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Quantitative Hazard and Risk Assessment in the Pulp and Paper Industry: Addressing Fire Safety, Air Pollution Impacts, and Environmental Damage Costs


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Abstract:

The pulp and paper industry is globally recognized as a high-risk sector due to its dependence on combustible materials like paper dust, biomass, and flammable chemicals in high-temperature processes. In India, with over 850 operating industries, the sector contributes significantly to industrial output but faces frequent fire incidents, causing financial and economic losses along with human and environmental impacts. Fires often stem from dust accumulation, unsafe storage, overheating machinery, electrical faults, and inadequate safety practices. Although preventive measures such as dust suppression, audits, and BIS/NFPA compliance exist, they remain largely qualitative and reactive. A four-pronged approach is therefore essential to establish a quantitative, globally benchmarked framework. The first prong focuses on hazard identification using HAZOP, PHA, and indices such as the Fire Load Index and FEI. The second involves quantitative risk assessment with PHAST, ALOHA, SAFETI, and CFD simulations under the ALARP principle. The third emphasizes environmental impact assessment using AERMOD modeling within 5–10 km zones, and the fourth addresses environmental damage cost evaluation translating exposure into monetary terms. By adopting this four-pronged approach, pulp and paper sector can move beyond qualitative assessments to a comprehensive, internationally aligned methodology that enhances fire safety, sustainability, and responsible growth.

Keywords: *Quantitative Risk Assessment (QRA); Pulp and Paper; Industrial Safety; Hazard Analysis; Fire and Explosion Risk; MCA; ALARP; Dispersion Modeling; Environmental Damage Cost; Sustainability Goals*

Introduction

Paper products are essential in daily life, but their production involves significant fire and explosion hazards due to the flammability of paper and associated materials (Liu et al., 2025). Inadequate storage or handling of biomass, wood pulp, and other combustibles can lead to fires or dust explosions, resulting in injuries, fatalities, financial losses, and environmental damage (Manić et al., 2021). In recent years, several major incidents have highlighted these risks – for example, the 2017 explosion at the DeRidder paper mill in the United States (Johnson, 2025), a large fire at a Sahibabad paper plant in India in (Hindustan Times, 2025), and a blaze at Suchi Paper Mills in 2022 (PrintWeek India, 2022). These events underscore the critical need for effective risk management throughout the design, construction, and operation of paper industry (Ahonen et al., 2006).

In modern industrial practice, rigorous risk assessment is essential for systematically identifying hazards and evaluating their potential impacts (Shuaib Kaka et al., 2024). A combination of qualitative and quantitative methods is used to recognize and mitigate risks. For example, Hazard and Operability (HAZOP) studies, Preliminary Hazard Analysis (PHA), and hazard indexing techniques (such as calculating a facility's Fire Load and Dow's Fire & Explosion Index) facilitate early hazard identification and prioritization (Kundnani et al., 2022; Gupta et al., 2003). In addition, analytical tools like Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and software-based Quantitative Risk Assessment (QRA) models (e.g., DNV PHAST and SAFETI or EPA's ALOHA) support decision-making within structured safety management systems (IS 15656:2006; Goerlandt et al., 2017; Pouyakian et al., 2023). Advanced computational modeling approaches also enhance risk evaluation; for instance, Computational Fluid Dynamics (CFD) simulations can model dust explosion scenarios and complex fire dynamics, providing deeper insight for effective risk mitigation strategies (Islas et al., 2023).

Beyond on-site safety, the environmental consequences of accidents must also be considered. Large inventories of paper, pulp, fuels, and other flammable materials create high fire loads, which, if ignited, release substantial smoke, particulate matter, and toxic gases into the atmosphere. Atmospheric dispersion modeling tools such as AERMOD can predict the spread of these pollutants and help assess the air quality impact on surrounding populations and ecosystems (Fadavi et al., 2016). Furthermore, an Environmental Damage Cost Assessment (EDCA) framework can quantify the economic costs of pollution-related damages—translating excess emissions, ecological degradation, and public health impacts into monetary terms—to reinforce regulatory compliance and "polluter pays" accountability (Liu et al., 2021; Bherwani et al., 2020; CPCB, 2022).

This paper aims to demonstrate that integrating these diverse risk assessment tools and techniques can substantially improve the identification and mitigation of fire hazards in the pulp and paper industry. By applying a comprehensive quantitative risk assessment approach, encompassing hazard identification, risk quantification, air pollution impact analysis, and damage cost evaluation, paper industries can prioritize effective control measures, enhance operational safety, and minimize adverse environmental and health consequences through informed decision-making.

2.Materials and Methods

The proposed methodology for hazard and risk assessment follows the structure shown in Figure 1, consisting of four interlinked components, hazard assessment, risk assessment, risk mitigation, and damage assessment. These stages can be applied iteratively to evaluate risks throughout a plant's lifecycle, from design to operation.

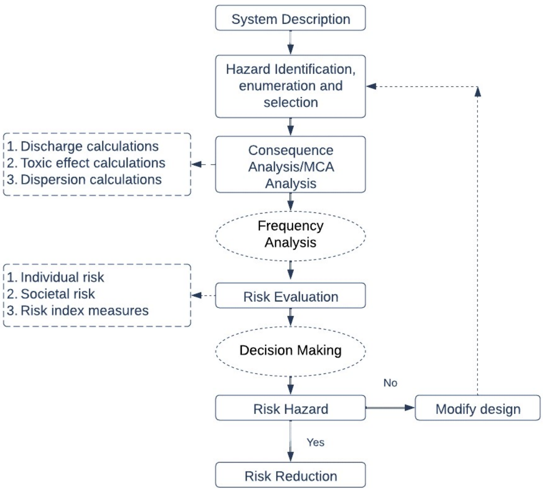


Figure 1: Flowchart showing methodology for Risk and Hazard Assessment

2.1.Hazard Assessment

In the first phase, detailed information about the paper industry's processes, materials, and environment needs to be compiled to identify potential hazards, which includes system data for core units such as wood handling, pulping, bleaching, washing, stock prep, forming, drying, and chemical recovery etc.., including chemical inventory data), along with process conditions (temperatures, pressures, and safety protocols), environmental data (meteorology, topography, nearby populations) and past incidents etc. Multiple complementary approaches can be employed for hazard identification:

- **Comparative analysis:** The facility's design and operations need to be benchmarked against similar plants, engineering codes, and best practices. Standard safety checklists should be applied to systematically screen for common hazards and failure modes, and past incident records need to be reviewed to pinpoint relevant accident scenarios.
- **Hazard indices quantification:** Quantitative indices can be calculated to gauge inherent fire and explosion hazards in different units. For example, Dow's Fire and Explosion Index (F&EI) can be computed as the product of material factor and unit hazard factors for each major processing area. The resulting F&EI values can be classified into hazard severity categories (Light, Moderate, Intermediate, Heavy, Severe) according to Dow's guidelines (Table 1).

Table 1: Dow Fire and Explosion Index: degree of hazard (Source: Dow, 1994)

F&E Index Range	Degree of Hazard
1–60	Light
61–96	Moderate
97–127	Intermediate
128–158	Heavy
≥ 159	Severe

Similarly, the Dow Chemical Exposure Index (CEI) can be used to evaluate acute toxicity hazards of potential chemical releases by relating the estimated airborne release quantity to Emergency Response Planning Guideline (ERPG) concentrations. In the paper industry, various hazardous chemicals are utilized, the CEI can be instrumental in identifying and mitigating risk, which can be calculated using the formula:

$$\mathrm{CEI} = \frac{655 \times AQ}{ERPG - 2} \qquad (1)$$

Where, AQ = Airborne quantity of the chemical released (kg/sec) ERPG-2 = Emergency Response Planning Guideline-2 concentration (mg/m³).

A fire load analysis can also be performed for storage and process areas, calculating the total combustible heat content per unit floor area (in kcal/m²) to categorize fire load severity. Fire load indicates the quantity of heat liberated per unit area when a building and its contents are completely burnt, can be calculated using the formula:

$$\text{Fire Load} = M \times C / A \qquad (2)$$

where M = mass of combustible material (kg), C = calorific value (kcal/kg), A = area over which it is stored (m²).

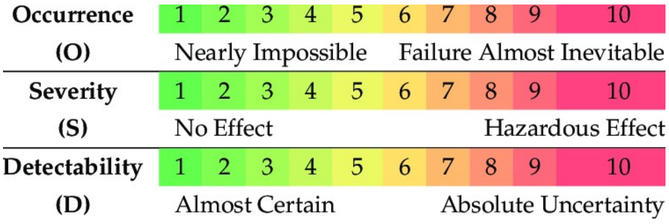
Areas exceeding 550,000 kcal/m² fire load is classified as "High Fire Load," triggering enhanced fire resistance measures per national fire safety codes.

- **Structured hazard studies:** Formal analytical techniques can also be used to examine process deviations and failure modes. A Hazard and Operability (HAZOP) study can be conducted by breaking the process into nodes (e.g., pulping digesters, chemical recovery boilers) and systematically applying guide words (such as "No", "Less", "More", "Reverse") to each key parameter to identify deviations from design intent. For each deviation, the HAZOP team can document possible causes, consequences, existing safeguards, and recommend actions in a HAZOP worksheet (Table 2).

Table 2: HAZOP Worksheet Sample (Source: IJSRD, 2020)

<table>
<tr><th colspan="10">HAZOP STUDY WORK SHEET</th></tr>
<tr><td>DATE</td><td colspan="5"></td><td colspan="4">PARAMETERS</td></tr>
<tr><td>PLANT</td><td colspan="5">cGMP-2</td><td>P (Kg/cm²)</td><td>T (°C)</td><td>V (mmHg)</td><td></td></tr>
<tr><td>PROCESS DESCRIPTION</td><td colspan="5">Charging of Methanol 200 ± 20 L into the Reactor through AOD pump</td><td>DESIGNED</td><td>Up to 80 Kg/cm²</td><td>-175°C to 295°C</td><td>F V</td></tr>
<tr><td>EQUIPMENT</td><td colspan="5">HAR-218</td><td>OPERATION</td><td>ATM</td><td>27.5 ± 2.5°C</td><td>N/A</td></tr>
<tr><td>NODE</td><td colspan="5">Charging of Methanol 200 ± 20 L into the Reactor through AOD pump</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Parameter</td><td>Guide words</td><td>Deviation</td><td>Potential Causes</td><td>Consequences</td><td>Protection Provided/Existing Controls</td><td colspan="4">Recommendation</td></tr>
<tr><td>Quantity</td><td>No</td><td>No Quantity</td><td>-AOD pump not working
-Human error</td><td>-Line pressure ~1.5 kg/cm²
-No hazard</td><td>-BMR & requisition slip ensures correct qty
- Line designed up to 10kg/cm² & tested up to 2kg/cm²
-operator training</td><td colspan="4">Pump must be SS material to avoid static charge during Methanol charging</td></tr>
<tr><td>Quantity</td><td>Less</td><td>Less than 180 L (as per BMR)</td><td>-Less qty in drum
-Vent valve closed
-Line leakage/spillage
-Human error -Bottom valve passed</td><td>-No hazard
-Pressure may build to 1.5 kg/cm²
-Health hazard
-No hazard
-Methanol spill</td><td>-BMR & requisition slip ensures correct qty
-follow BMR
-double bottom valve fitted</td><td colspan="4">Vent valve instruction in BMR; line to be pressure-tested at 1.5× operating pressure</td></tr>
<tr><td>Quantity</td><td>More</td><td>More than 220 L (as per BMR)</td><td>Manual error</td><td>No hazard</td><td>Calibrated dip-stick pre-charge qty check</td><td colspan="4">—</td></tr>
<tr><td>Quantity</td><td>Reverse</td><td>Reverse addition of AHF before Methanol</td><td>Human error</td><td>Dehydrate will form & corrosion starts</td><td>Dehydration to 60 °C under vacuum; follow BMR</td><td colspan="4">—</td></tr>
<tr><td>Quantity</td><td>Part of</td><td>Part of –</td><td>Other valve opened</td><td>Explosive mixture may form</td><td>-Other valves closed/disconnected vacuum test pre-charge</td><td colspan="4">Other lines/valves to be blind off for charging header</td></tr>
<tr><td>Quantity</td><td>Other than</td><td>Unknown chemical charged instead of Methanol</td><td>Human error</td><td>Unknown hazard</td><td>-QC check label & drum Supervised charging</td><td colspan="4">—</td></tr>
<tr><td>Quantity</td><td>As well as</td><td>As well as – methanol & moisture</td><td>-Analysis results wrong
-Ingress of moist air during charging</td><td>DHF will form & corrosion will start</td><td>Dehydration done at 50-60 °C under vacuum & follow the BMR</td><td colspan="4">—</td></tr>
</table>

Likewise, a Failure Modes and Effects Analysis (FMEA) can be carried out to evaluate critical equipment: potential failure modes need to be listed, and each can be rated for severity of consequences, likelihood of occurrence, and detection capability. These ratings (on a 1–10 scale) can used to calculate a Risk Priority Number (RPN = severity × occurrence × detection) for each failure, so that high-RPN issues could be prioritized for mitigation (Nurul Retno et al, 2020). FMEA risk factors rated on a scale of 10 is shown in Figure 2.



Occurrence	1	2	3	4	5	6	7	8	9	10
(O)	Nearly Impossible					Failure Almost Inevitable				
Severity	1	2	3	4	5	6	7	8	9	10
(S)	No Effect							Hazardous Effect		
Detectability	1	2	3	4	5	6	7	8	9	10
(D)	Almost Certain						Absolute Uncertainty			

Figure 2: FMEA parameters for the Risk Priority Number (RPN) (Joao Oliveira et al, 2020)

In addition, a Preliminary Hazard Analysis (PHA) can be performed during the early design stage to identify major accident hazards associated with the plant's storage units and key process operations. The PHA provides an initial list of potential hazard scenarios, which should then subjected to more detailed consequence analysis in later stages (Ravanth R. et al, 2024).

2.2. Risk Assessment

The next phase involved quantitative modeling of accident scenarios to estimate consequences and risk levels.

2.2.1.Impact on the plant premises and close vicinity

Consequence analysis can be performed for credible worst-case events (also known as Maximum Credible Accident scenarios) involving fires, explosions, and toxic releases. Specialized software tools can be used for this purpose such as DNV PHAST and SAFETI ALOHA, FLACS, FLUIDYN etc. can be employed to simulate fire and explosion phenomena and to calculate impact distances for thermal radiation, blast overpressure, and flammable vapor dispersion. Key accident types that can be analyzed include jet fires, pool fires, flash fires, and vapor cloud explosions. The modeling assumes conservative fatality probabilities based on exposure, for example, exposure to a flash fire will assume to be 100% fatal for unprotected individuals outdoors (and 10% indoors), while a jet fire or pool fire carried ~70% fatality probability outdoors.

2.2.2.Impact on the surrounding/buffer areas

To evaluate the zone of impact on the surrounding environment especially in terms of toxic gases and particles pollution, the atmospheric pollutant dispersion model AERMOD can be applied which is a U.S. EPA-recommended model for regulatory purposes (USEPA, 2024). Basis on the pollutant specific emission rates from combustion byproducts from a fire, site-specific meteorological data and surface terrain features, the model can predict ground-level concentrations in downwind and suggest the impact zone. The fire emission can be simulated considering as area sources (wider fire zones). The model simulations will produce concentration isopleths (contours) showing the spatial extent of hazard zones for various time intervals after the incident.

2.2.3.Frequency Estimation

Historical data, fault trees, and event trees can be used to estimate the probability of hazardous events. Fault Tree Analysis (FTA) can be constructed to trace causes of incidents such as a chemical spill, while Event Tree Analysis (ETA) can estimate outcomes of initiating events like boiler tube failure. These methods help in visualizing the pathways leading from basic causes to major accidents. When historical data are limited, probabilistic models can be employed to predict event frequencies. The probability of failure per year (Pf) can be expressed as:

$$\boldsymbol{P_f} = \sum_i (\boldsymbol{f_i} \times \boldsymbol{C_i}) \qquad (3)$$

where is the frequency of the i-th event and the consequence coefficient.

2.2.4.Risk Evaluation

Finally, a risk evaluation can be conducted by comparing the calculated risk levels to established risk acceptance criteria. Individual risk, expressed as Individual Risk Per Annum (IRPA), can be calculated as the probability per year of a hypothetical person at a given location becoming a fatality due to industrial hazards. Societal risk can be evaluated by constructing cumulative frequency–fatality (F–N) curves for the facility. The F–N curve can be interpreted against normative risk tolerance bands, typically divided into an acceptable region, an ALARP ("As Low As Reasonably Practicable") region, and an unacceptable region (Figure 4).

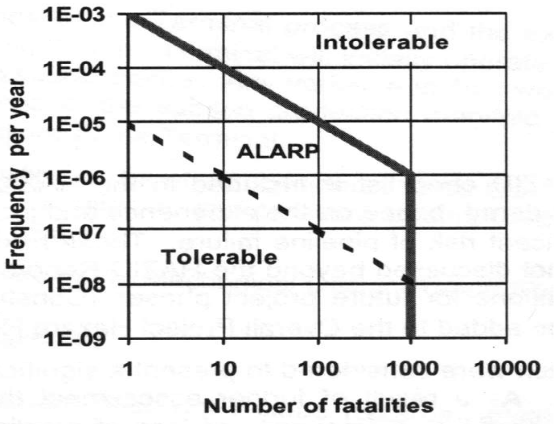


Figure 4: FMEA parameters for the Risk Priority Number (RPN) (Joao Oliveira et al, 2020)

Risks falling into the ALARP band require additional mitigation unless demonstrated to be disproportionately burdensome, while risks above the upper threshold are considered intolerable and demand immediate risk reduction. The computed individual and societal risk values need to fall within the tolerable or ALARP range recommended by international standards (such as UK Health and Executive Safety guidelines for hazardous industries etc.). Any scenarios with risks above acceptable levels shall be marked for further mitigation in the subsequent phase.

2.3.Risk Mitigation

Risk mitigation aims to minimize the likelihood and severity of potential accidents by introducing a combination of engineering, administrative, and design-based controls. In the context of the pulp and paper industry, such measures can be strategically implemented across chemical handling, utility systems, and mechanical operations. Engineering controls form the first line of defence and can include the installation of chlorine leak detectors, flame arrestors near chemical storage areas, automatic shutdown and interlock systems for process upsets, and continuous emission monitoring systems for boiler operations. These controls can be supplemented by robust administrative measures, such as the development and enforcement of standard operating procedures (SOPs), competency-based safety training, and periodic mock drills to ensure workforce preparedness. Furthermore, plant layout design can be optimized by maintaining safe separation distances between process units and locating control rooms or administrative offices in upwind directions, in accordance with the recommendations outlined in OISD-118. Fire protection systems such as water curtains, hydrant networks, and automatic sprinklers can be employed in areas where combustible materials like pulp dust or paper rolls are stored. Electrical safety measures, including proper earthing, insulation, and the use of explosion-proof equipment, are equally critical to prevent ignition in flammable environments. Collectively, these strategies can be integrated within a comprehensive risk management plan, supported by routine audits and maintenance programs, to ensure that residual risks remain within acceptable limits as defined by regulatory frameworks and industry best practices.

2.5 Environmental Damage Cost Assessment (EDCA)

EDCA provides a quantitative mechanism to monetize ecological degradation and public health impacts arising from industrial operations. Importantly, such assessments are applied only in cases of non-compliance, violation, or exceedance of environmental standards, for example, when pollutant levels surpass prescribed regulatory limits or when unauthorized discharges occur. The total environmental damage cost (EDC) is expressed as:

$$EDC = FPC + DC + AC + RC \qquad (4)$$

Where, FPC denotes fixed penalty cost, DC the damage cost, AC the abatement or avoidance cost, and RC the restoration or remediation cost.

The Damage Cost (DC) is quantified using a combination of empirical and model-based methods. The Value Transfer Method (VTM) and Meta-analysis Approach are used to derive pollutant-specific unit cost factors from existing global and Indian studies (e.g., ExternE, OECD, CPCB, NEERI). These are normalized for local purchasing power parity and inflation to yield representative per-unit damage values (e.g., ₹1,462/kg for PM_{10}, ₹460/kg for NO_x, ₹516/kg for SO_x, ₹716/kg for BOD, ₹222/kg for TSS). The Avoidance and Abatement Cost Methods estimate damage based on the expenditure that would have been required to prevent or reduce pollution, such as costs for effluent treatment, gas cleaning, or hazardous waste containment. The Impact Pathway Analysis (IPA) approach models the full causal chain, from emission and dispersion to exposure and impact quantification, linking pollutant release with environmental and health outcomes.

For soil and heavy-metal contamination, a hybrid framework combining Avoidance and Cleanup Cost Methods can be used. Per-kg cost coefficients derived through meta-analysis and adapted from ExternE (1995) and Wuana & Okieimen (2011) studies were adjusted for Indian economic conditions. The resulting coefficients were ₹124,320 for Cd, ₹26,276 for Cr, ₹3,038 for Hg, and ₹74 for Zn. Together, these methods enable a comprehensive quantification of damages across air, water, and soil media, ensuring that only exceedances and violations of environmental standards are monetized within the "polluter-pays" framework.

3.Results and Discussion with case studies

Using the above methodologies, a range of findings can be obtained that demonstrate the value of a comprehensive risk assessment for the pulp and paper sector.

3.1.Hazard Assessment Findings:

Quantitative hazard indices and structured analyses provided a clear mapping of the mill's risk profile. For instance, in one case study the bagasse pulping unit (which handles fibrous biomass) was assigned a Dow F&EI of 97, placing it in the "Intermediate" hazard category, whereas the diesel generator (powerhouse) had a much lower F&EI of 32, classified as "Light" hazard. This indicates that the sections dealing with bulk combustible materials pose significantly higher inherent risk than auxiliary facilities (The Panipat Coop, 2021). Armed with such insights, managers can prioritize more stringent fire prevention and protection measures (e.g., extra sprinklers, temperature monitoring) for the high-index areas. Fire load calculations further quantified the worst-case fire potential: in a representative mill, the stored pulp exhibited an extremely high fire load (~6.75×10^5 kcal/m^2), far above the threshold for High Fire Load classification. This confirmed the need for robust fire safety design (such as 4-hour fire-resistant construction and enhanced sprinkler capacity) in those storage areas (ITC Limited, 2023).

Structured hazard studies also yielded actionable findings. The HAZOP analysis identified specific deviation scenarios and their safeguards, for example, a potential "High Pressure" deviation in a chemical recovery process (due to nitrogen purging left on) is found to risk over-pressurizing a vessel beyond its design limit. In response, it can be recommended to implement engineering changes (e.g., installing a larger rupture disk and an alarm) to prevent these outcomes (Deccan Fine Chemicals, 2016). Applying HAZOP to the paper mill's high-pressure systems (digesters, boilers, etc.) similarly ensures that deviations like overpressure or flow interruptions can be anticipated and addressed (e.g., by adding relief valves and automated shutdown controls). The FMEA highlighted a handful of equipment items with the highest Risk Priority Numbers, prompting targeted improvements (such as adding redundancy for a critical pump with an unreliable seal). Early-stage PHA reviews of the facility's layout and machinery also helped flag inherent hazards (for instance, potential ignition sources near flammable storage), enabling their mitigation through design changes before the plant went into operation.

3.2Risk Analysis Findings:

3.2.1. Impact on the plant premises and close vicinity

The consequence modeling of worst-case accidents provided concrete data to guide emergency planning and design improvements. For a test case of 200 kL furnace oil storage tank fire, simulations using DNV-PHAST predicted that life-threatening thermal radiation (37.5 kW/m^2) could extend up to ~20–21 m from the tank, while significant heat levels capable of igniting secondary fires (12.5kW/m^2) might reach nearly 50m. The impact diagram is given in Figure 5.

This analysis reveals that certain adjacent units, such as a nearby transformer yard and a chemical preparation area, would lie inside the high-hazard zone. To protect these exposures, constructing an RCC firewall around the tank to shield surrounding equipment (with the wall extending at least 0.6 m beyond the tank's height and radius) shall be recommended. Such engineered barriers, along with spatial separation, are seen to substantially reduce the radiative heat impacts on critical equipment.

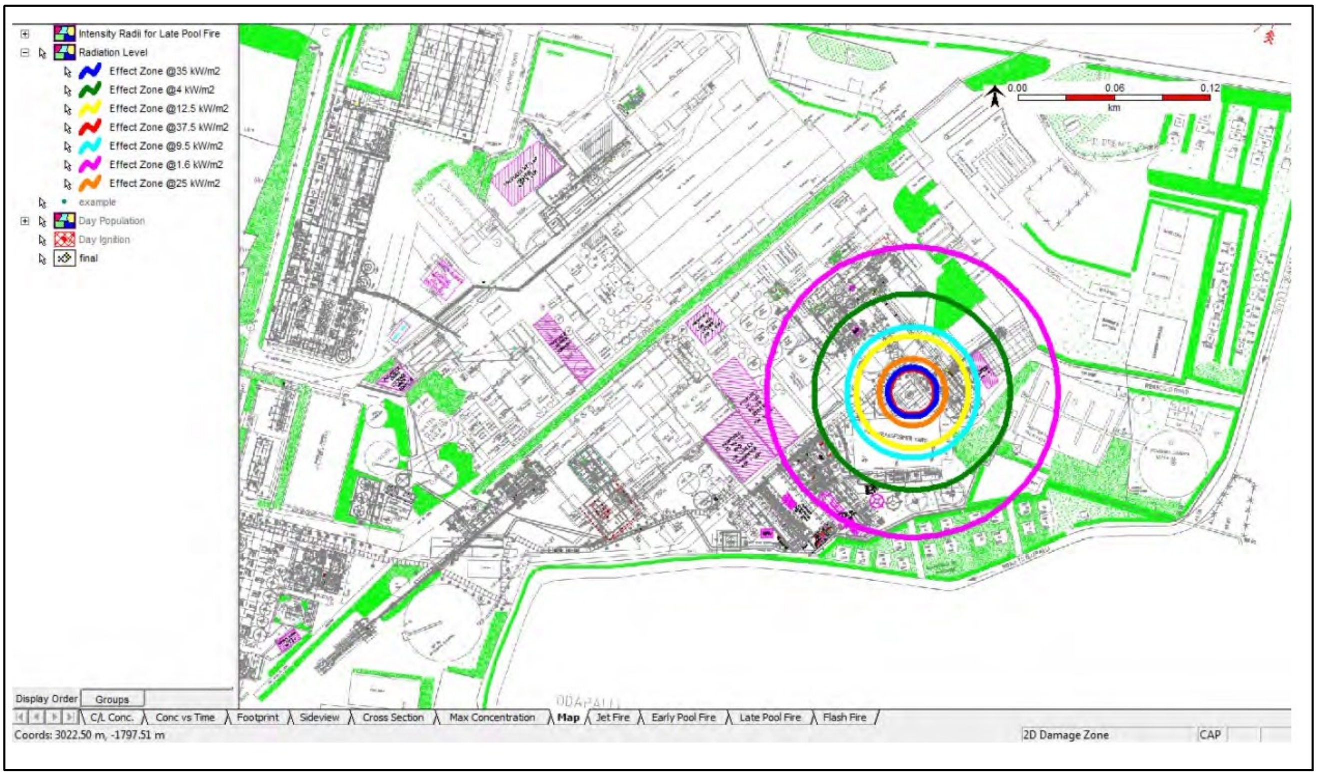


Figure 5: Impact Zone Analysis after Leak furnace oil storage tank (Source: SPBL,2014).

3.2.2. Impact on the surrounding/buffer areas

CSIR-NEERI (2023) conducted a simulation study on pollutant dispersion from a firecracker shop fire using the AERMOD model. Although not directly related to the paper sector, this case serves as an analogue for short-duration, high-intensity fire events in paper mills, which also involve rapid combustion of large quantities of combustible materials. The model was executed under controlled meteorological conditions (unidirectional wind at 1 m/s) to estimate one-hour average concentrations following the burning of 600 kg of firecrackers. The source was defined as a small area (2 m × 1.5 m, positioned 1 m above ground) within a 20 × 20 km domain employing nested grids for high-resolution impact prediction near the source.

The results demonstrated extremely high but short-lived pollutant concentrations, with PM_{10} levels peaking at 89,561 µg/m^3 within 5 m of the shop, decreasing to 1,512 µg/m^3 at 100 m and 75 µg/m^3 at 1 km downwind (Figure 6). The effective impact zone was limited to approximately 150–200 m for a duration of about two hours. Such findings highlight the critical relevance of dispersion modeling for the paper and pulp industry, where accidental fires involving stacked paper, biomass, or packaging materials could produce similarly intense but localized air quality deterioration.

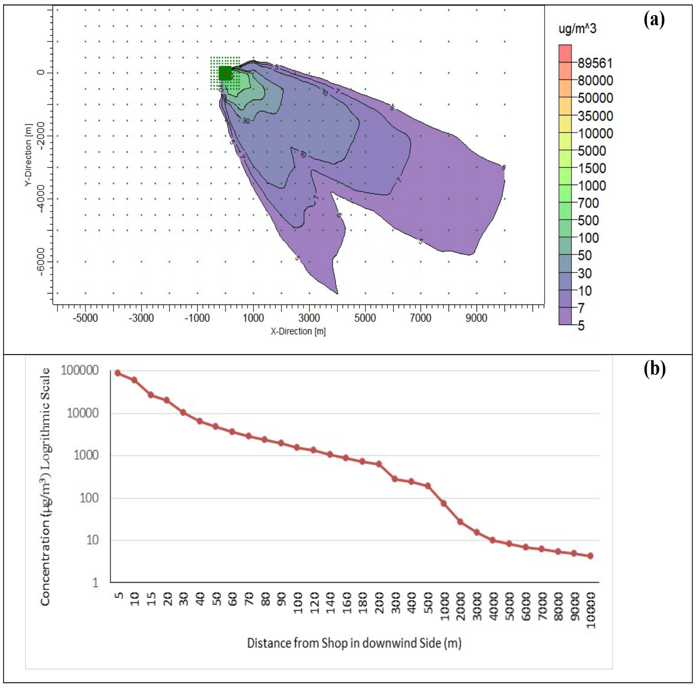


Figure 6: Dispersion of PM10 Concentration after fire accident of 600 kg storage shop (CSIR-NEERI 2023)

H_2S is also recognized as a major gaseous pollutant in paper industry, often exceeding emission standards, posing health risks especially under long-term exposure. H2S concentrations near effluent sludge tanks can be significant. In another studies, Li Yee Lim et al., (2022) have simulated the H2S emission from the paper industry using AERMOD and defined the zone of impact for base case as well as use of neutralizer. Thus, dispersion modelling can effectively be used to predict the dispersion of pollutants from paper industry to the surrounding to prevent impact on air quality.

3.2.3. Frequency Analysis

The event tree analysis further underscored the importance of mitigation systems. For a major fuel leak scenario, the probabilistic model indicated that in ~42% of cases the spill would eventually ignite after some delay, resulting in a flash fire or a late pool fire, and in ~28% of cases an explosion could occur before controls took effect. Only about 1% of large leak events would ignite immediately as a pool fire, while roughly 30% might luckily result in no ignition.

Event Tree Analysis (ETA) systematically maps these possible scenarios from an initiating event to identify and estimate the risks of each potential outcome as shown in Figure 7.

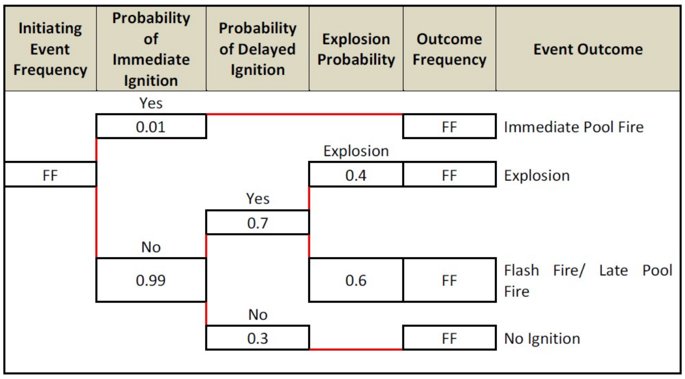


Figure 7. Sample Event Tree (Leak of furnace oil storage tank) (Source: SPBL,2014)

These results emphasized that delayed ignition (which gives time for vapor clouds to form and explode) is a dominant risk, justifying the installation of improved gas detection and emergency ventilation to prevent vapor accumulation. Based on the event tree findings, the paper industry implemented additional ignition source controls and explosions venting in areas at risk, aiming to drive down the probability of a worst-case explosion.

3.2.3. Risk Evaluation

Assessment of population exposure is crucial for evaluating the potential consequences and risks associated with industrial incidents. The individual risk profile (Figure 8) illustrates the variation of fatality risk with distance from the plant boundary, revealing a steep gradient—from per year at the facility perimeter to below per year beyond 750 meters. This confirms that hazard impacts are spatially limited and comply with acceptable risk criteria outside the immediate plant area.

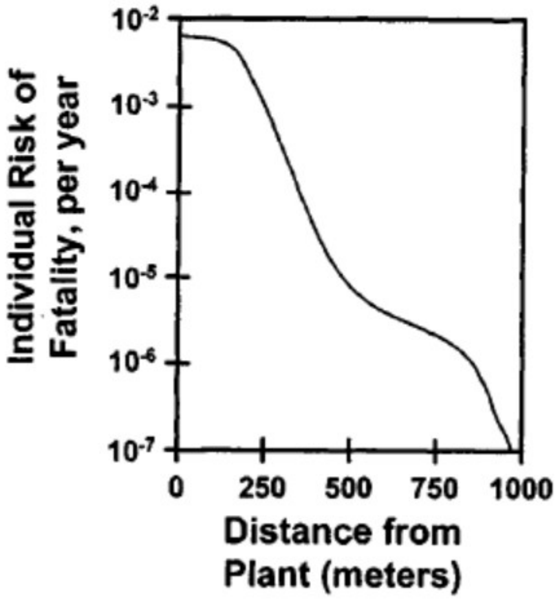
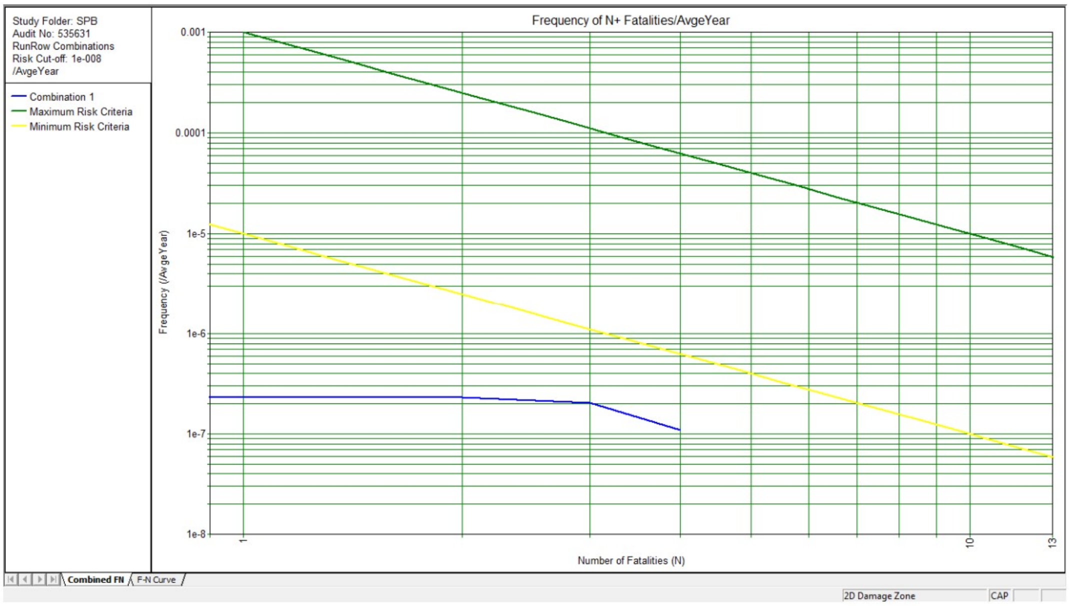


Figure 8. Example of an individual risk profile, or risk transect (Source: UK HSE)

For the 200 kL furnace oil storage tank, the Individual Risk Per Annum (IRPA) is estimated at 1.33×10^{-6} for a leak and 1.13×10^{-6} for a rupture. Correspondingly, the Societal Risk Per Annum (SRPA) values are 9.28×10^{-7} and 1.10×10^{-6}, respectively. These figures are significantly below the maximum tolerable risk threshold of 1×10^{-4} per year prescribed by the UK Health and Safety Executive (HSE) for existing hazardous installations.

The F–N curve analysis (Figure 9) demonstrates that the facility's risk profile lies within the "broadly acceptable" zone. The blue line, representing the actual facility risk, remains below the yellow caution line, confirming that the overall societal risk from the furnace oil tank and other hazards is within acceptable safety margins for both plant personnel and the surrounding community.



Study Folder: SPB
Audit No: 535631
RunRow Combinations
Risk Cut-off: 1e-008
/AvgeYear

Figure 9. F-N Curve for 200 kL furnace oil tank leak (Source: SPBL, 2014)

Nevertheless, plant workers experience approximately tenfold higher exposure compared to the general population, underscoring the importance of rigorous safety management, regular inspection, and continuous monitoring to sustain risks at ALARP (As Low As Reasonably Practicable) levels.

3.3.Environmental Damage Assessment Findings

Finally, the environmental damage cost analysis put a price tag on the consequences of worst-case pollution. In a severe chronic pollution scenario examined (e.g., an unmanaged industrial waste dump), the model estimated total environmental damages on the order of ₹150 crore (approximately $18–20 million) due to prolonged air, water, and soil contamination. While this example lies outside the paper industry, it illustrates the scale of external costs that can arise from unchecked pollution. Applying EDCA to the pulp and paper context, even a single large fire incident could incur significant societal costs (from smoke emissions, cleanup of runoff, soil remediation, health care costs, etc.) if not promptly controlled. This reinforces the business case for investing in robust risk reduction and pollution control measures: preventing an environmental disaster avoids not only regulatory penalties but also the substantial financial and economic losses associated with environmental degradation.

In summary, the four-pronged quantitative assessment provided a much more holistic understanding of risk in the pulp and paper industry compared to traditional approaches. Hazard identification efforts clarified where and how potential dangers originate in the process, linking specific materials and operations to their associated hazards. The use of indices and fire load calculations translated those hazards into measurable values that indicate the relative severity of fire/explosion risk and potential toxic exposure zones. The HAZOP, PHA, and FMEA studies collectively uncovered a wide range of possible deviations and failure modes, covering most credible risk scenarios and allowing the team to focus on the most critical issues. The quantitative consequence and frequency analyses (MCA, FTA/ETA) put numbers to scenario outcomes and accident likelihoods, which greatly informed emergency preparedness planning and the design of protective measures. Lastly, the EDCA connected the environmental and health impacts of accidents to economic terms, strengthening accountability and highlighting the often-overlooked cost of environmental damage. Taking together, these outputs enable a thorough, prioritized, and economically informed approach to managing fire, explosion, chemical, and environmental risks in pulp and paper industries.

4.Conclusion

By adopting a holistic and comprehensive, data-driven approach to hazard and risk assessment, pulp and paper industries can substantially enhance their safety and environmental performance. This study demonstrated that a four-pronged framework, covering hazard identification, quantitative risk analysis, impact modeling, and damage cost evaluation, is not only feasible but highly beneficial for the paper sector. The integrated methodology enabled the identification of hidden hazards (through HAZOP/FMEA/PHA studies and indices) and provided quantification of worst-case accident consequences and likelihoods, which in turn guided targeted risk mitigation strategies. Implementation of these advanced assessment techniques in a paper mill context resulted in a prioritized action plan: high-risk processes were fortified with engineering safeguards, emergency preparedness was tailored to realistic accident scenarios, and pollution control measures can justified with cost-benefit insights from EDCA, mitigating financial and economic losses arising from any such industrial accidents.

Overall, the quantitative hazard and risk assessment approach moves the industry beyond reactive compliance checklists toward proactive risk management grounded in scientific analysis. Industry operators and decision-makers gain a clearer understanding of where to focus safety investments, whether it is upgrading fire protection in high fire-load areas, installing better ventilation and dust controls to prevent explosions, or improving containment and emergency systems for chemical releases. The inclusion of environmental impact modeling and damage cost analysis further extends the responsibility of the industry to surrounding communities and ecosystems, ensuring that the full consequences of accidents are considered in planning and operations. Adopting such rigorous risk assessment practices can significantly reduce the frequency and severity of accidents in the pulp and paper industry, protecting both human lives and the environment. In addition, it positions the industry to meet stricter safety regulations and sustainability goals. In essence, transitioning to a quantitative, internationally benchmarked risk assessment framework fosters safer, more resilient, and environmentally responsible pulp and paper manufacturing.

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