F		L	
Race 9	EE		G		B	
Race 10	C		M		Q	
Race 11	R		S		W	
Race 12	FF		II		A	

36 Car Round robin Schedule *continued*

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
Round 4						
Race 1	Q		V		CC	
Race 2	D		X		K	
Race 3	T		O		R	
Race 4	II		Y		BB	
Race 5	U		L		I	
Race 6	AA		E		H	
Race 7	N		DD		A	
Race 8	W		JJ		EE	
Race 9	J		M		B	
Race10	FF		Z		C	
Race 11	F		G		P	
Race 12	GG		S		H	
Round 5						
Race 1	W		C		II	
Race 2	HH		H		N	
Race 3	CC		J		D	
Race 4	I		A		F	
Race 5	JJ		O		FF	
Race 6	U		B		Y	
Race 7	V		K		M	
Race 8	E		P		S	
Race 9	X		Q		G	
Race 10	AA		R		BB	
Race 11	DD		EE		T	
Race 12	L		GG		Z	
Round 6						
Race 1	H		C		J	
Race 2	CC		EE		M	
Race 3	II		R		Z	
Race 4	Y		GG		G	
Race 5	DD		V		P	
Race 6	A		AA		K	
Race 7	L		FF		W	
Race 8	B		BB		Q	
Race 9	E		HH		U	
Race 10	F		JJ		X	
Race 11	N		D		T	
Race 12	O		I		S	

39 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
			Round 1			
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
Race 4	J		K		L	
Race 5	M		N		O	
Race 6	P		Q		R	
Race 7	S		T		U	
Race 8	V		W		X	
Race 9	Y		Z		AA	
Race 10	BB		CC		DD	
Race 11	EE		FF		GG	
Race 12	HH		II		JJ	
Race 13	KK		LL		MM	
			Round 2			
Race 1	B		Z		W	
Race 2	K		P		S	
Race 3	EE		U		Y	
Race 4	F		JJ		AA	
Race 5	BB		L		O	
Race 6	LL		H		E	
Race 7	I		CC		J	
Race 8	C		D		M	
Race 9	R		N		T	
Race 10	V		DD		FF	
Race 11	GG		MM		HH	
Race12	X		II		Q	
Race 13	KK		A		G	
			Round 3			
Race 1	GG		JJ		Z	
Race 2	AA		MM		V	
Race 3	R		HH		EE	
Race 4	S		E		BB	
Race 5	Q		Y		CC	
Race 6	FF		KK		H	
Race 7	I		W		A	
Race 8	DD		F		M	
Race 9	II		O		P	
Race 10	G		LL		B	
Race 11	J		C		T	
Race 12	D		K		N	
Race 13	U		L		X	

39 Car Round robin Schedule *continued*

	Lane 1 Car	Lane 1 Place	Lane 2 Car	Lane 2 Place	Lane 3 Car	Lane 3 Place
Round 4						
Race 1	X		DD		Y	
Race 2	CC		EE		B	
Race 3	K		AA		W	
Race 4	N		P		C	
Race 5	L		M		Q	
Race 6	H		U		R	
Race 7	FF		D		S	
Race 8	HH		F		Z	
Race 9	O		GG		KK	
Race 10	T		G		BB	
Race 11	II		A		V	
Race 12	JJ		I		LL	
Race 13	MM		J		E	
Round 5						
Race 1	L		EE		II	
Race 2	W		Y		D	
Race 3	JJ		V		CC	
Race 4	LL		AA		A	
Race 5	DD		GG		G	
Race 6	Z		C		I	
Race 7	MM		M		U	
Race 8	B		Q		J	
Race 9	N		S		HH	
Race 10	T		O		F	
Race 11	E		R		FF	
Race 12	H		X		K	
Race 13	P		BB		KK	
Round 6						
Race 1	A		J		H	
Race 2	C		R		DD	
Race 3	CC		G		MM	
Race 4	E		I		GG	
Race 5	F		B		K	
Race 6	M		S		EE	
Race 7	O		FF		JJ	
Race 8	Q		V		D	
Race 9	AA		T		II	
Race 10	U		BB		LL	
Race 11	W		HH		L	
Race 12	Y		KK		N	
Race 13	Z		X		P	

Homework Problems

1. **Scoring functions.** For the Pinewood Derby system described in this chapter, sketch scoring functions for the following Utilization of Resources Figures of Merit: Total Event Time, Number of Electrical Circuits, and Number of Adults.

2. **Matching functions.** This is a schedule for a nine car Pinewood Derby round robin.

9 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
	Round 2					
Race 1	I		A		E	
Race 2	C		D		H	
Race 3	F		G		B	
	Round 3					
Race 1	H		F		A	
Race 2	B		I		D	
Race 3	E		C		G	
	Round 4					
Race 1	A		D		G	
Race 2	B		E		H	
Race 3	C		F		I	

With this schedule, each car races four times. Each scout races every other scout exactly once. Each car races in each lane at least once. Assume these are the race times for each car *not* in temporal order:

Car	Race Times, seconds			
A	2.40	2.41	2.42	2.43
B	2.41	2.42	2.43	2.44
C	2.42	2.43	2.44	2.45
D	2.43	2.44	2.45	2.46
E	2.44	2.45	2.46	2.47
F	2.45	2.46	2.47	2.48
G	2.46	2.47	2.48	2.49
H	2.47	2.48	2.49	2.50
I	2.48	2.49	2.50	2.51

The system has three input ports, the three lanes. They accept data pairs as inputs, each data pair consisting of a car name and a time. The system has three output ports, the names of the first, second, and third place cars. We will look only at the outputs at times $12n$ where $n = 0, 1, 2, 3, \ldots$ We are judging this event on a basis of 1 point for first place, 2 points for second place, and 3 points for third place. At the end of four rounds, the car with the fewest total points wins. On the following pages we show three possible input trajectories, then several possible output trajectories. Your job is to derive a matching function that is appropriate for these trajectories.

Input Trajectory 1 (call it f1) with Output g1

		Inputs						Outputs		
		Lane 1		Lane 2		Lane 3		1st	2nd	3rd
Time		Car	Time	Car	Time	Car	Time	place	place	place
					Round 1					
0	Race 1	A	2.40	B	2.41	C	2.42			
1	Race 2	D	2.43	E	2.44	F	2.45			
2	Race 3	G	2.46	H	2.47	I	2.48			
					Round 2					
3	Race 1	I	2.49	A	2.41	E	2.42			
4	Race 2	C	2.43	D	2.44	H	2.45			
5	Race 3	F	2.46	G	2.47	B	2.48			
					Round 3					
6	Race 1	H	2.49	F	2.47	A	2.45			
7	Race 2	B	2.43	I	2.50	D	2.42			
8	Race 3	E	2.46	C	2.44	G	2.48			
					Round 4					
9	Race 1	A	2.43	D	2.46	G	2.49			
10	Race 2	B	2.44	E	2.47	H	2.50			
11	Race 3	C	2.45	F	2.48	I	2.51			
12								A	B	C

Input Trajectory 2 (call it f2)

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
			Round 1			
Race 1	A	**2.43**	B	2.41	C	2.42
Race 2	D	2.43	E	2.44	F	2.45
Race 3	G	2.46	H	2.47	I	2.48
			Round 2			
Race 1	I	2.49	A	2.41	E	2.45
Race 2	C	2.43	D	2.44	H	2.48
Race 3	F	2.46	G	2.47	B	2.42

	Car	Place	Car	Place	Car	Place
	Round 3					
Race 1	H	2.49	F	2.47	A	2.42
Race 2	B	2.43	I	2.50	D	2.45
Race 3	E	2.46	C	2.44	G	2.48
	Round 4					
Race 1	A	**2.40**	D	2.46	G	2.49
Race 2	B	2.44	E	2.47	H	2.50
Race 3	C	2.45	F	2.48	I	2.51

Note: The differences between tables f2 and f1 are in boldface type.

Input Trajectory 3 (call it f3)

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A	**2.43**	B	**2.44**	C	2.42
Race 2	D	2.43	E	2.44	F	2.45
Race 3	G	2.46	H	2.47	I	2.48
	Round 2					
Race 1	I	2.49	A	2.41	E	2.45
Race 2	C	2.43	D	2.44	H	2.48
Race 3	F	2.46	G	2.47	B	2.42
	Round 3					
Race 1	H	2.49	F	2.47	A	2.42
Race 2	B	2.43	I	2.50	D	2.45
Race 3	E	2.46	C	2.44	G	2.48
	Round 4					
Race 1	A	**2.40**	D	2.46	G	2.49
Race 2	B	**2.41**	E	2.47	H	2.50
Race 3	C	2.45	F	2.48	I	2.51

Note: The differences between tables f3 and f1 are in boldface type.

Here are some possible values for the output trajectories at t=12.

g1(12) = (A, B, C),
g2(12) = (A, C, B),
g3(12) = (B, A, C),
g4(12) = (B, C, A),
g5(12) = (C, B, A),
g6(12) = (C, A, B),
g7(12) = (A, B, D),
g8(12) = (A, D, E).

For input trajectory f1, the total points are

A	=	4
B	=	5
C	=	6
D	=	7
E	=	8
F	=	9
G	=	10
H	=	11
I	=	12

Therefore, an appropriate output is g1.

Now you should compute appropriate outputs for f2 and f3 and then write the matching function.

[†]How many input trajectories are possible? How many output trajectory values are possible for each time 12*n*? How many matching functions are possible if you include all possible input and output trajectories? (Assume that the times given are only approximate and that electronic timing will ensure that no race ends in a tie. During actual Pinewood Derbies with human judges there are ties and those races rerun. Rerun races are very seldom ties. With electronic timing a whole derby is usually run with no ties.)

3. **Tradeoff studies.** Assume that you get a new Grand Marshall for the Pinewood Derby who is not worried about irate parents. He says he will tell irate parents to "get lost," so he changes the weight on "Number of Irate Parents" to 0. Recalculate the final score for the five race formats. Use the simulation data. (This is a long, tedious problem, but it will give you a good understanding of the tradeoff process.)

4. [††]**Functional decomposition.** This question is seven pages long! The following is from the Pinewood Derby case study.

[†] This part of the problem is intended for students who have had a class in probability.
[††] This problem uses more detailed notation than is used in the text.

9 Car Round robin Schedule

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A		B		C	
Race 2	D		E		F	
Race 3	G		H		I	
	Round 2					
Race 1	I		A		E	
Race 2	C		D		H	
Race 3	F		G		B	
	Round 3					
Race 1	H		F		A	
Race 2	B		I		D	
Race 3	E		C		G	
	Round 4					
Race 1	A		D		G	
Race 2	B		E		H	
Race 3	C		F		I	

Car	Race Times, seconds			
A	2.40	2.41	2.42	2.43
B	2.41	2.42	2.43	2.44
C	2.42	2.43	2.44	2.45
D	2.43	2.44	2.45	2.46
E	2.44	2.45	2.46	2.47
F	2.45	2.46	2.47	2.48
G	2.46	2.47	2.48	2.49
H	2.47	2.48	2.49	2.50
I	2.48	2.49	2.50	2.51

Our input/output requirement has three input ports, the three lanes. They accept data pairs as inputs, each data pair consisting of a car name (A through I) and a finish time (from 2.40 to 2.51). The system has three output ports that present the names of the first, second, and third place cars. We are judging points for this event on a basis of 1 point for first place, 2 points for second place, and 3 points for third place. At the end of four rounds, the car with the fewest total points wins. On the following pages we show three possible input trajectories, then several possible output trajectories.

Input Trajectory 1 (call it f1) with Output g1

Time		Inputs						Outputs		
		Lane 1		Lane 2		Lane 3		1st	2nd	3rd
		Car	Time	Car	Time	Car	Time	place	place	place
		Round 1								
0	Race 1	A	2.40	B	2.41	C	2.42			
1	Race 2	D	2.43	E	2.44	F	2.45			
2	Race 3	G	2.46	H	2.47	I	2.48			
		Round 2								
3	Race 1	I	2.49	A	2.41	E	2.42			
4	Race 2	C	2.43	D	2.44	H	2.45			
5	Race 3	F	2.46	G	2.47	B	2.48			
		Round 3								
6	Race 1	H	2.49	F	2.47	A	2.45			
7	Race 2	B	2.43	I	2.50	D	2.42			
8	Race 3	E	2.46	C	2.44	G	2.48			
		Round 4								
9	Race 1	A	2.43	D	2.46	G	2.49			
10	Race 2	B	2.44	E	2.47	H	2.50			
11	Race 3	C	2.45	F	2.48	I	2.51			
12								A	B	C

Input Trajectory 2 (call it f2)

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A	**2.43**	B	2.41	C	2.42
Race 2	D	2.43	E	2.44	F	2.45
Race 3	G	2.46	H	2.47	I	2.48
	Round 2					
Race 1	I	2.49	A	2.41	E	2.45
Race 2	C	2.43	D	2.44	H	2.48
Race 3	F	2.46	G	2.47	B	2.42
	Round 3					
Race 1	H	2.49	F	2.47	A	2.42
Race 2	B	2.43	I	2.50	D	2.45
Race 3	E	2.46	C	2.44	G	2.48
	Round 4					
Race 1	A	**2.40**	D	2.46	G	2.49
Race 2	B	2.44	E	2.47	H	2.50
Race 3	C	2.45	F	2.48	I	2.51

Note: The differences between tables f2 and f1 are in boldface type.

Input Trajectory 3 (call it f3)

	Lane 1		Lane 2		Lane 3	
	Car	Place	Car	Place	Car	Place
	Round 1					
Race 1	A	**2.43**	B	**2.44**	C	2.42
Race 2	D	2.43	E	2.44	F	2.45
Race 3	G	2.46	H	2.47	I	2.48
	Round 2					
Race 1	I	2.49	A	2.41	E	2.45
Race 2	C	2.43	D	2.44	H	2.48
Race 3	F	2.46	G	2.47	B	2.42
	Round 3					
Race 1	H	2.49	F	2.47	A	2.42
Race 2	B	2.43	I	2.50	D	2.45
Race 3	E	2.46	C	2.44	G	2.48
	Round 4					
Race 1	A	**2.40**	D	2.46	G	2.49
Race 2	B	**2.41**	E	2.47	H	2.50
Race 3	C	2.45	F	2.48	I	2.51

Note: The differences between tables f3 and f1 are in boldface type.

We now show values of some possible outputs. (*Note*: these are not technically trajectories, but they are only values of trajectories for some particular time.)

g1	=	(A, B, C),
g2	=	(A, C, B),
g3	=	(B, A, C),
g4	=	(B, C, A),
g5	=	(C, B, A),
g6	=	(C, A, B),
g7	=	(A, B, D),
g8	=	(A, D, E),
g9	=	(J, J, J)
g1	=	(A, B, E)

For simplicity, assume that no individual race ends in a tie. During actual Pinewood Derbies with human judge there are ties and those races are rerun. The rerun races are very seldom ties. With electronic timers, a whole derby is usually run with no ties.

The following is a set of theoretic description of what we have just said in words. First we give the original Input/Output and Functional Requirement for the Pinewood Derby Part 0 (IORpwd0). Later we do the same for Parts 1, 2, and 3 (IORpwd1, etc.)

IORpwd0 = (TRpwd0, IRpwd0, ITRpwd0, Orpwd0, OTRpwd0, MRpwd0),

where

TRpwd0 = IJS[0–12],

/*These requirements must be satisfied for the times 0 to 12.*/

IRpwd0 = IR1pwd0 x IR2pwd0 x IR3pwd0,

IR1pwd0 = (ALPHABET [A–I], RLS [2.40–2.51])

/*Name of car and finish time for lane 1*/

/*The notation ALPHABET [A-I] means any letter of the alphabet between*/

/*A and I*/

IR2pwd0 = (ALPHABET [A-I], RLS[2.40-2.51])

/*Name of car and finish time for lane 2*/

IR3pwd0 = (ALPHABET [A-I], RLS[2.40-2.51])

/*Name of car and finish time for lane 3*/

ITRpwd0 = FNS (TRpwd0, Irpwd0),

Orpwd0 = OR1pwd0 X OR2pwd0 X OR3pwd0, OR1pwd0 = ALPHABET [A-I]

/*Name of first place car*/

OR2pwd0 = ALPHABET [A-I]

/*Name of second place car*/

OR3pwd0 = ALPHABET [A-I]

/*Name of third place car*/

OTRpwd0 = FNS (TRpwd0, Orpwd0),

/*Any trajectories that can be made with the above input and output*/

/*requirements are legal.*/

/*The following line says that MRpwd0 is a function of f and G: where f is*/

/*an element of the set ITRpwd0; and G is a subset of the set OTRpwd0;*/

/*and G is further restricted in that the elements of G. represented with g,*/

/*are elements of the set OTRpwd0;*/

MRpwd0 = {(f, G): f $\in$ ITRpwd0; G is a subset of OTRpwd0;

G = {g: g E OTRpwd0;

if (f = f1) then g(12) = g1;

else if (f = f2) then g(12) = g4;

else if (f = f3) then g(12) = g6}}.

Now your engineers come to you and say, "It's going to be hard to build a system that satisfies IORpwd0, but in the back room we have systems on the shelf that satisfy IORpwd1, IORpwd2, and IORpwd3". They also claim that ICRpwd4 (which produces IORpwd4) decomposes IORpwd0 into IORpwd1,IORpwd2, and IORpwd3. Do you believe them? Draw or state what ICRpwd4 must be. Define the relationships between OTRpwd0 and OTRpwd4 and between MRpwd0 and MRpwd4. If you implement the system using the three systems your engineers recommend, what aspects of the customers requirements as stated in IORpwd0 will not be satisfied? Are there any new features the customer did not request?

IORpwd1 = (TRpwd1, IRpwd1, ITRpwd1, ORpwd1, OTRpwd1, MRpwd1),

where

TRpwd1 = IJS[0-12],

IRpwd1 = IR1pwd1 X IR2pwd1 X IR3pwd1,

IR1pwd1 = (ALPHABET[A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 1*/

IR2pwd1 = (ALPHABET[A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 2*/

IR3pwd1 = (ALPHABET[A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 3*/

ITRpwd1 = FNS(TRpwd1, IRpwd1),

ORpwd1 = ALPHABET{A-I] /*Name of first place car*/

OTRpwd1 = FNS(TRpwd1, ORpwd1),

MRpwd1 = {(f, G): where f $\in$ ITRpwd1; G is a subset of OTRpwd1;

G = {g: g $\in$ OTRpwd1; n $\in$ IJS[0-11];

g(n) = g9

if (f = f1) then g(12) = A;

else if (f = f2) then g(12) = B;

else if (f = f3) then g(12) = C;

else g(12) = g9}}.

IORpwd2 = (TRpwd2, IRpud2, ITRpwd2, ORpwd2, OTRpwd2, MRpwd2),

where

TRpwd2 = IJS[0-12],

IRpwd2 = IR1pwd2 X IR2pwd2 X IR3pwd2,

IR1pwd2 = (ALPHABET [A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 1*/

IR2pwd2 = (ALPHABET [A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 2*/

IR3pwd2 = (ALPHABET[A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 3*/

ITRpwd2 = FNS(TRpwd2, IRpwd2),

ORpwd2 = ALPHABET [A-I] /*Name of second place car*/

OTRpwd2 = FNS(TRpwd2, ORpwd2),

MRpwd2 = {(f, G): where f $\in$ ITRpwd2; G is a subset of OTRpwd2;

G = {g: g $\in$ OTRpwd2; n $\in$ IJS[0-11];

g(n) = g9

if (f = f1) then g(12) = B;

else if (f = f2) then g(12) = C;

else if (f = f3) then g(12) = A;

else g(12) = g9}}.

IORpwd3 = (TRpwd3, IRpwd3, ITRpwd3, ORpwd3, OTRpwd3, MRpwd3), where

TRpwd3 = IJS[0-12],

IRpwd3 = IR1pwd3 X IR2pwd3 X IR2pwd3,

IR1pwd3 = (ALPHABET A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 1*/

IR2pwd3 = (ALPHABET [A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 2*/

IR3pwd3 = (ALPHABET [A-J], RLS[2.40-2.51])

/*Name of car and finish time for lane 3*/

ITRpwd3 = FNS(TRpwd3, IRpwd3),

ORpwd3 = ALPHABET [A-I] /*Name of third place car*/

OTRpwd3 = FNS(TRpwd3, ORpwd3),

MRpwd3 = {(f, G); where f $\in$ ITRpwd3; G is a subset of OTRpwd3;

G = {g: g $\in$ OTRpwd3; n $\in$ IJS [0-11];

g(n) = g9

if (f = f1) then g(12) = C;

else if (f = f2) then g(12) = A;

else if (f = f3) then g(12) = B;

else g(12) = g9}}.

References

Chapman, W.L., Bahill, A.T., and Wymore, W.A. (1992). *Engineering modeling and design*, Boca Raton, FL: CRC Press Inc.

Karnavas, W.J., Sanchez, P., and Bahill, A.T. (1993). Sensitivity analyses of continuous and discrete systems in the time and frequency domains. *IEEE transactions on systems, man, and cybernetics*, 28(3), 488-501.

Wymore, W.A. (1993). *Model-based systems engineering*, Boca Raton, FL: CRC Press Inc.