MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ESD.04/1.041J

Frameworks and Models in Engineering Systems (FAMES)
Spring 2007

Solutions for Qualifying Problem

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Issued: Thursday May 3rd, 2007

Topics: Risk Assessment. Benefit Cost Analysis. Applications, insights, drawbacks.

Questions

In Parts 1 and 2 you are expected to base your answers only on the data given in the assignment. Note that these are stylized for simplicity. In Part 3 you should use the knowledge from the class discussion and the readings along with your own reasoning to answer the questions.

System Description

We will consider a simplified situation of the SNF transportation and storage CLIOS System as shown in Figure 1. There are 6 sites where SNF is currently stored numbered from 1 to 6 and marked as grey triangles on the map. There are two proposals for storing the fuel: (i) using a single centralized long-term facility (Marked X), or (ii) using two shorter-term smaller centralized facilities marked A and B. Finding acceptable sites for this use was hard and their position currently satisfies both political and scientific constraints for the anticipated length of storage. As a result identifying other potential areas or routes is not an alternative at this point. The transportation of SNF is expected to be completed within 10 years. SNF can be transported either by rail OR by truck – i.e. no hybrid transportation solutions can be implemented.

Table 1 displays information about the network routes that have already been found to provide the minimum exposure of general population while SNF is en route.

Table 1: Network distances and Population Centers

OD pair	Highway Distance (in miles)	Number of Cities	Population	Rail adjustment
1A	300	1	300.000	x1.1
2A	150	3	100.000 each	x1.2
3A	350	1	50.000	x0.9
4B	150	3	75.000 each	x1
5B	200	1	50.000	x1.3
6B	300	1	1.000.000	x0.8
BA	1000	4	100.000 each	x1.1
AX	1500	5	50.000 each	x1.1

Note that for rail access multiply the distances by the given factor.

Assume that all urban areas have a radius of 5 miles.

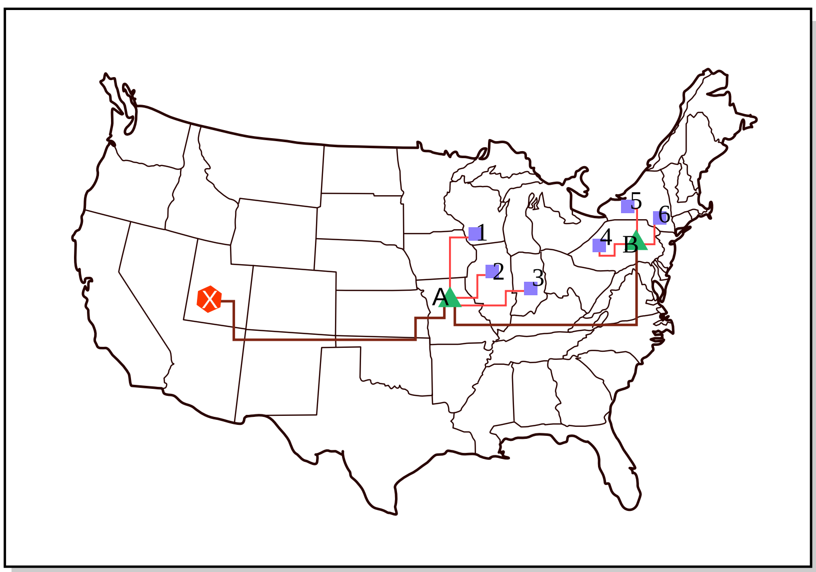

Figure by MIT OpenCourseWare.

Figure 1: SNF System Network (not in scale – for illustration purposes only)

The amount of SNF in each site has been calculated in container loads for your convenience (you have good staff!) as shown in Table 2.

Table 2 SNF Quantities in Container loads

1	2	3	4	5	6
2600	3000	4600	1000	4000	5000

Trucks carry 1 container load per trip while trains carry 20 container loads per trip.

The cost of transporting **one** container by truck is $5/mile while the same figure for train is $1.5/mile. (SNF transport is expensive!)

From historical observations, the accident probabilities for the two modes have been established. For intercity travel the accident probability for truck is $P_{truck\_accident} = 10^{-6}$ per truck-mile while the corresponding probability for trains is $P_{train\_accident} = 10^{-7}$ per train-mile. For urban travel this probability is doubled, because of traffic volumes, higher number of railroad crossings etc.

If an accident happens, then the probability of a significant leakage of radioactive material has been calculated based on drop and puncture test performance to be on average $P_{release} = 10^{-4}$ for **each** container carried. Container leakage in a given incident is independent of whether other containers have leaked or not. We assume that the consequences (health effects and restoration work) are the same if one or more containers leak in the same accident.

All containers carrying SNF will be equipped with tracking equipment that notifies the emergency response teams if it senses an accident. The probability that the GPS is affected by the accident and does not signal is $P_{GPS\_failure} = 10^{-2}$. If the system does not fail then the emergency response teams can arrive at the accident site early enough to prevent severe contamination with a probability of $P_{mild\_ER} = 0.7$. If they arrive late, $P_{mild\_ER} = 0.2$.

The costs for decontamination and toll on economic and population health have been estimated on an approximate basis and shown on Table 3.

Table 3 Event Costs

Event	Costs
Urban Mild	$\$100M*(S/100.000)^2$
Urban Severe	$\$1B*(S/100.000)^3$
Rural Mild	$10M
Rural Severe	$100M

where S is the urban area population size.

Part 1: Risk Assessment for the Transportation of SNF
You are asked to do a risk assessment for the transportation of the SNF and calculating certain risks for both the truck and rail transport options.

The following suggestions/questions will guide you in this effort.

1. Identify the solution space (bundles of strategic alternatives) implied by the problem formulation.
2. For the bundles of strategic alternatives you identified, calculate (or identify from the problem description) the following data for operation of the project for 1 year:
    a. Expected value of number of accidents for rural and urban settings.
    b. Probability of leak if an accident happens
    c. Probability of GPS failure if an accident happens
3. Now you are ready to provide an event tree for each bundle to aid your calculations of end probabilities.
4. Using the event trees, calculate the end probabilities for having zero incidents, mild incidents, or severe incidents. What are the expected values of their costs?
5. All else being equal which combination of storage site and transportation mode would you recommend? Does your answer change if you take transportation cost into account?
6. A research fund has been designated to improve reliability of the SNF transport. You are asked to choose how much money to allocate in increasing the reliability by one order of magnitude of the container or of the GPS unit. Assuming that any changes do not impact production costs, which of the two would be your top priority? How much money would you be willing to invest in it?

The use of a spreadsheet like Excel is highly recommended. You could also use decision analysis software e.g. the evaluation version of TreeAge or the Palisade PrecisionTree to draft the event trees but this is not necessary for completing the assignment and may actually delay your work.

Part 2: Project Benefit Cost Analysis (BCA)

Based on the expected values (costs) of accidents in the above scenarios and transportation costs, you are asked to conduct a BCA using solely net present value (NPV) comparisons to evaluate total project costs. Assume that all costs accrue on the beginning of the year. Perform the evaluation for two discount rates of 5% and 15% respond to the questions below.

Table 4 Costs

Cost Type	Cost	Projected Life (in years)	Maintenance Costs	Restoration Costs
Long-term Central Facility Construction	$1B	1000	$1M per year for the first 100 years	$0. At the end of the facility life, the SNF would be rendered harmless
Short-term Facility Construction (both facilities)	$200M	50	$4M per year for the life of the project.	($1B) Additional cost for making a permanent facility (P = 0.5) or benefit +$200M as value for use that has been developed from new technologies.*

* ignore all related transport costs for this case – teleportation would be feasible by then anyway ☺

The rail solution will require a $150M investment for the long-term central facility construction and $50M for the temporary facilities.

a) What is the cost of the bundles of strategic alternatives you identified in Part 1 ?

b) What is your preferred solution? Why?

c) If the decision-makers decided to go with the permanent storage is it cost effective to build the rail spur to access the site?

d) What difference in annual expected cost from extra risks would justify the other storage solution than the one you choose?

Part 3: Issues with the Application of RA and BCA

As discussed in class and in the readings both the methods illustrated in this assignment have limits to their applicability and effectiveness in making sound decisions about the system. In a one page memo describe the problems you identified and indicate some possible ways to fix them.

Solutions
Part 1 RISK ASSESSMENT

1.
There are two types of implied strategic alternatives:
- a) (Decision of storage type): permanent facility (X) akin to Yucca mountain or two temporary facilities (A and B).
- b) (Decision of transportation method): rail or truck.

These can be combined to four simple bundles of strategic alternatives:
1. temporary facilities and rail
2. temporary facilities and truck
3. permanent facility and rail
4. permanent facility and truck

The fact that the network route path to X passes anyway from A and B simplifies some calculations for the bundles 3 and 4.

2.

2a. To calculate the expected value of the number of accidents occurring, we multiply the number of miles traveled by the probability of accident per mile. This means that we need to calculate total loads and total miles for each bundle and distinguish whether they go through a rural or an urban setting since the accident probabilities differ. This is done in the attached spreadsheet in detail.

Table SOL1 summarizes these calculations per bundle.

Table SOL1: Vehicle-miles traveled and Expected Values of Accidents for all bundles in Urban and Rural settings.

Bundle	Rural vehicle-miles	Urban vehicle-miles	EV(Rural accident)	EV(Urban accident)
Temp+rail	24.775	1.410	2.48%	0.282%
Temp+truck	500.800	28.200	501%	56.4%
Perm+rail	+214.600*	7050	21.5%	14.1%
Perm+truck	+3.889.000*	141.000	3890%	282%

*in addition to the temp solution results

This means that for the truck bundles, based on the probabilities per vehicle-mile as offered in the problem description some type of accident is inevitable. This does not mean that these would be major accidents. This is calculated later in the event tree based on the probability of leak, if an accident occurs, which is:

2b.
Since trucks carry a single container, the probability of leak given an accident is simply the one indicated at the outset: $\mathbf{10^{-4}}$.

This is not the case for trains. Since it is assumed that each individual containers probability to leak is 10^{-4} and is independent of what the rest do, this means that carrying 20 containers will increase the probability of at least one leak. Since we assumed that the impact of an incident is not dependent on the number of containers that leaked there is no need to calculate the probabilities of higher order incidents (at least two containers leaking etc. which would have been the case otherwise).
The way to calculate this probability is the following. The probability of a container not leaking is $(1-10^{-4})$. The probability of twenty containers not leaking is $\mathbf{(1-10^{-4})^{20}}$. So the probability of at least one leaking will be: $\mathbf{1- (1-10^{-4})^{20} = 0.002}$.

2c.

The same thinking applies for calculating the probability of the GPS/notification device failure which for trucks would be simply **0.01.** For rail we need at least one functioning GPS device to send the signal. Since a device is fitted in each container the probability that all fail at the same incident is $(0.01)^{20}$ which for all practical purposes is **0.**

3.

Event trees removed due to copyright restrictions.

4.

The calculation of final probabilities of events has already been shown on the event tree. Probabilities are calculated by starting from the end node (signifying a final state) and moving down the branches towards the root. The probability of an event occurring is the product of probabilities of the events that it is dependent on. These are shown as blue numbers above the end-node sign (blue triangle).

The expected values of the event costs are given by multiplying the probability of an event with the cost it would incur if it actually happened.

For rural accidents, the clean-up cost of the events of mild and severe accidents have already been given by the problem description.

Calculating the costs of urban clean-up is a little more nuanced since it is dependent on the population and the relative frequency of each population size. As a first step we calculate the clean-up costs for each city as shown in the table below:

TABLE SOL 2

			Mild incident	Severe Incident	Mild incident	Severe Incident
Route	Number of Cities	Population	Clean-up cost per city (in $M)		Weighted costs	
1A	1	300,000.0	900.0	27,000.0	82.98	2489.36
2A	3	100,000.0	100.0	1,000.0	31.91	319.15
3A	1	50,000.0	25.0	125.0	4.08	20.39
4B	3	75,000.0	56.3	421.9	5.98	44.88
5B	1	50,000.0	25.0	125.0	3.55	17.73
6B	1	1,000,000.0	10,000.0	1,000,000.0	1773.05	177304.96
Total for Temp bundles					**1901.55**	**180196.48**
BA	4	100,000.0	100.0	1,000.0	28.37	283.69
AX	5	50,000.0	25.0	125.0	17.91	89.54
Total for Perm bundles					**46.28**	**373.22**

The second step is to weigh the cost calculated for each population size with the ratio of the number of miles that go through these cities over the total number of urban miles as shown in the last two columns of the table.

The resulting outcomes (shown in gray) are used to calculate the expected values as shown in the event trees above.

Finally, the transportation costs are easy to calculate for each bundle based on the container-miles and the respective price.

We summarize the results of the expected value of accidents for each bundle and the transportation costs below.

TABLE SOL 3

Bundle	Transport Costs (in $M)	Expected costs of accidents (in $M)
Temp+rail	0.786	0.314
Temp+truck	2.645	3.193
Perm+rail	0.786 + 6.650 = 7.435	0.314 + 0.056 = 0.370
Perm+truck	2.645 + 20.150 = 22.795	3.193 + 0.186 = 3.378

5.
The bundle temporary storage with rail transport is preferable if all else is equal.

Accounting for transport costs does not change the result since both costs are calculated on a per mile basis.

6.
If we decide to use rail transport, increasing the reliability of the GPS device gives us no real benefit since the probability of all 20 devices breaking is practically zero.

We will perform the calculation for the perm+truck bundle which is the most severe.

Increasing the reliability of GPS by a factor of 10 changes the two event trees for truck and yields the following expected costs: 3.148 + 0.189 = $3.332M which is ~50K different than the previous expectation (3.378M).

Which means that a risk-neutral decision maker would pay up to $50K for such an improvement.

PART 2: BCA

a) What is the cost of the bundles of strategic alternatives you identified in Part 1 ?

We will show the calculations for DR = 0.05 -- DR = 0.15 is similar. All values are in million dollars.

The capital costs for year 0 are calculated first:

Bundle		Year 0 Capital costs
Temp + rail	200 + 50 =	$250M
Temp + truck		$200M
Perm + rail	1000 + 150 =	$1150M
Perm + truck		$1000M

From Table SOL3 we find the transport costs per year and the related risk for the first 10 years of the project. Since transportation is completed in 10 years we convert it to net present value using the formula:

Present Value of an Ordinary Annuity	$PV_A = Pmt\left[\frac{1-1/(1+i)^N}{i}\right]$

Figure by MIT OpenCourseWare.

Bundle	Annual transport costs	Annual risk related expected cost	Total	NPV (10 years DR = 0.05)
Temp + rail	0.79	0.31	1.1	8.5
Temp + truck	2.65	3.19	5.84	45.1
Perm + rail	7.44	0.37	7.81	60.3
Perm + truck	22.8	3.38	26.18	202.2

Maintenance NPV is calculated for 50 years in the temp solution and for 100 years in the perm solution. DR = 0.05

$NPV_{TEMP\_Maint.}$ = $73.0M
$NPV_{PERM\_Maint.}$ = $19.8M

Finally the closing costs need to be addressed. The perm solution does not have any. The temp solution is a simple expected value calculation: there is a 50% chance of getting a benefit of $200M and 50% chance of having to build the permanent facility anyway:

Closing cost = -0.5*200 + 0.5*1000 = $400M

Since this expenditure happens in year 50 we transform it into present value using the formula:
$NPV_t = C / (1 + DR)^t$

$NPV_{TEMPCLCOST}$ = $34.9M

The total costs are shown below:

Bundle	Year 0 Capital costs
Temp + rail	$366.4M
Temp + truck	$353.0M
Perm + rail	$1230.2M
Perm + truck	$1222.0M

b) What is your preferred solution? Why?

The numbers show temp + truck but there is evaluative complexity…

c) If the decision-makers decided to go with the permanent storage is it cost effective to build the rail spur to access the site?

No, it is not cost effective for either discount rate since the savings from the transportation costs do not offset the additional capital cost of building the spur.

d) What difference in annual expected cost from extra risks would justify the other storage solution than the one you choose?

The temp solution can accept ~$48M annual expected costs in additional risk (calculated by solving for PMT in the formula and setting PVA as the difference between the two solutions).