A Risk-Based Framework to Prioritise Safety Improvement Alternatives

To present at

HKIE-SSC AGM

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HKIE-SSC

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The presentation material will be posted at www.hkarms.org

Under HKARMS Web Resources

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Background

- New York City Penn Station was constructed in 1910
- Federal Railroad Administration required Amtrak, LIRR, and NJT to improve fire life safety for the station and the connecting tunnels
- Over 170 possible life safety improvement alternatives
  - Several different construction options
  - Some alternatives can be grouped together to reduce costs

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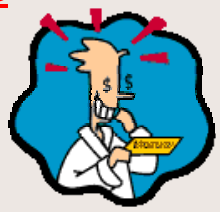
Factor Affecting Decision

- Regulatory Compliance
- Public Health & Safety
- Worker Health & Safety
- Public Perception
- Facilities/Equipment Damage
- Operational Impact
- Revenue
- Adaptability
- Legal Liability
- Management Resources
- Environmental Impact
- COSTS



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Other Challenges

- Multiple stakeholders
- Short time line to complete
- Union issues
- Supporting infrastructure during construction
- LIMITED FUNDING

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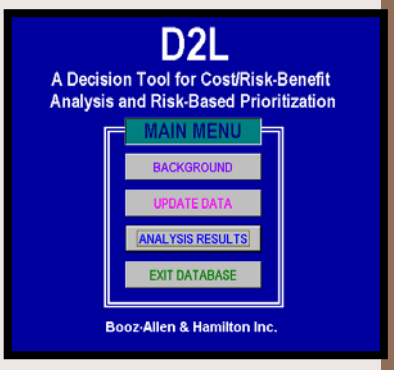
Project Objectives

- Prioritize life safety improvement alternatives according to their cost-effectiveness
- Develop methodology to accommodate multiple stakeholders decision-making with multiple attributes
- Conduct cost/risk-benefit analysis
- Develop a computer program to automate the process



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Topics to Discuss

- Decision Analysis
- MAU/AHP: Basic Concept
- Analysis and Results
- Concluding Remarks

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Decision Analysis

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Decision-Making: An Optimization Process

- Identify criteria (*decision attributes*) to judge options (*decision alternatives*) to select the optimal alternative that gives the best overall value/trade off
- Alternatives can be either independent, mutually exclusive, or interdependent
- There is always the "*do nothing*" alternative (status quo)
- Difficult when involves qualitative criteria coupled with perception, politics, emotion, etc.

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Decision-Making Techniques

- Visit temple, pray for god
- Muscling, loudest voice wins
- Roll dice, flip coin
- Qualitative approach
- Quantitative approach

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Decision-Making Strategies: Qualitative Approach

- Satisficing
- Elimination-by-aspects
- Incrementalism
- Mixed scanning
- Political approach
- Others

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Decision-Making Strategies: Quantitative Approach

- Voting, scoring
- Multi-Attribute Utility Theory (MAU)
- Analytical Hierarchical Process (AHP)

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Qualitative Approach: Satisficing

- Select the first alternative that is good enough with respect to some minimal criteria
- Cutoff level of constraints governs decision
- Apply to time-constrained situations

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Qualitative Approach: Elimination-by-Aspects

- Alternatives are examined by a series of aspects (attributes/criteria)
- An aspect is like a constraint involving one or more criteria
- An alternative is eliminated if it cannot meet the requirement of an aspect
- Make judgment by elimination
- Order of aspects can strongly influence results
- An alternative that superior in many aspects may be eliminated

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Qualitative Approach: Incrementalism

- Compare alternative courses of action to the current course of action
- Look for alternatives that can overcome shortcomings of the current course of action
- A decision that results in incremental improvement

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Qualitative Approach: Mixed Scanning

- Scanning: Collection, processing, evaluating and weighing of information
- Importance of decision determines the degree of scanning and choice
- Each alternative is briefly considered
- Reject alternatives for which strong objections are detected

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Qualitative Approach: Political Approaches

- Actions and decisions result from bargaining among players
- To predict decision, find out:
  - who the players are
  - what are the players' interests or stands?
  - what are the players' relative influence?
  - How does the combined dynamics of the above affect the decisions

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Decision Making: Other Strategies

- Dominance rule
  - Select the alternative that is better than other alternative(s) on at least one attribute and not worse on other attributes
- Lexicographic rule
  - Starts with the most important attribute and selects the attribute that ranks highest on that attribute
  - If two or more are tied, proceed to the next important attribute
- Maximizing number of attributes with greater attractiveness rule
  - Classify each alternative as better, equal or worse on each attribute
  - Select the alternative with the greater number of favorable attributes

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Decision Making Strategies: Other Strategies

- Conjunctive decision making
  - Compare all attributes of one alternative against all criteria
  - Reject the alternatives that do not meet the criteria
- Additive linear rule
  - Start with a set of predetermined weights of each alternative on each attribute (A)
  - Allocate weights against the attributes (B)
  - Multiply (A) by (B) to determine the score for each alternative
  - Select the alternative having the highest score

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Quantitative Approach: Multiattribute Utility (MAU) Theory

- Assumes a decision alternative can be characterized by a set of independent attributes
- Attribute scales are measured using utility
- Relative values of decision alternatives are measured by aggregating the attribute utilities
- Benefits of decision alternatives are measured by improvement of relative values attributable to their implementation

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Quantitative Approach: Analytic Hierarchy Process

- Decompose the overall decision objective into a hierarchic structure of criteria, sub-criteria, and alternatives
- Use pair-wise comparison matrix for criteria, sub-criteria and alternatives
- Process matrices to calculate relative weights of criteria and sub criteria
- Relative weights are used to arrive at a score for each alternative

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MAU/AHP: Basic Concept

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Cost/Risk-Benefit Analysis

- Measures the cost-effectiveness of life safety improvement alternatives
- Higher benefit-to-cost ratios indicate a more cost-effective decision alternative
- The benefit-to-cost ratio provides a basis for objective decision-making

$$B/C = \frac{Risk_{Existing} - Risk_{Improved}}{Cost}$$

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Using MAU in Evaluating Risk-Benefits

- Assumes a decision alternative (option) can be characterized by a set of independent attributes
- Attribute scales are measured by its ***utilities***
- Relative values of alternatives are measured by aggregating the attribute utilities
- Benefits of alternatives are measured by improvement of relative values attributable to their implementation; I.e., reduction in risks

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Utilities Theory

- An approach that can compare apples and oranges based on the assigned utility values of the items
- Every objective has a utility value
  - A utility is a common scale to measure quality of life
  - The most important objective has the highest utility value
  - The utility value of achieving 2 objectives is the sum of the individual utility values
- Advantages
  - Clearly shows interrelationships among objectives and alternatives
  - Allows quantifying non-quantifiable objectives
- Challenges
  - Difficult to get consistent utilities, meaningful probabilities, realistic objectives, etc.
  - Subjective. Must generate new utilities in every situation for every individual or group

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Utility Functions

- Real valued function on the space of possible outcomes
  - U(o) > U(o') ➔ o is a better outcome than o'
  - Allows evaluating actions

$$a > a' \text{ iff } EU(a) > EU(a'), \text{ i.e., } \sum_o \Pr(o \mid a)U(o) > \sum_o \Pr(o \mid a')U(o)$$

- Classical means of expressing preferences using quantitative representation
- Utility function is difficult to elicit from users
- Over-kill when tasks essentially deterministic

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Utility Conversion Factor, C

- Different attributes need to have common, easily comparable units
- Utility conversion factors convert the values measuring different ***attributes*** into one set of common utility units, usually a monetary value
- Example
  - Apple X has a utility value of 5A
  - Orange Y has a utility value of 2O
  - One can convert 1A=2U; 1O=7U
  - Thus, Apple X = 10U, Orange Y = 14U; Orange Y has a higher utility than Apple X in this case

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Measuring Risk by Utility

- Risk reduction, can be measured by change in utility:

$$\Delta R_i = \Delta u_i = u_{i,\,Existing} - u_{i,\,Improved}$$

where:

Δu_i = net risk reduction of alternative i

$u_{i,\,Existing}$ = baseline utility (with no improvements)

$u_{i,\,Improved}$ = modified utility (after improvement of alternative i)

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MAU for Safety Applications

- **Additive representation:**

$$U(o) = \Sigma_j U_j [C_A A_j(o)]$$

where

$U(o)$ = utility of alternative o

C_A is the utility conversion factor for A_j (o)

A_j = Measurement of risk for attribute A_j

$A_j = f(L_j S_j W_j)$

j = attribute j

Lj = likelihood of event for attribute j

Sj = severity of event for attribute j

Wj = relative weight of attribute j

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Cost/Risk-Benefit Analysis

$$B/C_i = \frac{Risk_{i,\,Existing} - Risk_{i,\,Improved}}{Cost_i}$$

where:

i	= *i^{th} decision alternative*
$Cost_i$	= *cost of decision alternative i*
B/C_i	= *benefit-to-cost ratio of decision alternative i*
$Risk_{i,baseline}$	= *baseline risk for decision alternative*
$Risk_{i,improved}$	= *Residual risk following implementation of decision alternative i*

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Cost/Risk-Benefit Analysis

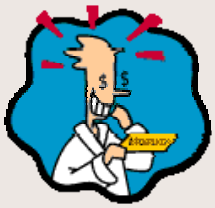
$$B/C_i = \frac{u_{i,\,Existing} - u_{i,\,Improved}}{Cost_i}$$

where:

i	$= i^{th}$ *decision alternative*
$Cost_i$	*= cost of decision alternative i*
B/C_i	*= benefit-to-cost ratio of decision alternative i*
$U_{i,baseline}$	*= baseline utility for decision alternative*
$U_{i,improved}$	*= Residual utility following implementation of decision alternative i*

Cost Evaluation

- Different decision alternatives incur different costs
- The costs may include:
  - capital costs
  - construction costs
  - life cycle costs
  - loss of revenue



- Cost is usually measured by monetary value (dollar); thus, making utility measuring in monetary value convenient for the analysis

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Challenges

- How do we get the utility function and conversion factor?
- By application of AHP to get utility conversion factors
- Use risk matrices to get weighted utility values for attributes of alternatives

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AHP – What is it?

- AHP: Analytic Hierarchy Process - A Simple Decision System
- Use pair-wise comparison method to rank order decision attributes and alternatives
- Assist in providing quantitative basis for decision making
- Process:
  - Determine various available alternatives
  - Select criteria on which to base the decision
  - Determine relative importance of criteria
  - Score criteria for the alternatives
  - Make the decision

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AHP – Example

- **Buying a car (Objective)**
  - **Which one do I purchase? (Alternatives)**
    - **Volvo**
    - **Ferrari**
    - **Toyota**
    - **Red Star**
  - **What are the decision criteria (Attributes):**
    - **Safety**
    - **Comfort**
    - **Style**

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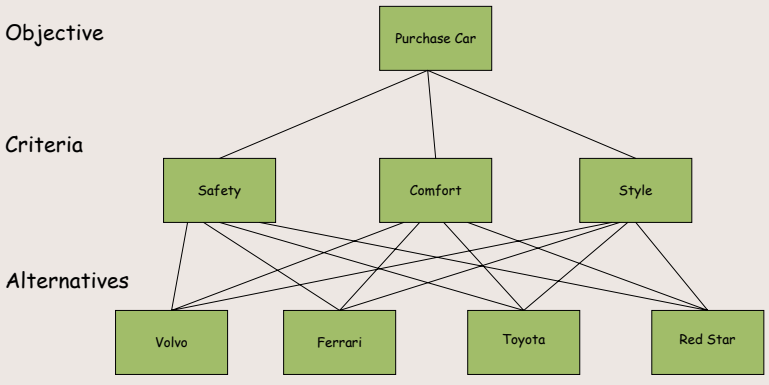
An Example



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Pairwise Comparisons

- Compare Safety to Comfort
  - Which is more important?
    - Safety
    - Comfort
  - How much more important?
    - A little?
    - A lot ?
    - Somewhere in-between?
- Compare Comfort to Style, then Style to Safety

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Scales to Be Used

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally
3	Weak Importance of one over another	Experience & Judgment slightly favor one over another
5	Essential or Strong Importance	…Strongly favor one over another
7	Very Strong and Demonstrated	…Strongly favored and its dominance demonstrated in practice
9	Absolute Importance	Evidence favoring one over another is of the highest possible order
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed

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The Matrix (by Volvo Owner)

	Safety	Comfort	Speed
Safety	1	3	5
Comfort	1/3	1	1/3
Speed	1/5	3	1

Intensity of Importance	Definition	Explanation
3	Weak Importance of one over another	Experience & Judgment slightly favor one over another
5	Essential or Strong Importance	…Strongly favor one over another

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The Matrix (by Ferrari Owner)

	Safety	Comfort	Speed
Safety	1	3	1/7
Comfort	1/3	1	1/9
Speed	7	9	1

Intensity of Importance	Definition	Explanation
3	Weak Importance of one over another	Experience & Judgment slightly favor one over another
7	Very Strong and Demonstrated	…Strongly favored and its dominance demonstrated in practice
9	Absolute Importance	Evidence favoring one over another is of the highest possible order

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AHP- Pairwise Comparisons

- Apply the matrix to compare the decision attributes
- Apply the matrix again to compare the decision alternatives based on EACH attribute
- Apply mathematical calculations to obtain the eigenvector and eigenvalue, which represent the weighing factors of the alternatives and the consistence
- Ranking of decision alternatives based on the eigenvector

This topic is beyond the scope of today's talk.
Will have a separate talk on the applications of AHP

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Analysis and Results

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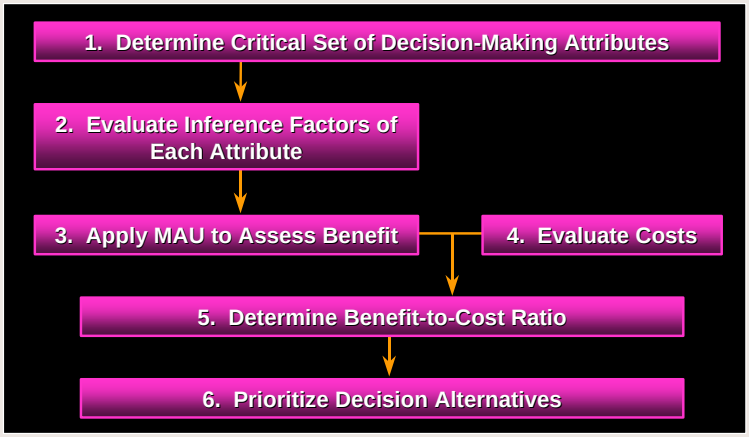
Project Procedure



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1.1 Identify an Initial Set of Decision-Making Attributes

- Regulatory Compliance
- Public Health & Safety
- Worker Health & Safety
- Public Perception
- Facilities/Equipment Damage
- Operational Impact
- Legal Liability
- Management Resources
- Environmental Impact

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1.2 Screen the attributes for their importance

Apply AHP to determine attribute importance factors (i.e., relative weights)

Attribute	Relative Weight
Public Health & Safety	4.93
Worker Health & Safety	4.03
Regulatory Compliance	1.35
Operational Impact	1.18
Facility/Equipment Damage	1.00
Environmental Impact	0.94
Legal Liability	0.77
Public Perception	0.64
Management Resources	0.43

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1.3 Screen Critical Set and Consistence

- Apply AHP in multiple turns between stakeholders
- Check for consistence and weighing for consensus
- Apply treatment on consolidation of expert opinion
- Screen a final critical set of attributes with relatively higher weighing

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1.4 Final Set of Decision-Making Attributes

Critical Attribute	Relative weight
Regulatory compliance	1.4
Public health and safety	5.0
Worker health and safety	4.0
Facility/equipment damage	1.0
Operational impact	1.2

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Step 2. Evaluate Inference Factors of each Attribute

2.1 Determine the inference factors for the critical set of decision-making attributes

2.2 Determine the scales for each inference factor

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2.1 Determine the inference factors for the critical set of attributes

- Each attribute is characterized by two inference factors:
  - the attribute-specific severity of event
  - the likelihood of event (expressed as the frequency of occurrence)
- Each inference factor is further divided into internal scales

2.2 Determine the scales for each inference factor

- Actual data are used to determine the internal scales
- Severity scales should be based on data representative of the range of impacts due to a particular event or incident
- Likelihood scales should be based on data representative of the frequency of occurrence of these events or incidences.

Inference Factor – Public Health and Safety Effects with Severity Measures

Category	Severity of effect description	Severity*
A	Most serious effect. • Exposures will produce multiple fatalities (> 10) and/or are likely to produce permanent and near total loss of quality of life (e.g., death, coma, quadriplegia, disabling birth defects, etc.). This type of impact may include a large number of lesser injuries in addition to the very serious types listed.	$27,000,000 to $81,000,000
B	Very serious effect. • Exposures will produce fatalities (< 9) and/or are likely to produce permanent and near total loss of quality of life (e.g., death, coma, quadriplegia, disabling birth defects, etc.). This type of impact may include a large number of lesser injuries in addition to the very serious types listed.	$2,700,00 to $24,300,000
C	Serious effect. • Exposures may produce permanent debilitating injury or serious long-term illness (effects last 5 years or more) (e.g., permanent loss of function of hand, leg, eye, serious heart attack, etc.). Again the number of total injuries may be increased with a variety in the severity of the injuries.	$520,000 to $2,700,000
D	Moderate effect. • Exposures may produce moderate injury or illness, but the effects are not likely to be long-term (effects last 1 year or less) or life threatening (e.g., broken bones, shock, third degree burns, etc.). The number of injured will be slightly higher with a greater variety of injuries, but none more serious than listed.	$40,000 to $520,000
E	Minor effect. • Exposures are unlikely to produce more than minor injury and/or temporary discomfort (e.g., cuts, bruises, minor burns, etc.) and the number of injured will be quite few (1 to 3 people).	< $40,000
F	No effect.	0

* Values are subject to refinement.

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Inference Factor – Likelihood forPublic Health and Safety Effects

Category	Annual likelihood description	Likelihood*
A	Frequent. Likely to occur frequently.	10^{-2}
B	Probable. Will occur several times in the life of the item.	10^{-3}
C	Occasional. Likely to occur sometimes in the life of an item.	10^{-4}
D	Remote. Unlikely but possible to occur in the life of an item.	10^{-5}
E	Unlikely. Very unlikely, but possible to occur in the life of an item	10^{-6}
F	Improbable So unlikely, it can be assumed occurrence may not be experienced.	10^{-7}

* Values are subject to refinement.

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Step 3. Apply Utility Theory to Assess the Benefit

3.1 Develop an expression for the overall utility

3.2 Apply the expression to all life safety improvement alternatives

3.1 Develop an Expression for the Overall Utility

$$U_i = \sum_j A_{ij} \quad ; \quad A_{ij} = f\,(L_{ij}, S_{ij}, W_j, C_j)$$

Where:

- i = alternative i
- j = alternative j
- U_i = utility of alternative i
- L_{ij} = likelihood of event for alternative i and attribute j
- S_{ij} = severity of event for alternative i and attribute j
- W_j = relative weight of attribute j
- C_j = utility conversion factor for attribute j

3.2 Apply the Expression to All Alternatives

- Determine the overall utility of each life safety improvement alternative (170+)
- The overall utility is the reduction in risk as a result of implementing the alternative
- The unit of overall utility is U (or $/hour)

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3.2 Apply the Expression to All Alternatives (Example for Alternative i)

$Benefit = Risk_{baseline} - Risk_{improved} = \$486.7/hour$

$= \$487.7U$

Where:

$Risk_{baseline} = \{(LxSxWxC)_{RC}+(LxSxWxC)_{PHS}+ (LxSxWxC)_{WHS}+(LxSxWxC)_{FED}+(LxSxWxC)_{OI}\}_{baseline}$

$= \$514.5/hour = \$514.5U$

$Risk_{improved} = \{(LxSxWxC)_{RC}+(LxSxWxC)_{PHS}+ (LxSxWxC)_{WHS}+(LxSxWxC)_{FED}+(LxSxWxC)_{OI}\}_{improved}$

$= \$27.8/hour = \$27.8U$

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3.2 Apply the Expression to All Decision Alternatives (Example for Alternative i)

		BASELINE		IMPROVED	
Attribute	W	S × C ($)	L (/hr)	S × C ($)	L (/hr)
RC	1.4	6.5×10^{4}	1.0×10^{-5}	1.5×10^{4}	1.0×10^{-6}
PHS	5.0	2.8×10^{5}	1.0×10^{-4}	2.8×10^{5}	1.0×10^{-5}
WHS	4.0	1.6×10^{6}	1.0×10^{-5}	1.6×10^{6}	1.0×10^{-6}
FED	1.0	2.8×10^{5}	1.0×10^{-4}	2.8×10^{5}	1.0×10^{-5}
OI	1.2	2.4×10^{6}	1.0×10^{-4}	4.0×10^{5}	1.0×10^{-5}

By AHP Inference Factor by Risk Matrices

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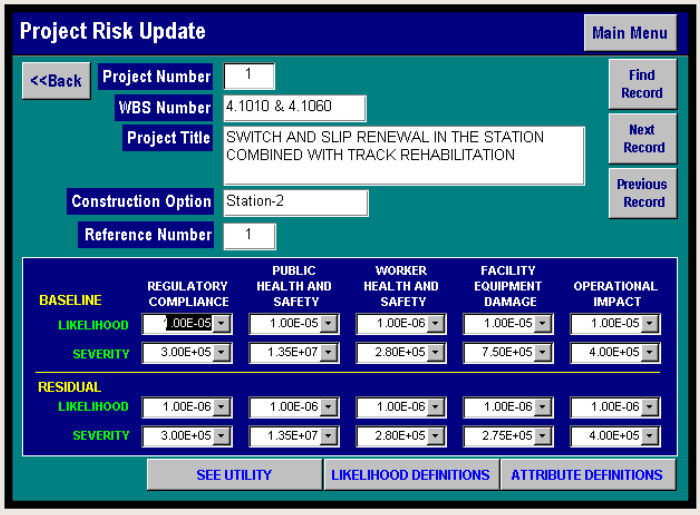
3.2 Apply the Expression to All Alternatives



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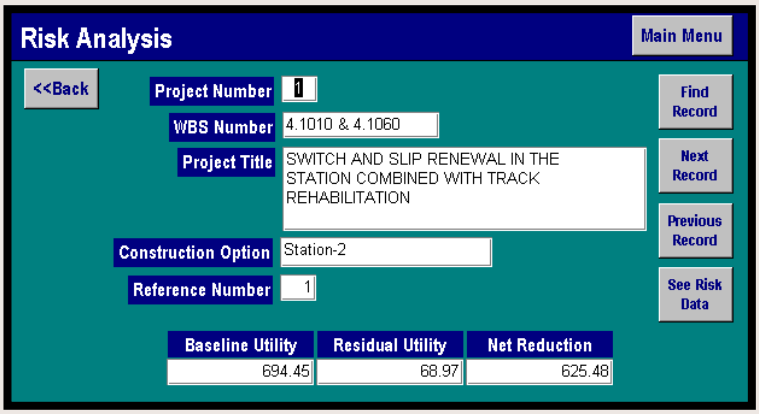
Utility Calculation



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Step 4. Evaluate Costs

- **Financial cost data for each alternative is obtained by evaluating:**
  - **capital costs**
  - **construction costs**
  - **life cycle costs**
  - **loss of revenue**
  - **Decommissioning and salvage value**

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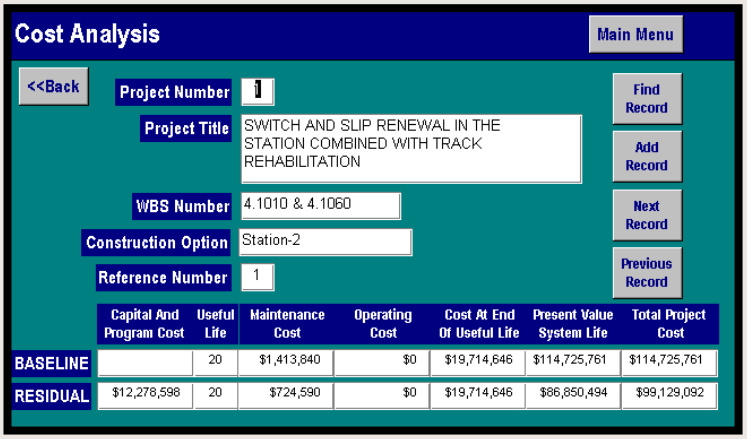
Cost Evaluation



Step 5. Determine the Benefit-to-Cost Ratio

$$B/C_i = \frac{Risk_{i,\,baseline} - Risk_{i,\,improved}}{Cost_i}$$

Where:

- $i = i^{th}$ life safety improvement alternative
- B/C_i = benefit-to-cost ratio or alternative i
- $Risk_{i,\,baseline}$ = baseline risk for alternative i
- $Risk_{i,\,improved}$ = baseline risk for alternative i
- $Cost_i$ = cost of alternative i

Step 6. Prioritize Decision Alternatives

- Rank-order decision alternatives according to their benefit-to-cost ratio
- A high rank ordering is indicative of a high benefit-to-cost ratio, which in turn indicates a cost-effective decision alternative.

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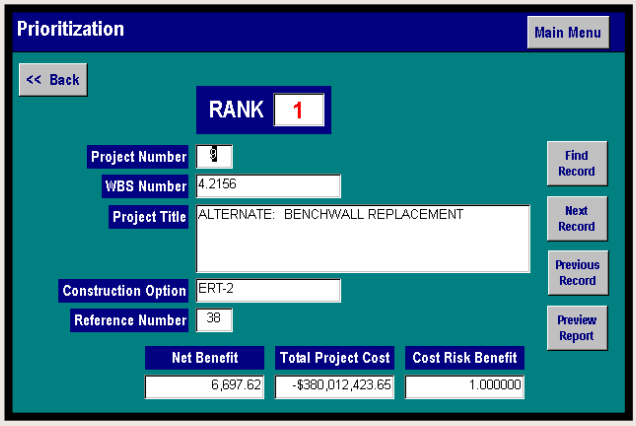
Alternative Prioritization



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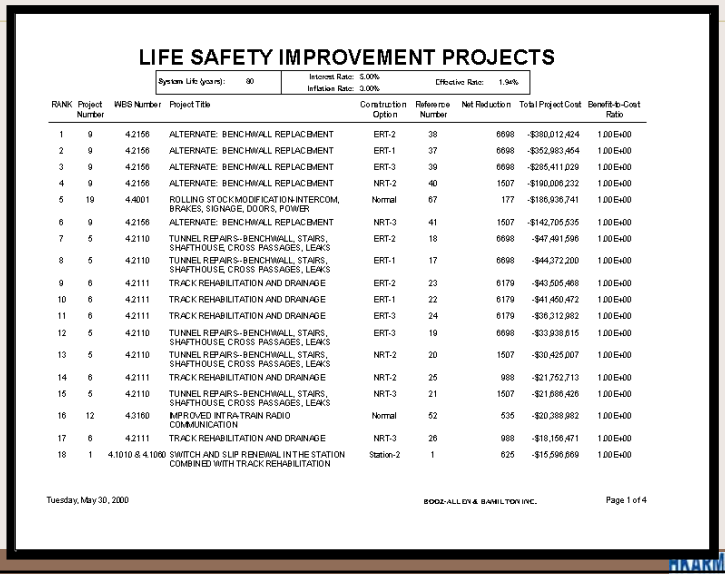
Prioritization Report



LIFE SAFETY IMPROVEMENT PROJECTS

System Life (years): 30 | Interest Rate: 5.00% | Inflation Rate: 3.00% | Effective Rate: 1.94%

RANK	Project Number	WBS Number	Project Title	Construction Option	Reference Number	Net Reduction	Total Project Cost	Benefit-to-Cost Ratio
1	9	4.2156	ALTERNATE: BENCHWALL REPLACEMENT	ERT-2	38	6698	-$380,012,424	1.00E+00
2	9	4.2156	ALTERNATE: BENCHWALL REPLACEMENT	ERT-1	37	6698	-$352,983,454	1.00E+00
3	9	4.2156	ALTERNATE: BENCHWALL REPLACEMENT	ERT-3	39	6698	-$285,411,029	1.00E+00
4	9	4.2156	ALTERNATE: BENCHWALL REPLACEMENT	NRT-2	40	1507	-$190,006,232	1.00E+00
5	19	4.4001	ROLLING STOCK MODIFICATION-INTERCOM, BRAKES, SIGNAGE, DOORS, POWER	Normal	67	177	-$186,936,741	1.00E+00
6	9	4.2156	ALTERNATE: BENCHWALL REPLACEMENT	NRT-3	41	1507	-$142,705,535	1.00E+00
7	5	4.2110	TUNNEL REPAIRS--BENCHWALL, STAIRS, SHAFTHOUSE, CROSS PASSAGES, LEAKS	ERT-2	18	6698	-$47,491,596	1.00E+00
8	5	4.2110	TUNNEL REPAIRS--BENCHWALL, STAIRS, SHAFTHOUSE, CROSS PASSAGES, LEAKS	ERT-1	17	6698	-$44,372,200	1.00E+00
9	6	4.2111	TRACK REHABILITATION AND DRAINAGE	ERT-2	23	6179	-$43,505,468	1.00E+00
10	6	4.2111	TRACK REHABILITATION AND DRAINAGE	ERT-1	22	6179	-$41,460,472	1.00E+00
11	6	4.2111	TRACK REHABILITATION AND DRAINAGE	ERT-3	24	6179	-$36,312,982	1.00E+00
12	5	4.2110	TUNNEL REPAIRS--BENCHWALL, STAIRS, SHAFTHOUSE, CROSS PASSAGES, LEAKS	ERT-3	19	6698	-$33,938,615	1.00E+00
13	5	4.2110	TUNNEL REPAIRS--BENCHWALL, STAIRS, SHAFTHOUSE, CROSS PASSAGES, LEAKS	NRT-2	20	1507	-$30,425,007	1.00E+00
14	6	4.2111	TRACK REHABILITATION AND DRAINAGE	NRT-2	25	988	-$21,752,713	1.00E+00
15	5	4.2110	TUNNEL REPAIRS--BENCHWALL, STAIRS, SHAFTHOUSE, CROSS PASSAGES, LEAKS	NRT-3	21	1507	-$21,686,426	1.00E+00
16	12	4.3160	IMPROVED INTRA-TRAIN RADIO COMMUNICATION	Normal	52	535	-$20,388,982	1.00E+00
17	6	4.2111	TRACK REHABILITATION AND DRAINAGE	NRT-3	26	988	-$18,156,471	1.00E+00
18	1	4.1010 & 4.1060	SWITCH AND SLIP RENEWAL IN THE STATION COMBINED WITH TRACK REHABILITATION	Station-2	1	625	-$15,596,669	1.00E+00

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Conclusions

- Methodology allows a decision-maker to prioritize alternatives while considering several attributes
- Risk-based combining AHP and MAU
  - AHP simplifies the utility analysis by providing an efficient, straight forward screening and weighting tool
  - MAU provides a methodology to compare different attributes using a common scale and easily handles a large number of alternatives
- Automated by easy to use computer module
  - allow sensitivity analysis
  - allow uncertainty analysis

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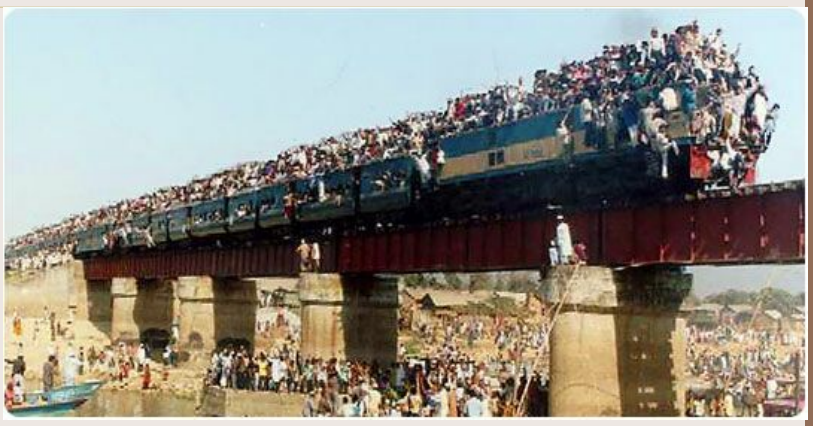
If there is no risk…



there is no opportunity.

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HKARMS

The presentation material will be posted on www.hkarms.org

Under HKARMS Web Resources

END

For enquires, please contact Vincent Ho

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