

A HOLISTIC APPROACH TO ENVIRONMENTAL ISSUES IN PROCESS DEVELOPMENT AND DESIGN

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This paper presents a methodology that uses a risk-based approach and life-cycle principles to incorporate environmental considerations into process design and development. Using a risk assessment model, a framework has been developed to assess the risk of harm that the process poses to the environment and conversely, the sensitivity of the process to environmentally related issues. A set of criteria has been introduced within the framework to select design tools and techniques applicable to the different stages of process design and development. By considering the life-cycle of the process and the relevant stakeholders, a holistic treatment is given to the risk assessment - which differs this methodology from traditional risk assessment approaches. Integrating such a risk approach to the design and development activity enables risk assessment to be used proactively in contrast to its typical audit function. The methodology is illustrated with a simplified example of a PVC process case study.

Keywords: environmental risk assessment, Life-Cycle Assessment (LCA), design tools

INTRODUCTION

The process industries have long recognised the importance of assessing and managing safety risks. There is currently a tendency to try to develop inherently safer processes. This is reflected in the existence of a wide range of safety-based tools and techniques that are used in the design and development of processes within the industries. However, there is now a need to expand this safety culture and include the environment as a "stakeholder" of the process. Hence, processes should be designed and developed with the inherent ability to minimise and control pollution risks to the environment and to satisfy stakeholders. Stakeholder is taken to mean an individual or group who has an interest in the company because he can affect, or is affected by company activities[1].

The definition of "green design" has widened beyond the concept of "environmentally friendly" products and the control of pollution at the manufacturing site. Problems can arise that are away from the manufacturing site and are linked to other parts of a product or its life-cycle. For instance, the liabilities that Shell incurred over the Brent Spar incident[2] shows that disposal is an environmentally important issue that contributes to the "eco-efficiency" of a design. Fluorinated materials developed as fire extinguishants to replace materials banned under the Montreal Protocol have been discovered to be contributors to environmental damage not only through the products themselves but also as a result of the manufacturing process[3].

Currently, governments and industries are progressively shifting attention to the environmental impacts incurred throughout the life-cycle stages of a product. In the US, regulatory pressures are increasingly directing industry towards the life-cycle approach[4]. The UK government has encouraged the use of "life-cycle thinking" and Life-Cycle Assessments (LCAs) as tools to improve environmental performance[5,6]. Mounting evidence for the application of life-cycle approaches reflect the value of such principles. For example, B&Q[7], The Body Shop[8] and Belfast City Council[9] have added environmental criteria into their supplier selection procedures. Volvo has secured customer preference by verifying their products based on the LCA[10].

The PERA (Process Environmental Risk Assessment) methodology described in this paper attempts to address the long-perceived need[11] to integrate environmental issues into process design. The application of life-cycle concepts in conjunction with risk assessments gives design a holistic approach in terms of the scope of environmental issues considered. The life-cycle framework is used to identify and organise data regarding potential environmental issues concerning the process. Risk assessments help to assess and prevent problems during design. PERA takes into account both the environmental impacts that occur during normal operations, defined as "steady-state risks", and as a result of accidents, defined as "incident risks".

THE PERA METHODOLOGY

STRUCTURE

The methodology consists of 5 stages as illustrated in Figure 1. The bold arrows indicate progression between stages. PERA has the intention of supporting a process project throughout its life-cycle. Hence, it is iterative in nature, resulting in progressively more detailed risk assessments at various design stages of the project. The loops between stages 2 and 5 allow the return to a previous stage should the need arise. The dotted arrow between stage 5 and stage 1 shows the completion of an assessment at one design stage and the beginning of the next assessment at the following design stage.

For the purpose of this work, the process design and development activity was divided into three stages (Figure 2), namely, the Block diagram (BD) Stage, the Flowsheet (FS) Stage, and the Piping and Instrumentation Diagram (PID) Stage. The stages were categorised by the output of the design and development activity, rather than on the type of activity.

The main purpose of Stage 1 (Figure 1) is to keep PERA focused on its objectives. As the methodology is multi-functional, defining its goals at the outset is important for planning and the overall effectiveness of the risk assessment activity. The main activities of the risk assessment lie in Stages 3 and 4. Figure 3 shows a flowchart of the procedures for these two stages. The flowchart illustrates how the risk estimation activity continues into risk evaluation and how risk assessment eventually leads to risk management. In the paper, the term risk estimation means the identification and initial screening of risks, evaluation refers to prioritisation and management refers to the action taken (see Figure 3).

RISK ASSESSMENTS

Incident Risk Assessment

The aim of this assessment is to evaluate the vulnerability of the environment to the process. General hazard identification techniques[12] such as checklists and safety reviews, HAZOP and FMEA (Failure Mode, Effects (and Criticality) Analysis), can be used to estimate and rank the risks involved. Figure 4 models the flow of information throughout an incident risk assessment. The Priority Lists show the importance of the stakeholders to the company and the degree of attention given to a consequence arising from a hazard.

Steady-State Risk Assessment

It is assumed that a process will comply with the regulatory constraints for its normal operations. The steady-state risk assessment aims to evaluate the exposure of the process to environmental issues, for example those that may lie elsewhere in the supply chain or arise from future changes to regulation. Life-Cycle Assessment (LCA) is a tool that is able to identify potential issues throughout a product life-cycle and provide qualitative/quantitative data to support the steady-state risk assessment. The information flow throughout the assessment is illustrated in Figure 5[a].

Checklists

For both incident and steady-state risk assessments, checklists and keywords can be used to ease the identification of hazards, stakeholders and consequences. The list in Figure 6 is an illustrative checklist for stakeholder and consequence.

Estimation and Evaluation Profiles

The estimation profile (a model is shown in Figure 7) summarises the severity of estimated risks of the consequences, as well as representing a company's criteria for risk acceptance. The profile has magnitude/impact divisions, frequency/likelihood divisions and action divisions. Action divisions show the acceptability criteria of the risks, which will then be used by the design team to determine suitable risk management efforts. The evaluation profile (a hypothetical one is shown in Figure 8) summarises the importance of consequences against the importance of stakeholders to the firm. In Figure 8, levels of stakeholder importance are indicated by ranks of 1 to 3, where '1' is most important and '3' is least important. The ranks help evaluate the risks according to the firm's priorities and policies.

APPLICATIONS OF PERA

PERA was formulated with the intention of supporting a project throughout its life-cycle. It is a framework in which risk assessments can be utilised in different ways to meet the changing needs of a project as it develops. Three potential applications at different stages of a project life-cycle are described below.

Formation of design strategy and design criteria

Using a risk assessment to identify potential issues of a project before design allows strategic decisions to be made with the purpose of keeping risks at a minimum level within cost constraints. It helps a company to devise plans at the outset of a project to channel adequate time, resources and expertise to reduce the environmentally-related risks of a process and product by design and the overall risk of the project by management. An aspect of process design that would benefit from establishing a design strategy as such is in the selection of design tools. Four selection criteria are proposed to identify appropriate tools based on the degree of risk in a project[15]. The criteria are presented in Table 1.

Investigating process design options for decision-making

An example is illustrated in the case study presented in the following section of this paper. The study concerns the evaluation of three transportation options for a PVC manufacturing site.

Process control and management of environmental, health and safety issues

The traditional audit function of a risk assessment is applied after the design and development stages. A risk assessment is usually used to evaluate the final design and to develop control measures and emergency procedures.

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[a] In Figures 4 and 5, the term 'hazard/consequence' indicates an environmental consequence arising from a hazard, as opposed to 'stakeholder/consequence' which refers to the effects of actions by stakeholders. This slightly cumbersome nomenclature is to facilitate the instant recognition of the source of a consequence.

Table 1: Tools Selection Criteria

Criterion	Match....	With...
Level of detail	Data quality available at a given design stage	Data quality required to use the tool
Appropriateness	Assessment of the overall risk of the project	Depth of analysis provided by tool
Resources	Resources available from company - related to factors such as company size, management style, policies...etc	Resources demanded by tool
Function	1. Incident / steady-state consideration of design activity and risk assessment 2. Type of problem in design activity and risk assessment	1. Incident / steady-state capability of tool 2. Scope of tool

CASE STUDY

BACKGROUND

Polyvinyl chloride (PVC) resins are manufactured by the polymerisation of vinyl chloride monomer (VCM). Having been commercially produced since the 1939-45 War[16], PVC is now a material that has widespread applications in the transport, packaging, electrical/electronic and health-care industries among others. It is a major commodity plastic and its demand is forecast to be strong and stable[17,18,19].

Despite scientific research and regulatory standards, PVC has come under tremendous scrutiny by environmental pressure groups, governments, trade bodies and public interest groups who question the health and environmental effects of PVC[20,21,22,23]. Issues that have been raised include the environmental and health effects of chlorinated organic materials, plasticisers, metal additives as well as the impacts of the production of VCM and chlorine and the incineration of PVC[23]. As a result, PVC and its related production processes have become sensitive media topics within and without the plastic industry.

This has consequences on the types of risks and impacts that potentially affect the design and operation of the PVC manufacturing process. For example, efforts are needed to reduce and manage the exposure of the process to environmental issues that threaten the image of PVC. The design of the process needs to consider the perception of stakeholders on, not only the PVC manufacturing process itself, but also other processes throughout the PVC life-cycle.

To illustrate the methodology, PERA was applied to transportation issues for a PVC manufacturing process. In the design of a new plant, this would be one among many issues that would be raised through the PERA activity, and has been chosen for illustration. A more complete life-cycle framework for the PVC product chain is shown in Figure 9. Transportation would be identified as an issue through consideration of the life-cycle. This would initiate a risk assessment of that activity. A new PVC manufacturing site belonging to Company A was considered. The company has two existing facilities, Site V that manufactures VCM and PVC, and Site C that compounds PVC. Company A has decided to increase the production of PVC resin by building a new factory, P, which will receive the VCM raw material from Site V and deliver the finished PVC resin to Site C.

TRANSPORTATION

Transportation is an essential element of a plant's operation and needs to be considered at the beginning of a design activity. Once the block diagram stage is reached, there is enough information to identify basic transportation needs and to select a mode (or a combination of different modes) to transport raw materials or products. Further developments can then be made to determine details such as transportation inventory, delivery frequencies and packaging requirements.

Transportation should be designed and managed to minimise material losses, energy usage and the environmental impact of traffic movement[24]. Material losses can occur as a result of accidents, fugitive emissions and loading/unloading operations. Hence, material releases to environment are both incident and steady-state risks. Both the energy usage and environmental impact of traffic movement are the result of normal process operations and can be evaluated as steady-state risks.

This case study simulates transportation design at the block-diagram level of a design activity. The focus of this study was to compare the characteristics of road, rail and sea transport in terms of:

1. The risks associated with the environmental load of a transport mode, and
2. The risks of containment losses during transportation

Using process data and information from the literature, PERA was applied to conduct a qualitative risk assessment to assess these risks and to identify information needs for future analysis. The risk assessment took into account the differences in the amounts of material transported by all three types of vehicle, properties of the materials transported, distances travelled and the effects on transportation costs. (Cost comparisons between the three modes were not included in the scope of the risk assessment.)

Environmental Load of Transportation Mode

All transportation modes have environmental loads. During the steady-state operation of the process, the impacts on the environment due to transportation are inevitable as well as continuous. Hence, the 'hazards' arising to the operator from the environmental loads are from external stakeholders, for example, the government and the environment. The government can use economic instruments (such as taxes/charges) and regulation to impose quality and quantity limits in terms of the receiving environment and resource usage[25]. The natural environment is a reactive stakeholder from which resource depletion and increased levels of emissions will result in environmental constraints. These 'hazards' affect Company A in varying degrees depending on the choice of vehicle used. The steady-state risk assessment was limited to these two stakeholders.

Table 2 presents a few risk scenarios (based on published data[26,27]) and consequences related to capital and operational costs that are, respectively, cost of the vehicle and fuel costs. The impacts on the three transport modes were assessed, giving a score of '1' for the largest effect and '3' for the smallest. The evaluation was made based on the distance travelled for each mode (Table 3) and the inputs/outputs from transportation (Table 4) based on published data[28]). As the tables show, the environmental loads for the PVC and VCM routes are very similar and hence, the results are representative of both routes.

Using the Estimation Profile in Table 5 an Evaluation Profile (Table 6) was produced for the three transportation modes. The degrees of risks are represented on a Priority scale, whereby '1' and '4' respectively indicate the risks of highest and lowest concern.

From the Evaluation Profile, it can be observed that the risk profiles for the three modes of transport are very different. Transportation by lorry has a fair distribution of high to low degrees of risks. The profile for rail transport has a concentration of risks in the Priority 2 and 3 categories. The risks for ships tend to be fairly low, with approximately 45% of the risks falling under Priority 4. On the whole, the steady-state risks regarding the emission loads for ships are the lowest among the three modes of transportation.

Table 2: Scenarios and Consequences

Scenario/Stakeholder	Consequences	Likelihood	Label/Relative Impact		
			Road	Rail	Sea
GOVERNMENT General increase in standards for vehicle emissions for heavy duty diesels	1. Cost of vehicle increases	High	L1 1	R1 2	S1 3
Increase in standards for sulphur levels in heavy fuel oil	2. Cost of fuel oil increases	High	L2 2	R2 3	S2 1
Increase in standards for CO emissions	3. Increase in taxes/duties and the cost of vehicle rises	Low	L3 1	R3 2	S3 3
	4. Cost of vehicle increases	Medium	L4 3	R4 2	S4 1
More stringent measures for SO_2 reduction	5. Price of coal increases, increasing the cost of fuel rises	High	L5 3	R5 2	S5 1
	6. Cost of vehicle increases	Medium	L6 1	R6 2	S6 3
Increase in measures for NO_2 reduction	7. Cost of diesel fuel increases	High	L7 1	R7 2	S7 3
Increase in measures for VOC reduction	8. Increase in taxes/duties and cost of vehicle increases	Medium	L8 2	R8 1	S8 3
ENVIRONMENT Reduction in petroleum reserves	9. Heavy fuel prices increase	Medium	L9 2	R9 3	S9 1
	10. Diesel fuel prices increase	Medium	L10 1	R10 2	S10 3
Reduction in coal reserves	11. Prices of coal increase	Medium	L11 2	R11 1	S11 3

Table 3: Distances for VCM and PVC Routes

Distance /km	Site V to Site P (VCM Route)	Site P to Site C (PVC Route)
Road	329	326
Rail	290	279
Sea	618	618

Table 4: Inputs and Outputs by Transportation Mode [b]

Input/output per t	VCM Route			PVC Route		
INPUT, MJ	Road	Rail	Sea	Road	Rail	Sea
Coal	2.30	116	0.618	2.28	112	0.618
Heavy fuel	27.6	24.7	136	27.4	23.7	136
Diesel	295	72.2	1.85	292	69.5	1.85
OUTPUT, Emissions to air, g						
SO_2	59.9	90.8	147	59.3	87.3	147
VOC	105	117	22.2	104	112	22.2
NO_x	328	118	17.9	325	114	17.9
CO	155	49.6	3.09	154	47.7	3.09
Environmental loads for transportation/ Load, per t						
Units of polluted air, $(1x10^6)$ m^3	13.4	7.16	5.60	13.3	6.89	5.60

Table 5: Estimation Profile[c]

	Frequency		
Magnitude	**High**	**Medium**	**Low**
1	Significant (1)	Tolerable (2)	Tolerable (2)
2	Tolerable (2)	Acceptable (3)	Acceptable (3)
3	Acceptable (3)	Insignificant (4)	Insignificant (4)

Table 6: Evaluation Profile for Road (L), Rail (R) and Sea (S)

		PRIORITY 1 CONSEQUENCES											PRIORITY 2 CONSEQUENCES										
		1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11
1	L	•						•						•	•			•				•	
2	R												•				•		•	•			•
3	S		•			•										•					•		
		PRIORITY 3 CONSEQUENCES											PRIORITY 4 CONSEQUENCES										
		1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11
1	L								•	•		•				•	•						
2	R		•	•	•		•				•										•		
3	S	•						•							•			•		•		•	•

Accident Potential of Transportation Mode

The incident risk assessment aims to compare the magnitude and frequencies of a few accident scenarios for all three transportation modes. Incident risks are extremely case specific and in reality, depend on factors such as geography, route conditions, population density and weather, among others. This risk assessment is greatly simplified compared with reality, but suffices to illustrate PERA for the conditions of a general situation and the low data quality associated with the early stages of design. An evaluation profile was also excluded from this study as it had been previously illustrated in the steady-state risk assessment.

The incident tree in Figure 10 presents the accident scenarios that were considered and their relative frequency of occurrences for all three vehicles. A few assumptions were made regarding the frequency evaluation:

[b] Data are tabulated to 3 significant figures

[c] Number in brackets indicate Priority level

1. For accidents involving a third party, the order of descending accident risk for the vehicles is lorry > train > ship. This assumption was made based on the proximity of vehicles and the number of users on the transportation route.
2. For first party accidents (e.g. damaged carrier due to rough handling), there was an uncertainty towards the comparative risks of all three modes. Hence, the frequencies were assumed to be equal.

The different magnitude categories for the consequences of the scenarios are described in Table 7. From the list of consequences and their magnitude and frequency evaluations in Table 8, estimation profiles for both VCM and PVC transport were plotted in Tables 9 and 10 respectively.

Predictably, the Estimation Profiles for both routes indicate that the level of risks for the transportation of VCM is higher than for PVC. Examining the results in more detail yielded a few other observations.

For the PVC route, all three modes of transportation have the same number of consequences in each magnitude division. This implies that the profiles for all three vehicles are the same. Hence, the choice of mode depends less on this factor of incident risk profile for a vehicle type than other factors such as the steady-state risks concerning emission loads and the cost of transportation.

Table 7: Magnitude Categories for Accidents

	Magnitude Divisions			
Effects	**High**	**Medium**	**Low**	**Very Low**
Consequences	Serious injuries Major environmental damage Evacuation Route closure Traffic diversion	Moderate injuries Route partly blocked Minor environmental damage	Minor injuries Contaminated vehicle	Trivial effects
Stakeholder Involvement	Media attention Public review of accident (by authorities) Attention by environmental pressure groups Injuries inflicted on public and workers	Media attention Inconvenience to public Injury to workers	Injury to workers	

Table 8: Frequency and Magnitude of Consequences

Item	**Frequency Level**	**VCM Transport**		**PVC Transport**	
		Relative Magnitude	**Ranking**	**Relative Magnitude**	**Ranking**
L'1	6	High	3	Medium	3
R'1	7	High	2	Medium	2
S'1	8	High	1	Medium	1
L'2	3	Medium	5	Low	6
R'2	4	High	4	Low	5
S'2	5	Low	6	Low	4
L'3	2	Low	9	Very Low	9
R'3	2	Low	8	Very Low	8
S'3	2	Low	7	Very Low	7
L'4	1	Very Low	12	Very Low	12
R'4	1	Very Low	11	Very Low	11
S'4	1	Very Low	10	Very Low	10

Table 9: Estimation Profile for VCM Transport. Each entry in the table represents a risk scenario that has been identified (see Figure 10).

		Low ← Frequency → High							
Magnitude	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
High	1								S'1
	2							R'1	
	3						L'1		
	4				R'2				
Medium	5			L'2					
Low	6					S'2			
	7		S'3						
	8		R'3						
	9		L'3						
Very	10	S'4							
Low	11	R'4							
	12	L'4							

Table 10: Estimation Profile for PVC Transport. Each entry in the table represents a risk scenario that has been identified (see Figure 10).

		Low ← Frequency → High							
Magnitude	**Rank**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
High									
Medium	1								S'1
	2							R'1	
	3						L'1		
Low	4					S'2			
	5				R'2				
	6			L'2					
Very	7		S'3						
Low	8		R'3						
	9		L'3						
	10	S'4							
	11	R'4							
	12	L'4							

Unlike the PVC route, there is a difference in the risk profiles for all three modes on the VCM route. Road transport showed an even spread of risks across all magnitude divisions. Accidents for ships tend to result in either high or low impacts, with a slight tendency towards the latter. The profile for rail transport also showed an inclination towards the extremities of the magnitude scale but with a tendency towards high impacts. The scenario that resulted in this observation was R'2 - a third party accident resulting in a minor/no spillage of VCM. Due to the nature of VCM, precautionary and emergency procedures would be tight, resulting in high consequences to the image and business of the company.

SUMMARY

As would be expected in the early stages of design, the results of PERA do not point to a definitive choice of the best transportation mode. Instead, the assessments have served to define the scope of data needed for transportation design and highlighted important qualitative data that need to be refined into better quantitative estimates. This would lead to the opportunity for more well-informed decisions. The risk assessments pointed to four environmental criteria for the selection of transportation modes. They are:

1. Profile of incident risks for a transportation mode
2. Profile of steady-state risks for a transportation mode
3. Scale of environmental impact

4. Frequency of incidents.

Together with other factors such as cost-effectiveness and interaction with transportation systems of existing plants, such criteria would contribute towards the selection of the best transportation strategy for the process. Note that the conclusions drawn are based only on publicly available information, and therefore do not necessarily represent the results that would be obtained if a PVC manufacturer carried out the study.

CONCLUSION

PERA is a design tool that is flexible, widely applicable and tailored to fit the activity of process design. It allows the user to take a more holistic view of the potential impacts of their decisions. It reflects the need for culture change that is facing industry as a whole – through life-cycle approaches and sensitivity to a wide range of stakeholders. It goes some way to meet Seiler's[29] challenge to move risk assessment to the early stages of process design. Clearly, the next step will be to apply PERA to live projects.

In principle, as well as dealing with a full range of environmentally-related issues, it could be extended as a framework for an integrated approach to safety, health and even social matters. This would provide a means for a company to identify and organise issues relevant to Sustainable Development.

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FIGURES

Figure 1: Overall Structure of Methodology

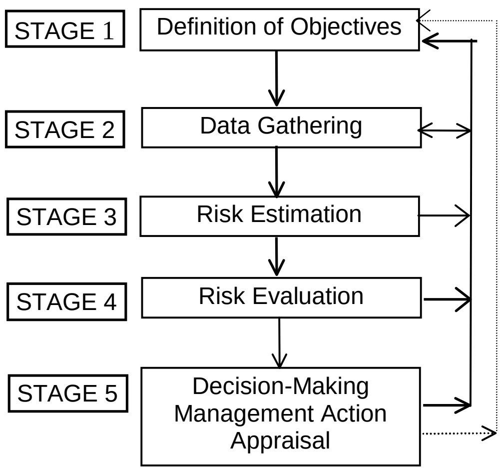

Figure 2: Project Life-Cycle

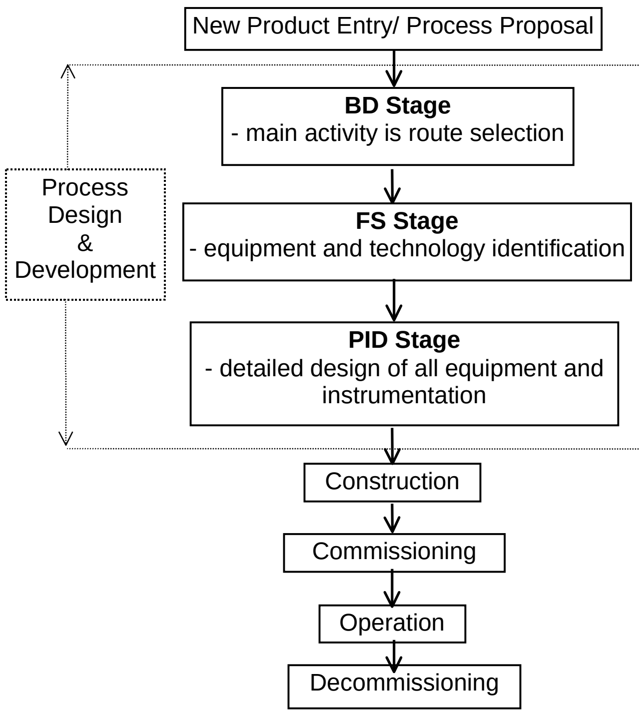

Figure 3: Flowchart for Risk Assessment: Risk Estimation, Evaluation and Management steps

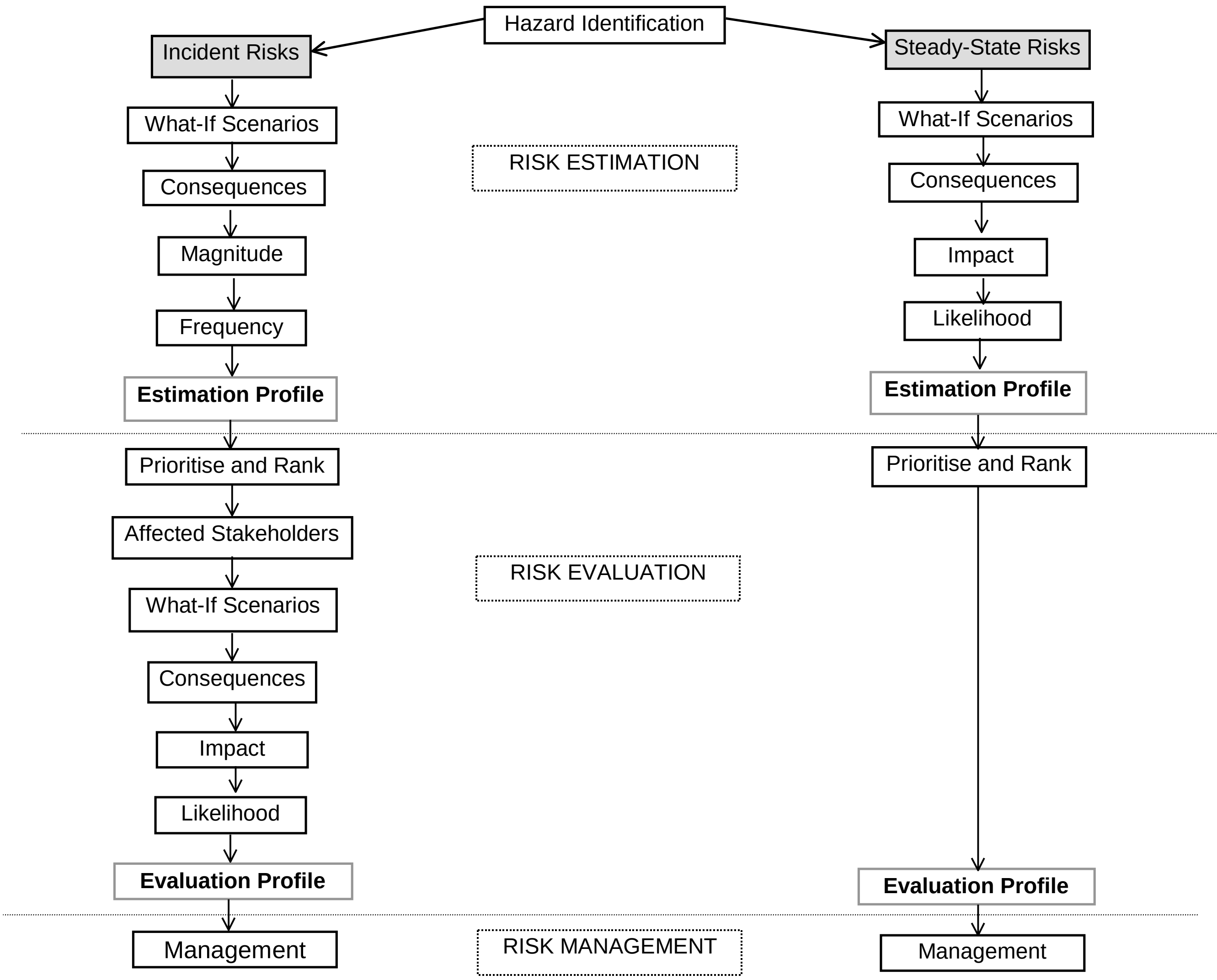

Figure 4: Information Flow Model for Incident Risks

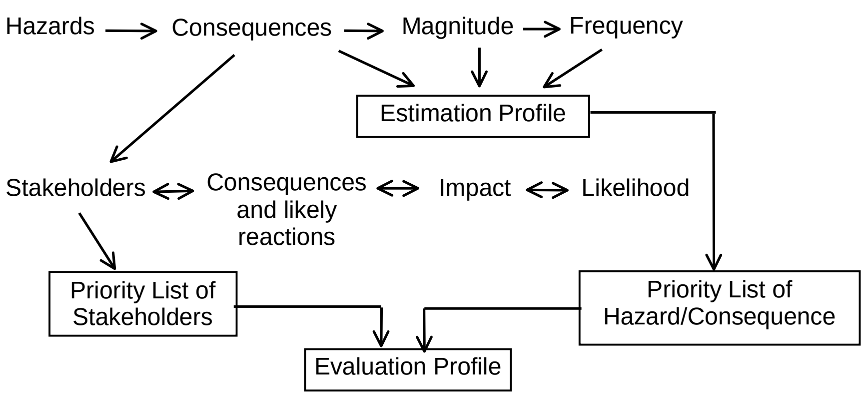

Figure 5: Information Flow Model for Steady-State Risks

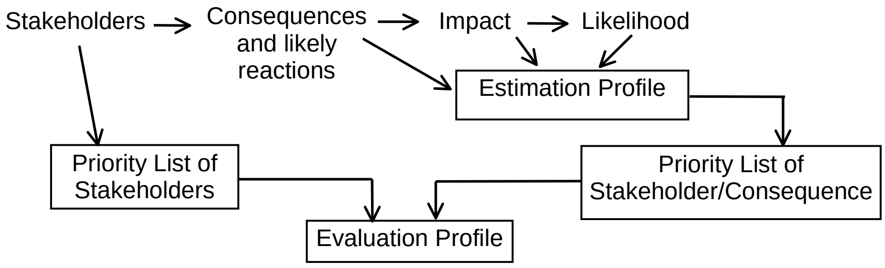

Figure 6: Example Checklist for Stakeholder and Consequence Identification[1,13,14]

Stakeholders	Possible Direct/Indirect Consequences
Environment	Harmful effects to the following environmental receptors – air and atmosphere, water resources, water bodies, soil, geology, landscape, climate, energy, urban and rural conservation areas, other living organisms
General Public, Geographical Neighbours Employees	Damage to human health – physical, mental health and well being (may include access to amenity benefits of the environment), acute and chronic effects. Loss of life – prompt and delayed fatality. Loss of employee morale – negative effects on work performance
Suppliers, Clients	Commercial effects – loss of production, sales or market share. Damage to company image, loss of stakeholder confidence
Insurance Companies, Creditors, Shareholders	Finances – Incur costs of accidents or other damage, cost of capital increases, loss of stakeholder confidence. Assets – damage to plant equipment and buildings
Management	Loss of management time, diversion of management from key functions, loss of management credibility
Authorities	Incur fines, liabilities (environmental related areas or not), law suits etc.
Media, Environmental Pressure Groups	Attract adverse attention and pressure – damage to company image
National Government, Voluntary Groups	Implementation of tighter environmental policies, agreement for code of practice

Figure 7: Hypothetical Estimation Profile

	Frequency		
Magnitude	**Regular**	**Occasional**	**Unlikely**
Severe	Control as priority	Control as cost-effective	Accept
Significant	Control as cost-effective	Control as cost-effective	Accept
Insignificant	Control as cost-effective	Accept	Ignore

Figure 8: Hypothetical Evaluation Profile

		Hazard/Consequence		
		C	A	B
Stakeholder	**Rank**	1	2	3
W	1		•	
R	2	•		•
P	3	•		

Figure 9: Flowchart for PVC Production

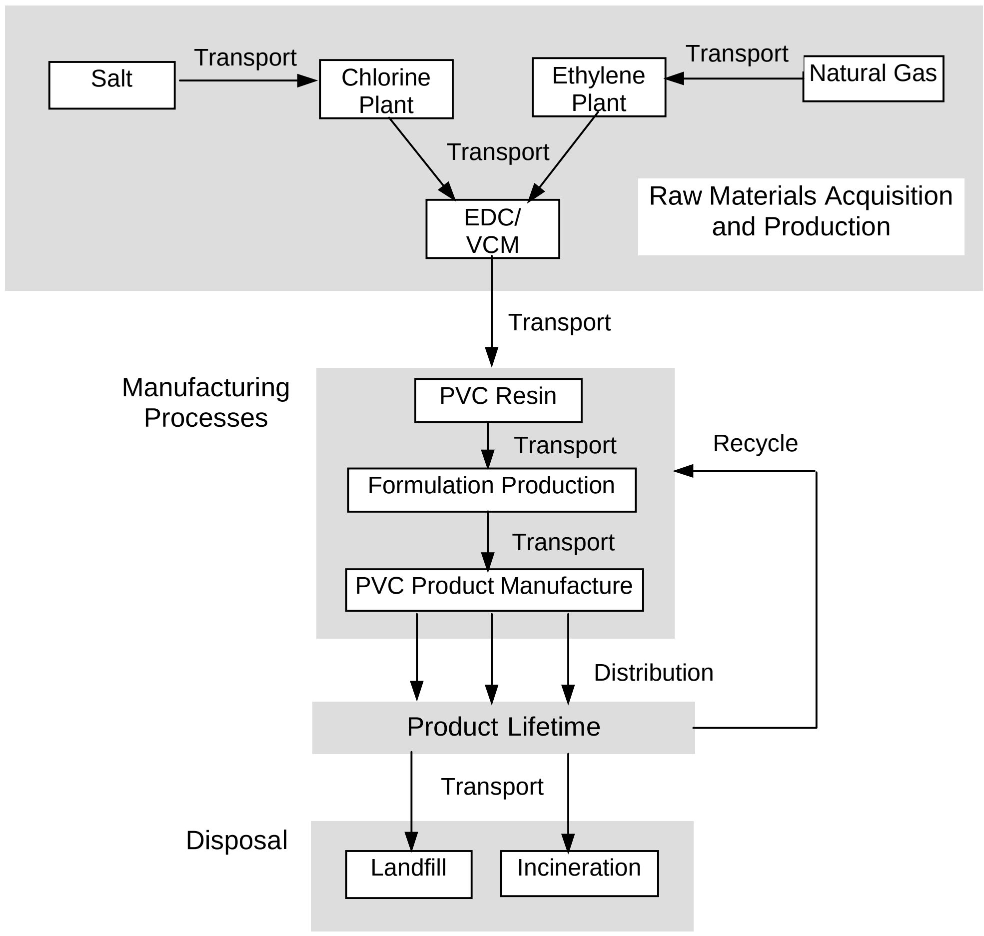

Figure 10: Incident Tree and Relative Frequency Levels