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## **COST-BENEFIT ANALYSIS – TO WIELD OR YIELD THIS DOUBLE-EDGED SWORD!**

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# COST-BENEFIT ANALYSIS – TO WIELD OR YIELD THIS DOUBLE-EDGED SWORD !

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## Abstract

This paper introduces a Cost-Benefit Analysis (CBA) technique that is increasingly used in the refining and petro-chemical industry and other chemical facilities at large. The monetary or safety evaluation of a risk of implementing a new or revised IPL versus the benefit (risk reduction) of implementing the new feature is the primary pattern for a CBA analysis, where the result re-defines the action (or inaction) based on the risk appetite of an organization. Frequently confused with Return on Investment (ROI), this paper also explains the difference between these two approaches. The paper then delves into more detail on the benefits of the CBA technique and elaborates on its characteristic or typical assumptions, process flows, and algorithm.

The paper then highlights the level of detail and accuracy required to conduct a CBA without misplacing the values on safety. From selecting the right economic equivalency factors to the final judgement of the CBA result can be a complicated and data-hungry process, which (with the right expertise and approach) can be accomplished optimally and quickly, and also provide key indicators to assess the robustness and outcomes of the CBA.

## Introduction

Cost-benefit analysis (CBA), in general terms, is the exercise of evaluating an action's consequences by weighing the pluses, or benefits, against the minuses, or costs. It is the fundamental assessment behind virtually every business decision, due to the simple fact that businesses do not want to spend money unless the resulting benefits are expected to exceed the costs. At chemical facilities large and small, when a decision-maker has to consider a number of complicated environmental, economic and/or personnel-safety factors to make a cost-optimum choice, an intensive Cost-benefit analysis (CBA) study is often chosen to evaluate investment decisions by translating safety and risk concepts into monetary values, integrating well-known indicators and measures from economic theory. Yet the quality of Risk Analysis for a scenario can tip the balance of the CBA results. So, it is imperative to invest in expert risk analysis and perform CBA right so that the results are reliable and robust.

## Placing a value on Safety

Safety of employees, contractors and other onsite personnel should be (and most often is) the highest priority of a chemical facility. The risks of scenarios vary, some with much higher risk compared to others. Placing a high value on safety in a chemical plant is a fundamental requirement that goes beyond mere regulatory compliance; it is a moral imperative to protect human life, the environment, and property. In the chemical industry, where operations often involve hazardous, flammable, or explosive substances, integrating safety as a core value is crucial for operational sustainability, reducing long-term costs, and avoiding catastrophic, reputation-damaging incidents.

## Managing risks and understanding the benefits of valuing safety

By fostering a safety culture, facilities ensure that workers are trained to recognize hazards, understand the risks associated with their work, and feel safe and confident in their daily tasks. This is practiced through adopting strong safety programs that possess key components such as:

- **Process Safety Management (PSM):** A proactive management system (often following OSHA standards) to prevent the release of hazardous chemicals.
- **Hazard Analysis (HAZOP):** Using techniques like Hazard and Operability Studies to proactively identify potential failure points in the plant's design.
- **Regular Auditing & Maintenance:** Proactive, scheduled maintenance of equipment to prevent failures, leaks, and explosions.
- **Emergency Preparedness:** Conducting regular drills, having clearly marked evacuation routes, and ensuring, functional, and accessible emergency equipment (e.g., showers, eyewash stations).
- **Proper Labeling and Storage:** Segregating incompatible chemicals to prevent accidental reactions

To effectively manage risk, top-tier chemical plants usually follow the **Hierarchy of Controls**, which ensures the most effective methods are prioritized:

1. **Elimination:** Completely removing a hazardous substance or process.
2. **Substitution:** Replacing a highly hazardous chemical with a less hazardous one (e.g., using less volatile materials).
3. **Engineering Controls:** Using physical barriers, automated systems, and improved ventilation (e.g., fume hoods, blast-resistant structures) to isolate workers from hazards.
4. **Administrative Controls:** Implementing safe work procedures, such as mandatory training, "permit-to-work" systems for high-risk tasks, and regular safety audits.
5. **Personal Protective Equipment (PPE):** Using gloves, masks, goggles, and suits as the last line of defense

The benefits of valuing Safety hence translate into saving **costs of consequence** such as :

- **Human Protection:** Savings due to prevented injury, long-term health issues, and death.
- **Financial Savings:** Savings in direct costs (medical bills, repairs) and indirect costs (lost productivity, legal fees, higher insurance premiums).
- **Business Continuity:** Savings from preventing catastrophic shutdowns, protecting the company's reputation and long-term viability.
- **Environmental Protection:** Savings from preventing pollution and damage to ecosystems, enhancing the company's standing with the community and regulators.

## The Cost of Accident ( $C_{ACC}$ )

The cost of accident is the potential loss, measured with equivalent monetary value, if an undesired event (incident) happens. Table 1 below is an example of a risk matrix's consequence level (C1 to C5) for health & safety, plotted with monetary value to represent potential loss that can be prevented by providing proposed additional protection layers. Other consequence categories (such as environmental) may have their own predicted monetary value (i.e. cost of environmental remediation) and potential direct cost may be estimated through industry practice or local regulation, such as API RP 754, Process Safety Performance Indicators for the Refining and Petrochemical Industries.

**Table 1 – Cost of Accident**

Consequence	Severity and Related Cost of EHSS Consequence - Personnel	Potential Direct Cost (as per API RP 754); USD
C1	Refer C2 ^ x No of fatalities	> 10M
C2	^ Single fatality, equivalent in USA to 10,000,000 USD	1 M < and ≤ 10 M
C3	Severe injury, lost workdays, equivalent in USA to 1,000,000 USD	100 K < and ≤ 1 M
C4	Serious injury; reportable injury; 100,000	10 K < and ≤ 100 K
C5	First aid; equivalent in USA to 10,000	≤ 10 K

The estimation and application of  $C_{ACC}$  is further elaborated in the section on the components of CBA which covers the technique of conducting CBA.

## Opting for a Cost-benefit analysis (CBA) study

Conducting CBA studies by an organization is associated with its risk tolerance (the level of risk an organization is willing to accept in pursuit of its objectives). In safety, this is often managed through the ALARP (As Low As Reasonably Practicable) framework, which mandates reducing risk unless the cost of doing so is "grossly disproportionate" to the benefit.

**Low Risk Appetite:** High investment in safety to minimize incidents, even if the payback period is long.

**Moderate/High Risk Appetite:** Accepting higher residual risks to reduce operational costs.

Companies seek to attain strategic benefits through Objectivity (converting subjective safety arguments into data-driven, financial metrics), Prioritization (helping allocate limited resources to the most critical risks) and Proactive Management (identifying and mitigating risks before they become costly accidents.) It enables organizations to balance their appetite for risk with the cost of mitigating those risks.

## Practical approach to decision-making

The approach to decide on conducting a CBA study is elaborated through an example. Consider that an organization has completed a Process Hazard Analysis (PHA) for its plant(s) along with LOPAs for all C1 and C2 scenarios identified. The organization has several recommendations generated as part of this study that reduces the risk to insignificant. The approach from here is to identify the recommendations that require a significant CAPEX or investment. The organization must then decide on the ALARP risk-level of those recommendations (based on its risk-appetite). Once this is identified, the decision to conduct the CBA study can be taken on the identified recommendations.



## Cost-benefit analysis (CBA) – The Technique

### Guidelines and Considerations

A CBA follows certain guidelines that emphasize the correct use of CBA within the ALARP framework, with any deviation from these guidelines reviewed case by case. The guidelines below have been listed to help explain the uses, limitations and considerations before conducting a CBA study.

#### 1. CBA cannot be used to argue against implementing a relevant good practice

A CBA cannot be used to argue against the implementation of relevant good practice, unless the alternative measures are demonstrated unequivocally to be at least as effective as statutory duties

#### 2. CBA cannot be used to justify risks that are intolerable

A CBA aids the decision-making process by giving monetary values to the costs and benefits and to enable a comparison of like quantities. The analysis can help make an informed choice between risk reduction options and not replace or undermine safeguards. The depth of analysis should be fit for purpose, i.e., more rigour is required where the risk is higher or the consequences themselves are great (e.g., multiple fatalities).

### 3. CBA cannot be used to argue against statutory duties

A CBA study cannot substitute compliance requirements with safety regulations, environmental protection, quality control standards, documentation and record keeping for regulatory audits, including equipment calibration, waste management, etc., and equipment safety compliance (e.g., ASME standards).

### 4. CBA cannot be used to justify what is evidently poor engineering

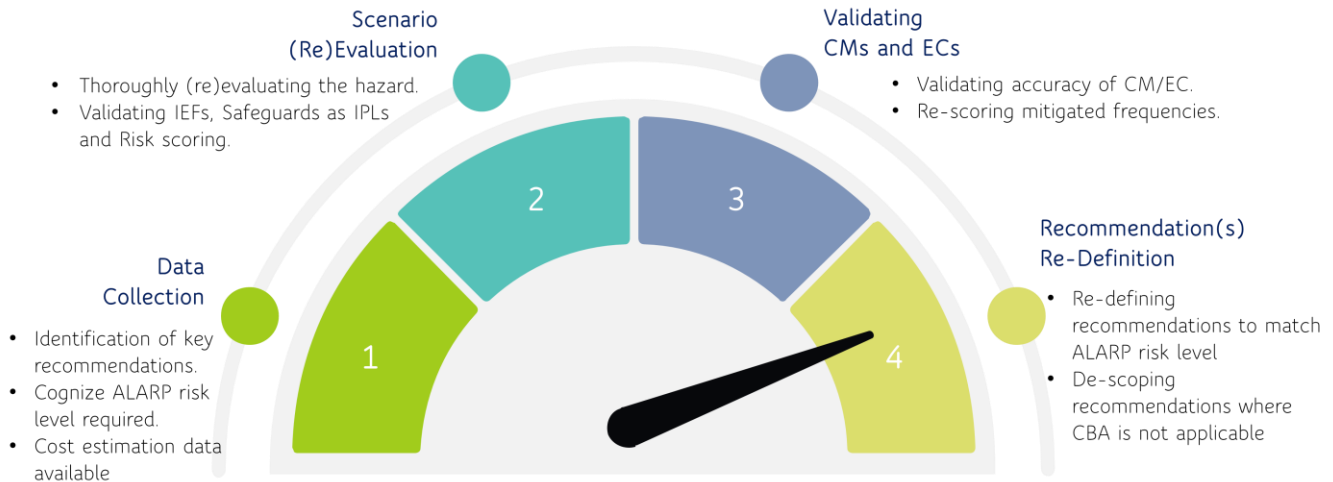
A CBA study is not recommended when the engineering of a process or mechanical assembly is questionable wherein the combination of discrete hazards cannot be foreseen and the decision-making process on risk reduction action is less straightforward, mostly unreliable.

Overall, a CBA cannot form the sole argument or a case on its own for an ALARP risk reduction action.

## Pre-cursors to a CBA study – PII’s best-practice approach

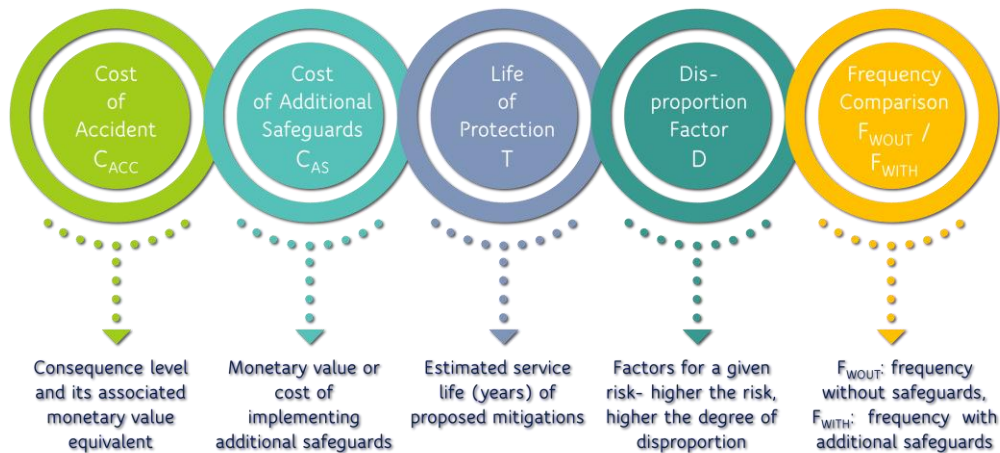
Though the approach to decide on conducting a CBA study is fairly straightforward as outlined earlier, it is not optimal enough to begin the study. The reality is more complex as it’s often seen (for example) that any single recommendation generated from a PHA study doesn’t always provide a single order of magnitude reduction in probability. Recommendations can be complex too, with multiple alternatives or linked actions, where a single recommendation can have multiple orders of magnitude reduction in probability. Hence the organization is unable to simulate the desired ALARP level on these recommendations through a CBA. An expert evaluation is imperative to conduct a thorough CBA study, with qualified personnel leading the study having a 15 to 25 years of experience in process safety management, process safety engineering, process reliability, human factors, CBA, PHA/LOPA leadership and documentation.

## Pre-cursors to a CBA study PII's best-practice approach



## Components of a CBA study

There are five (5) key components of CBA calculation.



### 1. Cost of Accident ( $C_{ACC}$ )

The cost of accident is the potential loss, measured with equivalent monetary value, if an undesired event (incident) happens. Focus in assessing CBA is to ensure that all the appropriate costs have been included and to challenge where costs appear extraneous or excessive.

- Include costs of installation, operation, training and any additional maintenance, and the business losses that would follow solely for putting the measure into place.

- b) Any savings because of the measure should be offset against the above costs.
- c) All claimed costs must be those incurred by the risk owner (costs incurred by other parties, e.g. members of the public should not be counted)
- d) Costs considered should only be those necessary to implement the risk reduction measure (without frills.)

## 2. Frequency of the consequence without safeguards ( $F_{WOUT}$ ) and with safeguards ( $F_{WITH}$ )

Expertly done PHAs, LOPA, or other equivalent assessments (i.e. QRA, Facility Siting), where the proposed additional safeguards shall have IPL (Independent Protection Layer) equivalent capability, are the main reference in determining the frequency of unmitigated ( $F_{WOUT}$ ) and mitigated ( $F_{WITH}$ ) consequence. If the team has more definitive likelihood data, then it optimizes the PFD value to have more accurate CBA calculation.

## 3. Estimated service life (in years) of the proposed mitigations (T)

It measures the life expectancy of proposed mitigations. It could be 25 years (generally) or it could be every 5 years needed to change/replace the mitigation with new installation (or upgraded technology), in which case the study should consider overall cost of mitigations for the entire (25 year) duration.

## 4. Cost of Additional Safeguards ( $C_{AS}$ )

This is the overall cost incurred in implementing the additional safeguards (additional layer of protections). They include cost of installation which are necessary and sufficient to implement the measure(s) and cost of operation and maintenance: including all costs due to any consequent productivity losses resulting directly from the introduction of the measure. Any monetary gains is offset against these costs.

## 5. Disproportion Factor (D)

On weighing the costs of a proposed control measure against its risk reduction benefits, a disproportion factor is applied to support rational judgement whether enough is done to reduce risks. For a given benefit, the higher the risk, the higher the degree of disproportion. These factors are whole numbers (W) such as 2xW for Significant risks and 1xW for Minor risks etc.

## Calculating CBA and the interpreting results.

The next step is estimating the Benefit (B), taking into account the benefit of avoiding a consequence ( $C_{ACC}$ ), the Frequency of consequences with and without safeguards ( $F_{WOUT}-F_{WITH}$ ) and the estimated service life (T) of the proposed mitigations. Calculating the benefit is straightforward as:

$$\text{Benefit} = C_{ACC} \times (F_{WOUT} - F_{WITH}) \times T$$

Once the benefit is determined, the next step is to compare value of benefit versus cost of additional safeguards.

$$\text{Is } [(B \times D) - C_{AS}] \geq 0 \text{ or } < 0$$

This comparison will have result of 0 or positive that indicates “risk and cost are proportionate” and result of negative indicate “risk and cost are grossly disproportionate”.

A CBA result that is  $\geq 0$  that may represent the potential benefit of implementing proposed mitigations whereas a CBA result  $< 0$  may represent a condition of grossly disproportion of having proposed mitigations thus keeping the risk as “unmitigated” is deemed as best available option and can be managed through approved waivers or other safety/risk management protocols within an organization.

### Critical pitfalls in CBA studies

PII has completed many hundreds of CBA studies and based on industry-wide experience it is seen that despite the best training, guidance, and intentions, practitioners still stumble: practical benefit-cost analysis is hard and mistakes get made. Many of the same mistakes occur over and over, like stepping in buckets; these buckets are the pitfalls that cause practitioners to fall, even as they attempt to apply the best methods and practices to estimate benefits and costs. Major/common pitfalls have been grouped (as buckets) and elaborated below:

#### 1. Valuing intangibles and the uncertainty in forecasting

Assigning accurate dollar values to health, safety, or environmental quality is challenging and often subjective. CBA also relies on predicting future costs and benefits, which can be inaccurate due to unforeseen technological changes, product shifts driven by market forces, or inflation. Together these errors bungle the analysis, and practitioners inadvertently conclude the analysis too soon or only look at partial measures (e.g., only looking at costs rather than the net effect on welfare), prompting misleading conclusions.

#### 2. Bias and Manipulation

Decision-makers may consciously or unconsciously underestimate costs and overestimate benefits to justify a preferred project. They may at times use too short a timeframe that overlooks long-term environmental or maintenance costs, making projects seem more beneficial than they are. There also exists the possibility of Double Counting wherein (incorrectly) counting the same benefit twice inflates total benefits.

#### 3. Over-use and often misuse of Conditional Modifiers (CM) and Enabling Conditions (EC)

One of the key pitfalls is seen in organizations that possess highly conservative risk-matrices, sometimes up to 2 orders of magnitude away from industry standard (such as a sample matrix shown

below), where CBA Analysts tend to rely heavily on conditional modifiers and/or enabling conditions to reduce probabilities and achieve a lower risk score.

5x7 Risk Matrix (Sample)				Likelihood							
				Frequency		Very Unlikely	Unlikely	Possible	Likely	Very Likely	
		Probability/annum		1.E-06	1.E-05	1.E-04	1.E-03	1.E-02	1.E-01	1.E+00	
				P7	P6	P5	P4	P3	P2	P1	
Consequence	Financial	Injury/Illness									
	> 10M	Multiple fatalities	Very High	C1	C1-P7	C1-P6	C1-P5	C1-P4	C1-P3	C1-P2	C1-P1
	1 M < and ≤ 10 M	Single fatality or multiple lost workday injuries	High	C2	C2-P7	C2-P6	C2-P5	C2-P4	C2-P3	C2-P2	C2-P1
	100 K < and ≤ 1 M	Lost workday injuries	Moderate	C3	C3-P7	C3-P6	C3-P5	C3-P4	C3-P3	C3-P2	C3-P1
	10 K < and ≤ 100 K	Serious injury, reportable injury	Low	C4	C4-P7	C4-P6	C4-P5	C4-P4	C4-P3	C4-P2	C4-P1
	≤ 10 K	First aid	Very low	C5	C5-P7	C5-P6	C5-P5	C5-P4	C5-P3	C5-P2	C5-P1

As the risk acceptable criteria move lower, the amount of CMs and ECs that a company uses increase proportionally because these fudge factors that cannot be validated become the only options for reaching the target ALARP risk level (as displayed in Table 2).

Table 2 Risk Tolerance Criteria Adjustment

	Consequence Categories		Use CM and EC
	Single fatality Loss of ~10MM USD Offsite injury	Multiple fatalities Loss of ~100MM USD Offsite fatality	
Risk Acceptance Criteria For final mitigated likelihood of scenario (per year)	1E-3	1E-4	None used; none allowed; LOPA and risk judgement are straightforward; all risk factors can be validated; almost no SIL 3 and no MooN relief valve configurations.
	1E-4	1E-5	CMs about half of the scenarios; almost no EC. Occasionally have SIL 3 and MooN relief valve configurations. CMs, EC, SIL 3 cannot be validated
	1E-5	1E-6	Heavy use of CMs and ECs required. Many uses of have SIL 3 and MooN relief valve configurations needed. CMs, EC, SIL 3 cannot be validated

The two originators of LOPA (William Bridges and Art Dowell, III) avoid the use of Enabling Events (EE) and Conditional Modifiers (CM), as these are not usually validated/proven and most are not controlled by management of change programs. One approach to prevent use of CMs and Ess was developing consequence severity categories based on the amount of release from a loss of containment and the

condition of the release (e.g., below or above the boiling point). The consequence severity categories inherently included the conditional modifiers of probability of ignition ( $P_i$ ), probability of presence of personnel ( $P_p$ ), and probability of fatality if present ( $P_f$ ). For LOPA, using  $P_i$ ,  $P_p$ , and  $P_f$  underestimates the risk. In such cases, some analysts have incorrectly used EEs and CMs to “cook” the numbers to meet the risk tolerance criterion for the consequence severity category, even though the ECs and CMs do not apply.

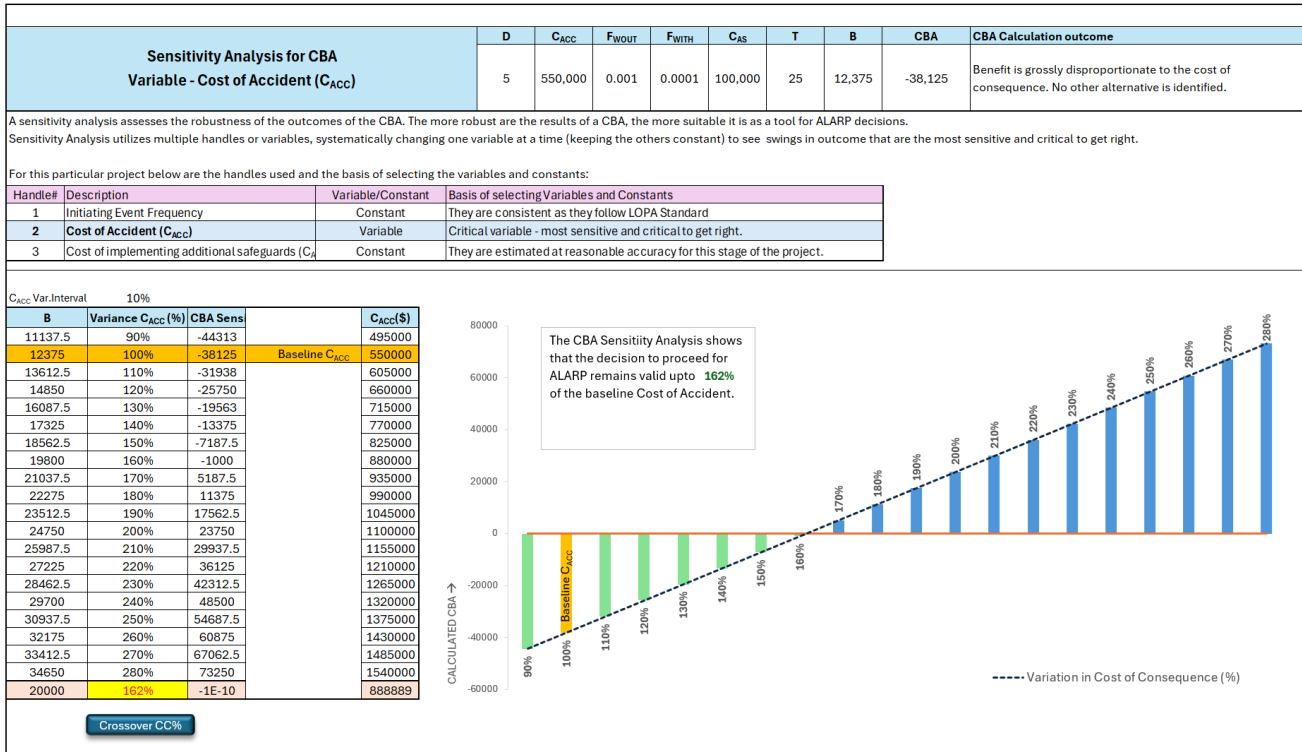
## Validating a CBA study

### Sensitivity Analysis

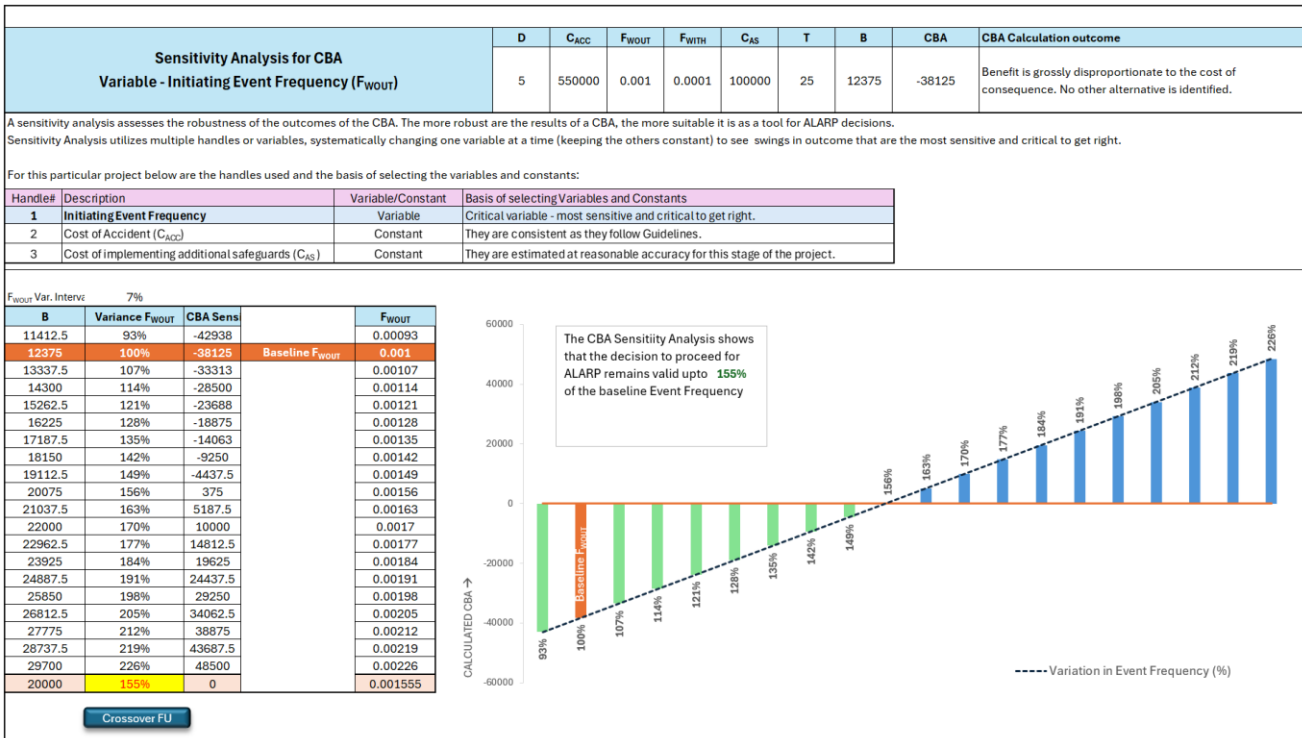
Conducting a **Sensitivity Analysis** to verify that the CBA is accurate is a reliable validation strategy. Sensitivity Analysis utilizes multiple handles or variables, systematically changing one variable at a time (keeping the others constant) to see swings in outcome that are the most sensitive and critical to get right. It is recommended to conduct a sensitivity analysis, particularly if the CBA is being used to “show” further measures are not reasonably practicable.

Sensitivity analysis is done only for scenarios where the Benefit is grossly disproportionate to the cost of consequence, and no other alternative is identified.

Snapshot of a sensitivity analysis exercise, varying only the Cost of Accident ( $C_{ACC}$ ) is shown below.



Snapshot of the same sensitivity exercise, varying only  $F_{WOUT}$  is shown below.



It can be inferred from the above snapshots, that the decision to stop at the ALARP risk level remains valid up to 162% of the baseline  $C_{ACC}$  and up to 155% of the baseline  $F_{WOUT}$  for the specific recommendation evaluated for CBA, which can hence be waived from implementation.

Sensitivity analysis is a way to deal with uncertainties, highlighting whether suitably cautious assumptions have been made and allows the risk owner and site management team to assess the robustness of the outcomes of the CBA. The more robust are the results of a CBA, the more suitable it is as a tool.

## Case study – By PII at its client facility

### Scope

Evaluating 129 (Consequence C1/C2) recommendations from the PHAs for Plants and Utilities at PII's client site to conduct CBA supporting ALARP risk-level justification for risk transition from Minor to Insignificant.

### Approach

Step 1	Collect background documents for the 129 recommendations including (but not limited to) the PHA report, LOPA worksheets, marked-up drawings and available cost-estimation data.
Step 2	Develop mutually agreed schedule, team composition and key milestones. (For PII, Mr. William Bridges and Mr. Sandeep Mohandas were the primary engineers)
Step 3	Thoroughly (re)evaluating the hazard and validating IEFs, Safeguards as IPLs and Risk scoring. Correcting the existing HAZOP tables if necessary to ensure accuracy during CBA analysis
Step 4	Validating accuracy of CM/EC used during the LOPA. Correcting or incorporating the right CM/EC as required and re-scoring mitigated frequencies
Step 5	Re-defining the recommendations into 2 levels: Level 1 that reduces the risk to Minor and Level 2 that reduces the risk to insignificant.
Step 6	De-scoping recommendations where CBA is not applicable such as those which do not transition from Minor to Insignificant
Step 7	Determine CBA components and estimate benefits. (Costs provided by client) Calculate the CBA and assess the outcome
Step 8	Conduct Sensitivity analysis and include comparative information on industry practices
Step 9	Develop CBA study sheet for each recommendation. Develop consolidated ALARP list
Step 10	Conclude the study and sign-off.
Multiple online meetings were required to complete the analysis stages	

## CBA Study and Validation

For this principal task, PII evaluated the risk reductions (benefit) related to each recommendation by evaluating the change in economic risk that results in implementing the recommendations. For harm to people, we used the economic equivalency factors in CBA. This was compared to the cost of implementing the recommendation; with approximate cost (+/- 40%) of implementing each recommendation (cost-estimates were provided by our client). The standard life estimates for the protection/equipment were used (25 years). From these results, the benefit was estimated. These two major steps resulted in the CBA for each recommendation that was evaluated.

PII conducted sensitivity analysis based on PII's expertise about some of the key inputs such as the frequency of events or the number of potential fatalities involved and ensured suitably cautious assumptions were made. Sensitivity analysis was conducted for all the recommendations under CBA evaluation by varying  $C_{ACC}$  and  $F_{WOUT}$  values to aid the decision to stop at the ALARP risk level (Minor) and waive the implementation of recommendations(s) that transition the risk to Insignificant (from Minor risk.)

PII included comparative information on industry practices relevant to each CBA study.

## CBA Study Deliverables

The analysis of each recommendation resulted in a CBA study sheet (ref Fig 1.0). The CBA study sheet for each recommendation included all the relevant information regarding the scenario, hazards, the risk-ranking, the CBA components and calculation, sensitivity analysis, information on industry practices, ALARP information and signatories on a single page.

A consolidated ALARP list (ref Fig 1.1) was also developed that included Node details, initial risk, safeguards, final recommendation (perhaps using alternative remedy) or acceptance per ALARP and final mitigated risk along with the CBA and ALARP information developed for all the recommendations. A summary table that includes the Risk category, recommendation to reduce the risk to Minor and recommendation with CBA to reduce the risk to Insignificant were also prepared.

Fig 1.0 - CBA Study Sheet

CBA STUDY SHEET				
1. SAFER ID	Utilities - Sc#2			
2. Consequence Scenario (C1-C5) & Description	General Utilities: Node 19: Tanker unloading through NaOH Transfer Pumps to NaOH Hold Tank Scenario: High pressure and Temperature due to Wrong chemical tanker (such as HCl) connected and unloaded in NaOH tank leading to loss of containment Consequence : C2 - Rupture of the tank and the vent tank due to chemical reaction and high pressure resulting in exposure of personnel to caustic with potential for multiple injuries or fatality			
3. Final Mitigated Risk Before CBA	<input type="checkbox"/> Significant (C1/C2)	<input checked="" type="checkbox"/> Minor (C3/C4)	<input type="checkbox"/> Significant (C3/C4)	<input type="checkbox"/> Minor (C3/C4/C5) directly go to section "8. ALARP Justification Approval"
4. Completed Risk Assessment	<input checked="" type="checkbox"/> PHA (e.g. HAZOP)	<input checked="" type="checkbox"/> Semiquantitative (e.g. LOPA)	<input type="checkbox"/> Others (specify):	
5. CBA - Cost Benefit Analysis				
<i>Cost of implementing additional safeguards C<sub>AS</sub> (USD):</i>				
Cost of Accident (C <sub>acc</sub> ), in USD	<input checked="" type="checkbox"/> Personnel fatality/injury	<input type="checkbox"/> Direct cost (environmental remediation, repair, etc)	3,800,000	
Cost of implementing additional safeguards C <sub>AS</sub> , in USD				250,000
F <sub>wout</sub> (frequency of occurrence of the incident with the existing Layers of Protection, without additional protection)				0.0001
F <sub>with</sub> (frequency of occurrence of the incident with the proposed Layers of Protection)				0.00001
Life of Protection (T, years, generally taken as 25 years)				25
<i>Benefits (USD):</i>				
Benefit = C <sub>acc</sub> x (F <sub>wout</sub> - F <sub>with</sub> ) x T				8,550
Disproportion Factor (D). Note: D is 10 for significant and 5 for minor.				5
Benefit x D				42,750
<i>CBA and ALARP</i>				
CBA Calculated = (Benefit x D) - C <sub>AS</sub>				-207,250
Sensitivity based on Increased Consequence	<p>The CBA Sensitivity Analysis shows that the decision to proceed for ALARP remains valid up to 585% of the baseline Cost of Accident.</p>			
Sensitivity based on Increased Frequency	<p>The CBA Sensitivity Analysis shows that the decision to proceed for ALARP remains valid up to 536% of the baseline Event Frequency.</p>			
CBA Conclusion (One justification for ALARP)	Benefit is grossly disproportionate to the cost of consequence. Sensitivity analysis on both increased Cost of Accident and increased Event Frequency show that the decision to proceed with ALARP is valid until much higher baseline values.			
Comparison to Industry Practice (One justification for ALARP)	Based on comparative information on industry practices and PII expertise, we recommend to stop at (1E-3) for a "Single fatality" consequence and (1E-4) for a "Multiple fatality" consequence.			
6. Final Mitigated Risk After CBA and ALARP	<input type="checkbox"/> Significant	<input checked="" type="checkbox"/> Minor	<input type="checkbox"/> Insignificant (section "8. ALARP Justification Approval" is not required)	
7. Accepting CBA & Approval				
CBA Study Leader	Name:	Title:	Sign:	Date:
Sr Manager (Process Eng./Process Safety or equivalent)	Name:	Title:	Sign:	Date:
8. ALARP Justification Approval				
Area/Risk Owner	Name:	Title:	Sign:	Date:
Operation Director/Equivalent (Minor)	Name:	Title:	Sign:	Date:
Site President/Equivalent (Significant)	Name:	Title:	Sign:	Date:

Fig. 1 - Consolidated ALARP list

Scenarios	Plant	Node	Scenario	Consequences	ML	MR	SR	Safeguards	ML	MR	SR	Recommendation	PL	PR	Justification for CM Applicability	MLL (after P1)	MRL (after P1)	SR (after P1)	Recommendation (Level 1)	PL1	PR1	CBA Requirement based on Residual Risk	Cost MMUSD (+/-40%)	CBA Calculated Outcome (Implement / Sign ALARP)	Recommendation (Level 2)	PL2	PR2	CBA Requirement based on Residual Risk	Cost MMUSD (+/-40%)	CBA Calculated Outcome (Implement / Sign ALARP)
39	General Utilities	Node 14: Tanker unloading through HCL Receiving Pump (P-XXXX) to HCL Hold Tank (TK-XXXX) including Vapor Seal SP-XXXX	Failure of the BV in TK-XXXX not breaking vacuum created in a tank during the pump out of the tank and loss of containment	Collapse of the tank resulting in release of hydrochloric acid to the surrounding area causing personnel burn injury and possible lost workday	1	3	3	Note: BV is replaced within 8 hours when taken out for maintenance and spare is installed. IPL Type: Non-IPL. Not tested/documented PFOOD: 1E+0 Breather valve for TK-XXXX (Note: BV-XXXX is 4" in size and bigger than other hydrochloric acid tanks) IPL Type: Non-IPL. Not capable/big enough PFOOD: 1E+0 Typical safeguards for loss of containment (see Table C.2) PM of the breather valves BV-XXXX every 3 years as per existing strategy IPL Type: Non-IPL. Not tested/documented PFOOD: 1E+0 The pressure of the tank (TK-XXXX) is not equalized with the pressure of the other hydrochloric acid tanks. No additional relief is available IPL Type: Non-IPL. Not capable/big enough PFOOD: 1E+0	3	2	3	S 16. Require respirators as part of the PPE for hydrochloric acid unloading SOP and other SOPs and for maintenance activities (SMAs) in the area. Confirm with the industrial hygiene specialist for the exact cartridge type. RRF: 10 S 17. Install a PV or a second BV to break the vacuum. PII recommends to accept the risk as per the industry practice instead of implementing this recommendation. RRF: 10 S 22. The dikes, pits, trenches, and culverts that are in contact with hydrochloric acid or caustic are periodically inspected by the civil engineer but the actions are not being followed through. Develop a management system with enforcement to ensure follow through on any repairs and correction of any findings. RRF: 10	4	3	Probability of Vessel Rupture (Pvr) = 1 (low pressure during pump out below the design pressure on vacuum) PI (prob of ignition) = NA (not fire scenario) Probability of Personnel Fatality (PF) = 1 (since it is part of the consequence severity selection) Probability of a Hazardous Atmosphere (Pha) = NA (since it is part of the consequence severity selection) Probability of Personnel Presence (PP) = 1 (Many alarms will draw workers into area; but the event happens so quickly, the operators will not have time to enter the hazardous area.) Time at Risk (PTr) = NA (not applicable since nothing is unique to a mode of operation) Campaign Enabling (PC) = NA (same as Pr. Since no change in raw materials (chemicals, concentrations, rates, quantities), catalysts, final products, operating conditions and/or process configuration (e.g., recycle vs. non-recycle mode of operation), and these differences do not result in non-uniform risk	3	2	S 17. Install a PV or a second BV to break the vacuum. RRF: 10	4	3	NO This recommendation is necessary to reach minor risk, so CBA is not applicable	1500000	Benefit is grossly disproportionate to the cost of consequence. If no other alternative identified then seek approval for SWFRR	S 16. Require respirators as part of the PPE for hydrochloric acid unloading SOP and other SOPs and for maintenance activities (SMAs) in the area. Confirm with the industrial hygiene specialist for the exact cartridge type. RRF: 10 - or - S 22. The dikes, pits, trenches, and culverts that are in contact with hydrochloric acid or caustic are periodically inspected by the civil engineer but the actions are not being followed through. Develop a management system with enforcement to ensure follow through on any repairs and correction of any findings. RRF: 10	5	4	YES This recommendation is necessary to reach insignificant risk from minor risk, so CBA is applicable	100000	Benefit is grossly disproportionate to the cost of consequence. If no other alternative identified then seek approval for SWFRR	
41C/42C	General Utilities	Node 19: Tanker unloading through NaOH Transfer Pump (P-YYY) to NaOH Hold Tank (TK-YYY)	High pressure and Temperature due to Wrong chemical tanker (such as HCl) connected and unloaded in NaOH tank leading to loss of containment	Rupture of the tank and the vent tank due to chemical reaction and high pressure resulting in exposure of personnel to caustic with potential for multiple injuries or fatality	1	2	2	Goose neck vent to atmosphere IPL Type: Non-IPL. Not capable/big enough PFOOD: 1E+0 Typical safeguards for loss of containment (see Table C.2) Sampling of the material (in a glass bottle that can visually confirm the material) in the truck and verify COA and awaiting the result (as sometimes the quality of the material is not on-spec) before connecting the tanker and unloading IPL Type: Human response to abnormal condition PFOOD: 1E+1 Caustic truck comes with its own hose, while hydrochloric acid hoses are supplied by the plant IPL Type: Non-IPL. Not independent PFOOD: 1E+0	3	2	3	S 10. Install a bigger relief system such as a Relief hatch on all the hydrochloric acid Tanks (TK-XXXX) and for the caustic tanks (TK-YYY) manways or any alternate design to relieve the sudden surge of pressure. RRF: 100 S 20. Add a procedure step where operator vents the pump suction before pumping is started that would help him notice is any caustic is reacting with the acid being pumped into the acid tank. RRF: 10 S 21. Provide an alternate confirmation for the chemical to be unloaded that utilizes the QR code of the SDS on the truck and checks it against the QR code on the flange before hooking up the truck to the flange/hose. RRF: 10 S 22. The dikes, pits, trenches, and culverts that are in contact with hydrochloric acid or caustic are periodically inspected by the civil engineer but the actions are not being followed through. Develop a management system with enforcement to ensure follow through on any repairs and correction of any findings. RRF: 10	6	4	Probability of Vessel Rupture (Pvr) = 1 (pressure can exceed 2x DP in case of wrong chemical unloading) PI (prob of ignition) = NA (not fire scenario) Probability of Personnel Fatality (PF) = 1 (since it is part of the consequence severity selection) Probability of a Hazardous Atmosphere (Pha) = NA (since it is part of the consequence severity selection) Probability of Personnel Presence (PP) = 1 (Many alarms will draw workers into area; but the event happens so quickly, the operators will not have time to enter the hazardous area.) Time at Risk (PTr) = NA (not applicable since nothing is unique to a mode of operation) Campaign Enabling (PC) = NA (same as Pr. Since no change in raw materials (chemicals, concentrations, rates, quantities), catalysts, final products, operating conditions and/or process configuration (e.g., recycle vs. non-recycle mode of operation), and these differences do not result in non-uniform risk	3	2	SR 20. Add a procedure step where operator vents the pump suction before pumping is started that would help him notice if any acid is reacting with the caustic between the pump suction valve and the pump, to warn that acid is being pumped into the acid tank. RRF: 10 S 21. Provide an alternate confirmation for the chemical to be unloaded that utilizes the QR code of the SDS on the truck and checks it against the QR code on the flange before hooking up the truck to the flange/hose. RRF: 10	5	3	NO This recommendation is necessary to reach minor risk, so CBA is not applicable	10000	Benefit is higher than cost of consequence. Consider to implement the proposed additional protection layer(s)	S 10. Install a bigger relief system such as a Relief hatch on all the hydrochloric acid Tanks (TK-811/811/3/811) and for the caustic tanks (TK-810/3/810) manways or any alternate design to relieve the sudden surge of pressure. RRF = 100	7	4	YES This recommendation is necessary to reach insignificant risk from minor risk, so CBA is applicable	1500000	Benefit is grossly disproportionate to the cost of consequence. If no other alternative identified then seek approval for SWFRR	
44A	General Utilities	Node 1: Sea Water (SW) Pit (W-ZZZ) to Pumps (P-ZZZ A-C, P-ZZZ A-C, P-ZZZ and P-ZZZ) and Heat Exchangers (E-XXX A-H) to Supply and Return SW headers	Person falls in the SW inlet pit chamber or discharge pit due to fatigue or tripping on rough surface leading to possible drowning	Possible drowning	1	2	3	Guard rail with toe boards IPL Type: Movement-limiting device, adjustable PFOOD: 1E-1	4	2	4	S 28. Install a ladder in the SW pit chamber after the screen and in SW return pit, as an emergency escape feature (similar to the ladders available in the intake pit). RRF: 10	5	3	Probability of Vessel Rupture (Pvr) = NA (not a high pressure/loss of containment scenario) PI (prob of ignition) = NA (not fire scenario) Probability of Personnel Fatality (PF) = 1 (since it is part of the consequence severity selection) Probability of a Hazardous Atmosphere (Pha) = NA (since it is part of the consequence severity selection) Probability of Personnel Presence (PP) = 1 (Many alarms will draw workers into area; but the event happens so quickly, the operators will not have time to enter the hazardous area.) Time at Risk (PTr) = NA (not applicable since nothing is unique to a mode of operation) Campaign Enabling (PC) = NA (same as Pr. Since no change in raw materials (chemicals, concentrations, rates, quantities), catalysts, final products, operating conditions and/or process configuration (e.g., recycle vs. non-recycle mode of operation), and these differences do not result in non-uniform risk	4	2	S 28. Install a ladder in the SW pit chamber after the screen and in SW return pit, as an emergency escape feature (similar to the ladders available in the intake pit). RRF: 10	5	3	NO This recommendation is necessary to reach minor risk, so CBA is not applicable	50000	Benefit is higher than cost of consequence. Consider to implement the proposed additional protection layer(s)	SR30: Perhaps install a second ladder or pursue an IPL option available that provides an additional RRF=10?	6	4	YES This recommendation is necessary to reach insignificant risk from minor risk, so CBA is applicable	50000	Benefit is grossly disproportionate to the cost of consequence. If no other alternative identified then seek approval for SWFRR	

## Conclusion

An intensive CBA study, when performed with expert practitioners with significant experience in PHA/LOPA, process reliability and human factors, provides an invaluable tool as a systematic, data-driven process that compares the financial and operational costs of implementing safety measures against the benefits of reduced accidents, injuries, and operational disruptions. It enables organizations to balance their appetite for risk—the level of risk they are willing to accept—with the cost of mitigating those risks. A mighty sword to wield within the ALARP framework. Yet lack of expertise creates risky pitfalls, tipping the balance of CBA results towards inaccuracy, occasionally leading to dangerous or short-sighted decision-making. Still, one global way to avoid the need for a CBA is to adjust the risk tolerance criteria for a single fatality to  $10^{-3}$  or at the lowest,  $10^{-4}$  per year (to match the confidence we have in LOPA math).

## Acronyms

**ALARP:** As Low As Reasonably Practicable

**B:** Benefit

**CBA:** Cost Benefit Analysis

**C<sub>ACC</sub>:** Cost of Accident

**CM:** Conditional Modifier

**C<sub>AS</sub>:** Cost of Additional Safeguards

**D:** Dis-proportion Factor

**EC:** Enabling Condition (same as Enabling Event)

**EE:** Enabling Event (same as Enabling Condition)

**F<sub>WITH</sub>:** Frequency of consequence with additional safeguards

**F<sub>WOUT</sub>:** Frequency of consequence without safeguards

**IEF:** Initiating Event Frequency

**IPL:** Independent Protection Layer

**ITPM:** Inspection, Test, Preventative Management

**LOPA:** Layers Of Protection Analysis

**PDF:** Probability of Failure on Demand

**PHA:** Process Hazards Analysis

**PSM:** Process Safety Management

**PSV:** Relief Valve / Pressure Safety Valve

**T:** Standard life estimates for the protection/equipment

## References

- [1] CCPS/AIChE, Guidelines for enabling conditions and conditional modifiers in layer of protection analysis, Wiley, 2014.
- [2] CCPS/AIChE, Layers of Protection Analysis (LOPA), Wiley, 2001.
- [3] API Recommended Practice 754 (RP 754), Process Safety Performance Indicators for the Refining and Petrochemical Industries.
- [4] G. Reniers, L. Talarico, N. Paltrinieri, Chapter 6 - Cost-Benefit Analysis of Safety Measures, Dynamic Risk Analysis in the Chemical and Petroleum Industry, Elsevier Inc 2016.