Chapter 9

COST EFFECTIVENESS ANALYSIS

9/26/2019

1. INTRODUCTION

Cost effectives analysis is synonymous with "marginal cost-benefit" analysis. It answers the question of whether or not a given technology should be made safer by the addition of extra safety equipment. It comprises an array of other methods of risk assessment such as:

1. Comparison of risks and benefits, where a set of alternatives may be used to choose among different options. This requires the risks and benefits to be expressed in the same units.
2. Placing risks into perspective, with the objective of determining whether the risks of a technology compare favorably with the existing risks of presently accepted technologies. The risk of a new technology should be at least a factor of 10 lower than well established technologies.

2. COST EFFECTIVENESS

Safety expenditures follow the economic law of diminishing returns, as shown in Fig. 1. According to this graph, it is possible to reduce a relatively high risk to a lower level by an amount:

$$\Delta R_1$$

at a low additional cost:

$$\Delta C_1$$

It becomes more and more expensive to reduce the risk even further, for instance from S_5 to S_6.

The slope of the curve at a point:

$$\frac{\Delta R}{\Delta C}$$

is a measure of the cost effectiveness of further risk reduction from the level of safety represented by that point.

The marginal cost of risk reduction is measured in terms of:

$$\frac{\text{Human health effects avoided}}{\text{Unit cost of risk reduction}}.$$

For instance, in terms of:

$$\frac{\text{Lost person-days avoided}}{\text{Million dollars}}.$$

3. OBSERVATIONS

Two main observations can be noticed:

1. The marginal cost of risk reduction increases with the level of safety achieved.
2. For any given safety level, it is possible to reduce any existing risk even further, however, it is not possible to reduce the risk to a zero value. Accordingly, absolute safety is not achievable.

4. SOCIAL COST OF DISABILITIES

Top account for the cost of disabilities, one model uses the relationship:

$$\begin{aligned}\text{Total social cost} &= \text{NC}(1+\text{i})^{\text{t}}, \quad t < 6,000 \\ &= \text{NC}(1+\text{i})^{6,000}, \; t \geq 6,000\end{aligned} \tag{1}$$

where: N is the number of individuals involved,
C is the cost of one disability day,
i is the daily interest rate,
t is the time in consecutive days of disability.

The National Safety Council considers a value of t = 6,000 days to represent a fatality.

5. COST BENEFIT RATIO

The cost benefit ratio takes into account both the predicted frequency and consequences of events as:

$$\text{Cost Benefit Ratio} = \frac{\text{C}}{\sum_{i=1}^{n} \text{f}_{\text{i}}\text{R}_{\text{i}} - \sum_{i=1}^{m} \text{f}_{\text{i}}^{'}\text{R}_{\text{i}}^{'}} \tag{2}$$

where: C is the annualized cost of a given installed safety feature, [$/year],
f_i is the frequency of the i-th accident sequence *without* the safety feature installed, [events/year],

f'_i is the frequency of the i-th accident sequence *with* the safety feature installed, [events/year],

R_i is the radiological consequence in person-rem or person-Sievert of the i-th sequence *without* the safety feature,

R'_i is the radiological consequence in person-rem or person-Sievert of the i-th sequence *with* the safety feature installed.

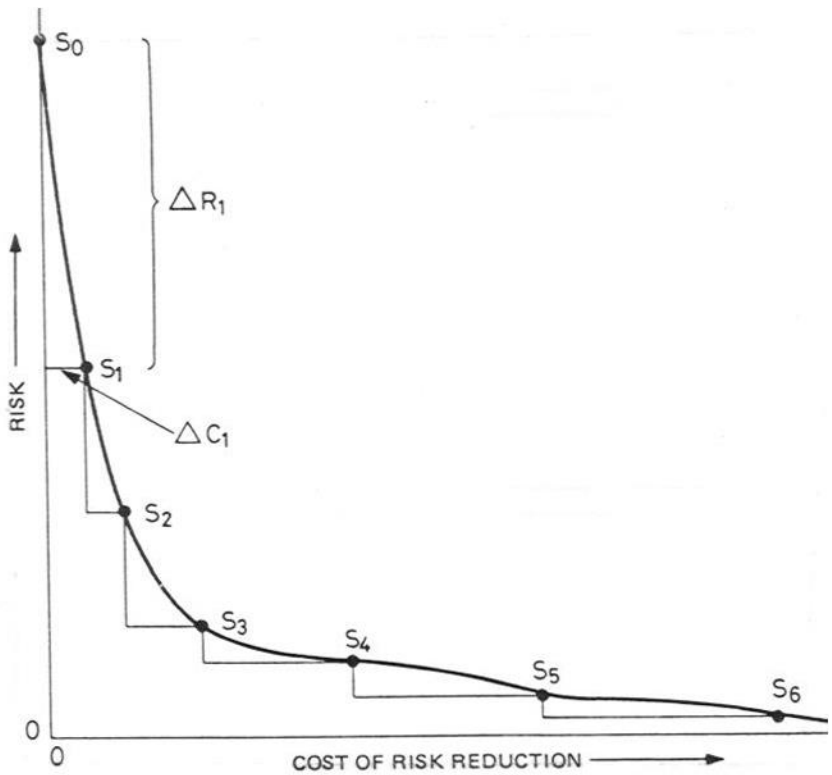

Figure 1. Cost Effectiveness curve, and the law of diminishing returns.

Notice that the number of accident sequence without the safety features, n is different from the number of accident sequences with the safety features installed. In general, m > n.

6. APPLICATION TO A PRESSURISED WATER REACTOR (PWR) SYSTEM

For the Emergency Core Cooling System (ECCS) for a Pressurized Water Reactor (PWR) system, it can be estimated that:

$$C = 1.5 \times 10^6 \text{ [\$/year]}$$

$$\sum_{i=1}^{n} f_i R_i = 1.4 \times 10^5 \text{[person.rem/year]}$$

$$\sum_{i=1}^{m} f_i' R_i' = 2.5\times10^4 [\text{person-rem/year}]]$$

$$\text{ECCS cost benefit ratio} = \frac{\$1.5\times10^6\,/\text{year}}{(1.4\times10^5 - 2.5\times10^4)[\text{person-rem/year}]} \qquad (3)$$

$$= 14/[\$/(\text{person-rem})]$$

This value is much less than the Nuclear Regulatory Commission (NRC) guideline value of $ 1,000 / (person.rem). This suggests that the safety feature is considered cost effective, and should be incorporated in the design.

The detailed calculation used for determining the cost benefit ratio of the ECCS is shown in Table 1.

Table 1. Risk calculation for the estimation of the cost benefit ratio of an Emergency Core Cooling System (ECCS).

ESF case	Accident event sequence[a]	Frequency, $year^{-1}$	Equivalent RSS consequence sequence[a]	Release category	Radiological consequences, man-rem	Risk, man-rem/year
		$\mathcal{F}_i$			R_i	$\mathcal{F}_i R_i$
No ESFs	A	1×10^{-4}	AB–α	1	8.0×10^{7}	8.0×10^{3}
	S_1	3×10^{-4}	S_1 B–α	1	8.0×10^{7}	2.4×10^{4}
	S_2	1×10^{-3}	S_2 B–α	1	8.0×10^{7}	8.0×10^{4}
	TMLB	3×10^{-4}	TMLB–α	1	8.0×10^{7}	2.4×10^{4}
						$\Sigma\mathcal{F}_i R_i = 1.4\times10^{5}$
		$\mathcal{F}_i'$			R_i'	$\mathcal{F}_i' R_i'$
ECCS only	A	1×10^{-4}	A–β	8	4.0×10^{4}	4.0×10^{0}
	S_1	3×10^{-4}	S_1–β	8	4.0×10^{4}	1.2×10^{1}
	S_2	1×10^{-3}	S_2–β	8	4.0×10^{4}	4.0×10^{1}
	AB	1×10^{-7}	AB–α	1	8.0×10^{7}	8.0×10^{0}
	AD	2×10^{-6}	ADC–α	1	8.0×10^{7}	1.6×10^{2}
	AH	1×10^{-6}	AH–α	3	4.4×10^{7}	4.4×10^{1}
	S_1 B	2×10^{-7}	S_1 B–α	1	8.0×10^{7}	1.6×10^{1}
	S_1 D	3×10^{-6}	S_1 DC–α	1	8.0×10^{7}	2.4×10^{2}
	S_1 H	3×10^{-6}	S_2 H–α	3	4.4×10^{7}	1.3×10^{2}
	S_2 B	8×10^{-7}	S_2 B–α	1	8.0×10^{7}	6.4×10^{1}
	S_2 D	9×10^{-6}	S_2 DC–α	1	8.0×10^{7}	7.2×10^{2}
	S_2 H	6×10^{-6}	S_2 H–α	3	4.4×10^{7}	2.6×10^{2}
	TMLB	3×10^{-4}	TMLB–α	1	8.0×10^{7}	2.4×10^{4}
						$\Sigma\mathcal{F}_i' R_i' = 2.5\times10^{4}$

The container failure modes alluded to in Table 1 are shown in Table 2. The accident initiating events are shown in Table 3, and the system failure modes are shown in Table 4.

Table 2. Containment Failure modes definitions.

Mode	Failure
α	Vessel steam explosion
β	Penetration leakage
γ	Overpressure due to hydrogen burning
ε	Base mat melt through

Table 3. Accident initiating events definitions.

Symbol	Accident sequence initiating event
T_1	Loss of offsite power (LOSP) transient.
T_2	Loss of power conversion system transient caused by other than a LOSP
T_3	Transients with power conversion system initially available.
S_1	Intermediate Loss of Coolant Accident (LOCA).
S_2	Small LOCA (4 inches <Pipe diameter <10 inches)
S_3	Small-Small LOCA (Pipe diameter < 4 inches).
V	Interfacing systems LOCA

Table 4. System failure modes definitions.

Symbol	System failure description.
(B_3)	Emergency power system failure.
D	Emergency coolant injection system failure.
F	Containment spray recirculation system failure.
H	Emergency coolant recirculation system failure.
K	Reactor protection system failure.
L	Emergency feedwater system failure with recovery of power conversion system and high head auxiliary feedwater system.
M	Power conversion system failure.
Q	Reclosure of pressurizer safety relief valves.
U	High pressure injection system failure.
O	Failure of reactor building cooling system.

The cost benefit ratios for other Engineered Safety Features (ESFs) applied to different sequences of implementation in the form of a matrix is shown in Table 5, and the cost benefit ratios for various health and safety measures are shown in Table 6.

Table 5. Cost benefit ratios matrix for Engineered Safety Features applied in different sequences.

ESF sequence	Sequence of ESF application 1	2	3
1	DG	ECCS	Containment
Risk reduction, Δ man-rem/year	2.4×10^4	1.1×10^5	1.4×10^3
Cost–benefit ratio, $/man-rem	83	14	2083
2	DG	Containment	ECCS
Risk reduction, Δ man-rem/year	2.4×10^4	1.1×10^5	4.8×10^2
Cost–benefit ratio, $/man-rem	83	27	3125
3	ECCS	DG	Containment
Risk reduction, Δ man-rem/year	1.1×10^5	2.4×10^4	1.4×10^3
Cost–benefit ratio, $/man-rem	14	85	2083
4	ECCS	Containment	DG
Risk reduction, Δ man-rem/year	1.1×10^5	6.8×10^3	1.8×10^4
Cost–benefit ratio, $/man-rem	14	441	111
5	Containment	DG	ECCS
Risk reduction, Δ man-rem/year	1.2×10^5	1.8×10^4	4.8×10^2
Cost–benefit ratio, $/man-rem	25	111	3125
6	Containment	ECCS	DG
Risk reduction, Δ man-rem/year	1.2×10^5	4.0×10^2	1.8×10^4
Cost–benefit ratio, $/man-rem	25	3750	111

Table 6. Cost benefit ratios for different health and safety implementations.

Safety Implementation	Cost benefit Ratio [10^6 $/life saved]
Medical and health Programs	
Kidney dialysis treatment units	0.2
Mobile cardiac emergency treatment units	0.03
Cancer screening programs	0.01-0.08
Fire protection	
Consumer Product Safety Commission (CPSC) upholstered furniture flammability standards	0.5
Smoke detectors	0.05-0.08
Automotive and Highway Safety	
Highway safety programs	0.14
Auto safety improvements, 1966-1970	0.13
Air bags	0.32
Seat belts	0.08
Environmental Protection	
Environmental protection Agency (EPA) vinyl chloride regulations	4
EPA drinking water regulations	2.5
Occupational health and safety	
Occupational Safety and Health Administration (OSHA) coke fume	4.5

regulations	
OSHA benzene regulations	300
Coal fired power plants	
High sulfur coal with 85 percent removal SO_2 scrubbers	0.1-1.4
Low sulfur coal with 85 percent removal SO_2 scrubbers	0.7-10
Nuclear power plants	
Emergency Core Cooling System (ECCS)	0.1
Radioactive waste (rad waste) effluent treatment systems	10
Containment system	4
Diesel Generator (DG) sets	1
Hydrogen recombiners	>3,000

7. COST EFFECTIVENESS CONSIDERING THE OVERALL ECONOMIC SYSTEM

If we consider the issue of reducing the risk of a given engineering alternative, one should account for the occupational and public risk involved in the production of the safety equipment itself. As shown in Fig. 2, a linear term should be added for this purpose.

This modifies the cost effectiveness curve in that the total risk now passes through an optimal value beyond which the risk increases. At high costs, the total risk curve no longer approaches asymptotically the zero risk level, but approaches the risk of producing the added safety equipment.

The minimum occurs when the marginal costs of risk reduction; that is the first derivative of the operational curve, are equal to the specific risk of the production of safety equipment; which is the slope of the linear term.

Table 7 shows the occupational risk of producing safety equipment worth one million dollars, assuming that the installed safety equipment consists of 30 percent construction work, 10 percent services and 60 percent machine tools plus electrical equipment.

Table 7. Working hours and occupational health effects of production of goods worth 10^6 dollars.

Industry	Total working hours	Occupational accidental deaths	Job related driving fatalities	Occupational chronic deaths	Lost working hours
Machine tools and electrical equipment	82,000	0.470×10^{-2}	0.354×10^{-2}	0.302×10^{-3}	416
Mining	76,600	1.916×10^{-2}	0.340×10^{-2}	8.740×10^{-3}	1,040

Stone and earth	63,200	1.182×10^{-2}	0.356×10^{-2}	0.894×10^{-3}	438
Textiles and clothing	119,600	0.270×10^{-2}	0.314×10^{-2}	0.232×10^{-3}	336
Services, provisions and fine goods	75,000	0.566×10^{-2}	0.210×10^{-2}	0.206×10^{-3}	118
Construction	101,000	1.492×10^{-2}	0.592×10^{-2}	0.344×10^{-3}	630

For instance, to produce machine tools, mining of ores and minerals is required, as well as refining the ores, producing coke, making steel, casting, transporting and use of electricity. There results a matrix of activities. This matrix is called an input/output table and is used in economics to describe the interrelationships among the economic sectors in monetary terms.

Using these tables and using occupational data on injuries and fatalities, it is possible to construct a matrix illustrating the health effects flows instead of monetary flows. A simple mathematical procedure called the inverse Leontief-Matrix allows one to sum the risks involved in all steps of preprocessing.

From Table 7 it is clear that mining causes the largest health effects per unit value of goods produced though it requires less total working hours than construction. The job related driving fatalities are largest for the construction sector.

Assuming that one death is equivalent to 6,000 lost person-days, the total working hours and the occupational risk is given in Table 8. The specific risk, r_p sets the slope of the straight line in Fig. 2.

Table 8. Total occupational risk of producing safety equipment worth 10^6 dollars.

Total working hours.	87,000
Lost working hours	450
Lost working days (450/8)	56.25
Occupational accidental deaths	7.860×10^{-3}
Driving fatalities	4.120×10^{-3}
Occupational chronic deaths	0.306×10^{-3}
Total deaths	12.286×10^{-3}
Equivalent lost person-days	73.716
Total equivalent lost person-days (r_p)	129.966

This value can now be used to determine the minimum risk of the total system curve. The minimum occurs where the marginal cost of risk reduction has the same slope, but opposite in sign as the investment line. At this point the production and installation of safety equipment would result in one equivalent health effect among the public at some future time. In other terms, a single statistically certain death would be caused at the present time instead of one hypothetical death at some time in the future.

Any costs of safety measures which exceed the minimum will cause more health effects than they prevent.

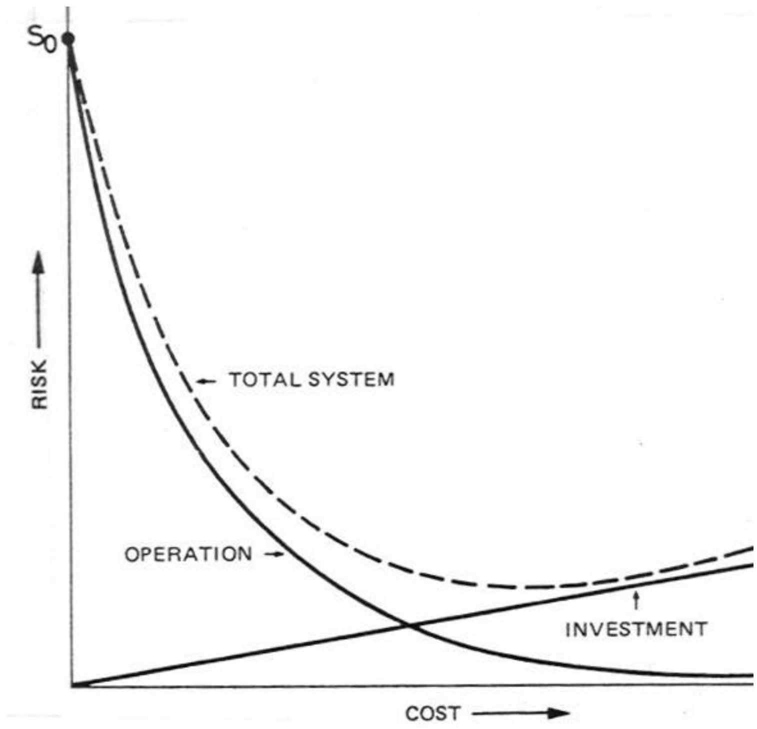

Figure 2. Cost Effectiveness considering the overall economic system.

It should be noted that such a principle has been used in medical practice. Recommendations for vaccination against smallpox have been withdrawn since the risk of the vaccination itself became at some point higher than the risk of contracting the disease.

Table 9 compares the marginal costs of risk reduction with r_p=1 [equivalent death / 33x10^6 dollars]. It can be noticed that r_p is exceeded in several cases. The second column gives the ratio between effects saved and effects caused. A ratio of 1 would indicate that no net savings are achieved. Numbers greater than unity indicate that the risk has been actually increased.

Table 9. Comparison of the marginal cost of risk reduction.
r_p = [1 equivalent death/33x10^6 dollars]

Safety measure	[10^6 $/life saved]	[10^6 $/life saved].$r_p$ *
Automobile seat belts	0.3	0.01
Fire control in high rise buildings	40	1.21
Coal plants with flue gas desulfurization (50 percent)		
30 meters stak	0.2	0.006
120 meters stack	2.5	0.08
Nuclear power plants**		

Hydrogen gas recombiners	9	0.27
Six charcoal beds added	22	0.66
Twelve charcoal beds added	150	4.5
Iodine treatment	500	15.0

* Value > 1 implies that the risk of providing safety exceeds the sought reduction in risk.

** Based upon two effects per 10,000 person.rem: fatal cancer plus serious effects for all generations

8. CONCLUSION

Total risk cannot be reduced beyond any given limit. Beyond an optimal point, the occupational risk of producing safety equipment becomes higher than the reduction achieved to an existing risk.

APPENDIX

RADIOLOGICAL UNITS

Radiological quantity	Conventional System Unit	SI System Unit	
Effective dose, dose equivalent	rem	Sievert, Sv	1 rem = 1 cSv
Absorbed dose	rad	Gray, Gy	1 rad = 1 cGy
Activity	Curie, Ci	Becquerel, Bq	1 Ci = 3.7×10^{10} Bq
Exposure	Roentgen, R	Cb /kg air	

EXERCISE

1. In Risk Assessment using Cost/ Benefit Analysis or Marginal Cost Analysis, calculate the Cost to Benefit Ratio (CBR) using the following information:
The annualized cost of an Engineered Safety Feature (ESF) is $C = 15\text{x}10^6$ [$/year], the risk before addition of the safety feature is $R_{before}=1.4\text{x}10^5$ [person.rem/year], and the risk after the addition of the safety feature is $R_{after} = 2.5\text{x}10^4$ [person.rem/year].
The current Nuclear Regulatory Commission (NRC) guideline is to spend $1,000 per [person.rem] reduction in the risk from a radiological accident. What is your recommendation as a Safety Engineer regarding the addition of this ESF?