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Developing Resilience-Oriented Indicators for Integrated Process Safety and Process Security Risk Management

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This study develops resilience-oriented performance indicators (PIs) that integrate process safety and process security risk management in the chemical process industry. Drawing on the resilience engineering principle, we propose a unified framework addressing both safety and security concerns through four system capabilities contributing to its resilience: Anticipation, Absorption, Adaptation, and Ascension. These capabilities provide a systematic structure for categorizing the PIs, which are further classified into Management, Process, and Result indicators. Insights from nine expert interviews spanning academia, consultancy, government, and industry helped refine the indicators and assess their practical relevance. The experts discussed eight hypothetical disruption scenarios, ranging from technical failures to supply chain disruptions and terrorism, offering valuable perspectives on implementation challenges and opportunities. The findings emphasize the importance of aligning safety and security measures while tackling systemic barriers such as resource constraints and procedural resistance. This research contributes a novel framework for integrated risk management, supported by actionable PIs that bridge theoretical resilience concepts with practical application. It also lays the groundwork for further validation in real-world settings and broader adoption across diverse industrial contexts.

Keywords: Process safety, process security, resilience, risk management, performance indicators, chemical process industry.

1. Introduction

Safety and security are two sides of the same coin in industrial risk management, yet they are often addressed in isolation (Ylönen et al. 2022; Reniers et al. 2020). For the chemical process industry (CPI), the increasing complexity of operations and the evolving nature of risks, ranging from hazardous chemical releases to cyberattacks, demand more cohesive and integrated solutions (Leveson 2011; Khan et al. 2015). Fragmented approaches can lead to inefficiencies and limit an organization's ability to anticipate and respond to disruptions effectively (Ab Rahim et al. 2025).

Resilience engineering offers a promising paradigm to address this challenge (Aven 2019; Hollnagel et al. 2012; Woods 2015). Rather than focusing on specific failure modes or isolated scenarios, resilience engineering emphasises a system's ability to withstand and recover from a broad spectrum of disruptions. Studies have shown that resilience-based frameworks can enhance safety and security in industrial operations (Ab Rahim et al. 2024; Pasman et al. 2020). However, gaps remain in translating these concepts into practical tools such as performance indicators (PIs).

PIs play a critical role in assessing and managing risks in industrial systems.

Conventional indicators often concentrate on either process safety or process security, overlooking their interdependencies (Swuste et al. 2016; Sultana et al. 2019). Translating resilience into PIs promotes a more holistic approach, enabling organizations to better anticipate, absorb, adapt, and recover from diverse disruptions. In this study, we introduce Ascension—a novel resilience capability focused on recovery, learning, and continuous improvement—to complement the widely examined capabilities of Anticipation, Absorption, and Adaptation (Yarveisy et al. 2022; Yang et al. 2023).

This paper addresses these gaps by developing a structured set of resilience-oriented PIs for the CPI. These indicators are designed to operationalize a resilience-based framework that aligns with the four capabilities, bridging theoretical concepts with practical risk management strategies. The findings provide actionable tools for industry practitioners and regulators, laying a foundation for future research on resilience-based approaches in industrial operations.

2. Conceptual Framework

This study's conceptual framework integrates process safety and process security risk management using a resilience engineering paradigm, structuring the proposed performance indicators (PIs) around four interconnected resilience capabilities: Anticipation, Absorption, Adaptation, and Ascension (4As) (Hollnagel et al. 2012). Each capability plays a vital role in preparing for, responding to, and recovering from disruptions stemming from safety failures, security breaches, or both.

Anticipation involves proactively identifying potential disruptions before they occur, including evaluating critical risks, assessing vulnerabilities, and planning resources. In industrial operations, Anticipation activities include risk assessments, employee training, and robust contingency planning.

Absorption focuses on sustaining functionality during adverse events by mitigating their immediate impact. This includes strategies such as infrastructure redundancies, real-time monitoring systems, and pre-established response protocols that keep critical systems operational despite challenges.

Adaptation highlights dynamic adjustments to changing conditions and implementing flexible operational strategies. It ensures that organizations can update work procedures, reallocate resources, and respond effectively to prolonged supply chain disruptions, shifting regulations, or other evolving risks.

Ascension, introduced in this study, extends beyond recovery to encompass learning and continuous improvement. It highlights the institutionalization of improvement cycles to reduce vulnerabilities over time, integrating lessons learned from past disruptions into future planning and operations.

Following Meyer et al. (2022) and Reniers et al. (2011), we operationalise these four capabilities through three types of PIs, each reflecting a particular function in resilience management and exhibiting proactive or reactive characteristics.

Management Indicators are proactive (leading) that measures "With what means?" to achieve certain safety/ security-related objectives. Hence, management indicators primarily support Anticipation, focusing on preparedness activities such as resource allocation and training efforts.

Process Indicators which are also proactive, mainly support Absorption and Adaptation. It measures operational activities and responses (e.g., system uptime, incident-response times) indicating "How" effectively processes perform under both normal and disruptive conditions.

Result Indicators are more reactive (lagging), asking "What was achieved?". Result indicators largely address Ascension, by evaluating medium and long-term recovery outcomes along with the incorporation of lessons learned into future operations.

This structured categorization bridges theoretical resilience concepts with practical risk management tools. While the framework is designed for the comprehensive integration of process safety and security, this paper focuses on developing and classifying the PIs. Future work will explore broader implementation details and validation efforts in real-world settings.

3. Methodology

A qualitative research design was adopted to develop resilience-oriented PIs that integrate process safety and process security risk management. The methodology involved a systematic literature review, conceptual framework development, and scenario-based expert elicitation through semi-structured interviews, providing a robust foundation for the proposed indicators.

The literature review revealed notable gaps in efforts to merge process safety and security within resilience-oriented frameworks (Ab Rahim et al. 2024). Although existing studies highlight the need for actionable tools (e.g., PIs) to operationalize resilience concepts, comprehensive metrics for integrated risk management are lacking (Jovanović et al. 2018; Pasman et al. 2014). These insights informed the design of the conceptual framework and guided the categorization of PIs across disruption types, resilience capabilities, and indicator types.

Next, nine experts from academia, consultancy, industry, and government were selected via purposive sampling to ensure diverse regulatory, operational, and strategic perspectives. Building on scenario-based expert elicitation principles (Van Der Sluijs 2002; Schoemaker 1993), each expert was presented with eight hypothetical disruption scenarios (e.g., technical failures, security breaches, natural disasters, supply chain disruptions) and a preliminary list of PIs. To accommodate time constraints and domain expertise, participants chose two or more scenarios most relevant to their background, providing open-ended feedback on each relevant scenario. Semi-structured interviews enabled discussions on three main questions: (1) How relevant are these indicators to your operations? (2) Which indicators would you prioritize or exclude? (3) What challenges and opportunities do you foresee in their implementation?

Table 1 summarizes the professional backgrounds of the nine interviewees, who collectively provided a balanced view on policy, operational, and strategic concerns in the chemical process industry.

Initially, the draft PIs were not assigned to any specific resilience capability. Following the interview, thematic analysis (Braun and Clarke 2006) was performed in Atlas.ti to identify recurring themes (such as resource constraints or procedural inertia) and refine the indicators based on expert feedback. Specifically, indicators were retained, removed, or adapted based on an inclusive threshold approach, whereby any indicator endorsed or received detailed feedback from at least one expert remained in the framework. This approach reflects the exploratory nature of the study and ensures that specialized insights relevant to certain risk scenarios are not prematurely excluded. During this process, the indicators were also mapped to the four resilience capabilities according to expert guidance, thereby finalizing their placement. Challenges and opportunities raised by the experts were synthesized into recommendations for practitioners.

Preliminary findings were validated through member checking, wherein a subset of participants reviewed the results for accuracy and relevance. This iterative approach enhanced the reliability and applicability of the final set of indicators. While these steps bolster confidence in the indicators, further real-world validation (e.g., pilot implementation in a chemical plant) will be required to determine broader feasibility and refine the indicator set as necessary.

4. Results and Discussion

4.1. *Structure of the Performance Indicators*

This research produced a set of resilience-oriented PIs designed to integrate process safety and process security risk management in the CPI. The indicators cover eight disruption types: Human Errors, Technical Failures, Managerial Failures, Internal Labour Disruptions, Natural Disasters, Terrorism, Supply Chain Issues, and External Social Hazards (Yang et al. 2023). The PIs also aligned with the four resilience capabilities: Anticipation, Absorption, Adaptation, and Ascension.

As described in Section 3, the PIs were initially developed without specifying which resilience capability each one would support. Through expert feedback, each indicator was mapped to the most appropriate capability. We further categorize the PIs into Management, Process, and Result indicators. In this structure, Management Indicators primarily support Anticipation by tracking preparedness activities (e.g., resource allocation and training completion rates). Process Indicators mainly assist Absorption and Adaptation, measuring real-time operational responses such as system uptime or the frequency of protocol updates. Result Indicators mainly address Ascension by capturing outcomes related to medium or longer-term recovery, learning, and continuous improvement (Reniers et al. 2011).

This structure ensures that the indicators are actionable, measurable, and adaptable across diverse operational contexts, providing a robust framework for advancing resilience practices. Table 2 provides a non-exhaustive list of PIs, categorised by disruption types, resilience capabilities, and the dimension of whether the indicators cater to safety, security, or both. Due to space constraints, only selected examples are shown to illustrate potential relevance and implementation considerations.

Table 1. Summary of interviewees by sector, position, experience, and expertise.

Sector	Position	Experience	Expertise
Academia	Associate Professor	25+ years	Process safety and chemical engineering expertise; former industrial professional
Consultant	Industrial Major Hazard Competent Person	20+ years	Process safety management and consultancy in multinational operations
Government	Director of Chemical Safety and Security Authority	20+ years	Policy development and enforcement in chemical safety and security
Government	Deputy Director of Industrial Major Hazard Division	15+ years	Regulation of process safety and security for major hazard installations
Government	Assistant Director of Safety and Health Policy Division	10+ years	Policy development in chemical safety and security risk management
Industry	Health and Safety Manager	30+ years	Process safety management in the chemical process industry
Industry	Safety and Security Officer	30+ years	Safety and security risk management, with expertise in physical and cybersecurity
Industry	Health and Safety Manager	30+ years	Safety management in major hazard installations and operations
Industry	Supply Chain and Procurement Manager	20+ years	Supply chain and procurement management for chemical process operations

Table 2. Performance indicators by disruption types, resilience capabilities, and safety/ security dimension (non-exhaustive list of indicator examples – one example is provided per sub-category).

Disruption	Resilience Capability	Indicator Type	Performance Indicator	Dimension
Human Errors	Anticipation	Management	Percentage of operators demonstrating competence (via annual assessment) to manage process safety/ security risk situations.	Safety and Security
Human Errors	Absorption	Process	Percentage of successful safety interlock activations that prevent (major) accidents.	Safety
Human Errors	Adaptation	Process	Percentage of safety/ security procedures updated within six months of a relevant incident.	Safety and Security
Human Errors	Ascension	Result	Reduction in repeated human error incidents (year-on-year) after lessons learned are implemented.	Safety
Technical Failures	Anticipation	Management	Ratio of annual budget allocated to scheduled preventive maintenance vs. total required for critical safety/security equipment.	Safety and Security
Technical Failures	Absorption	Process	Percentage of equipment with functional secondary containment to mitigate immediate leaks or fires.	Safety
Technical Failures	Adaptation	Process	Percentage of safety/ security-critical equipment under real-time condition monitoring that adjusts responses dynamically.	Safety and Security

Technical Failures	Ascension	Result	Decrease in repeated technical disruptions (year-on-year) after corrective actions have been implemented.	Safety and Security
Managerial Failures	Anticipation	Management	Percentage of the annual budget allocated to non-hardware process safety/ security initiatives (e.g., training, competency development, risk assessments, incident investigations).	Safety and Security
Managerial Failures	Absorption	Process	Percentage of emergency decisions executed within predefined timeframes during incidents	Safety and Security
Managerial Failures	Adaptation	Process	Percentage of emergency response protocols reviewed/ updated after incident investigation.	Safety and Security
Managerial Failures	Ascension	Result	Rate of injuries due to process safety/ security incidents per year.	Safety and Security
Internal Labour	Anticipation	Management	Percentage of workforce receiving risk-awareness training for potential strikes or labor disruptions.	Safety and Security
Internal Labour	Absorption	Process	Percentage of critical processes that remain operational with reduced human intervention.	Safety and Security
Internal Labour	Adaptation	Process	Percentage of labor relations meetings conducted on schedule (every 3 months), with > 80% participants satisfaction with the outcomes.	Safety and Security
Internal Labour	Ascension	Result	Percentage of employees satisfied with workplace conditions, safety, and security in annual survey.	Safety and Security
Natural Disasters	Anticipation	Management	Percentage of Business Continuity Plan (BCP) procedures reviewed/ updated annually to address natural disaster risks.	Safety and Security
Natural Disasters	Absorption	Process	Percentage of critical equipment supplied by backup power systems during regional blackouts.	Safety and Security
Natural Disasters	Adaptation	Process	Percentage of post-disaster assessment reviews integrated into infrastructure upgrades/ improvement plans.	Safety and Security
Natural Disasters	Ascension	Result	Reduction in operational downtime from natural disasters (event-to-event or year-on-year).	Safety and Security
Terrorism	Anticipation	Process	Percentage of physical/cybersecurity vulnerability assessments conducted on schedule (every 3 years).	Security
Terrorism	Absorption	Process	Number of updates/ patches applied to critical control systems to mitigate cybersecurity risks (every 3 months).	Security
Terrorism	Adaptation	Process	Percentage of security protocols updated after relevant threat assessments or incidents.	Security
Terrorism	Ascension	Result	Reduction in repeated security breaches or vulnerabilities (year-on-year) after remedial actions are implemented.	Security
Supply Chain	Anticipation	Management	Percentage of key suppliers undergoing annual reliability/ quality assessments.	Security
Supply Chain	Absorption	Process	Percentage of critical materials or components with pre-qualified alternative suppliers to prevent major delays.	Security
Supply Chain	Adaptation	Process	Percentage of corrective/ improvement actions from critical supply-route audits implemented on time.	Security
Supply Chain	Ascension	Result	Reduction in supply chain-related disruptions year-on-year (operational or financial).	Security
Social Hazards	Anticipation	Process	Percentage of stakeholder engagement meetings conducted (every 2 years) to address potential external social risks, with >80% satisfaction.	Security

Social Hazards	Absorption	Process	Number of contingency measures activated during workforce shortages or utility interruptions.	Security
Social Hazards	Adaptation	Process	Percentage of operational procedures updated after each major external social disruption.	Security
Social Hazards	Ascension	Result	Reduction in recurring external social hazard disruptions (year-on-year).	Security

4.2. *Relevance of Indicators*

The proposed PIs provide a unified framework that explicitly integrates process safety and process security. Each indicator supports one of the four resilience capabilities, ensuring that organizations can not only prevent disruptions but also respond, recover, and learn from them (Yang et al. 2023).

For Anticipation, indicators focusing on early detection and preparedness, such as the '*ratio of annual budget allocated to scheduled preventive maintenance vs. total required for critical equipment*,' enable organizations to proactively address potential failures. By quantifying commitment to preventive measures, these PIs reinforce a forward-looking risk management culture.

Under Absorption, indicators like the '*percentage of critical processes that remained operational with reduced human intervention*' during labor disruptions reflect the system's capacity to maintain functionality under stress. They highlight how well an organization's infrastructure, technology, and procedures can "absorb" unexpected shocks without halting production or compromising safety and security.

Adaptation PIs (e.g., '*percentage of safety/security-critical equipment under real-time condition monitoring*') showcase an organization's ability to adjust processes in response to evolving conditions. By measuring responsiveness and flexibility, these indicators encourage continual refinement of protocols and resource allocation.

Ascension, a novel resilience capability introduced in this study, focuses on recovery and continuous improvement. Long-term improvement is captured through Result indicators such as the '*reduction in recurring disruptions year-on-year*.' By quantifying organizational learning and continuous enhancement, Ascension indicators promote a culture in which lessons learned from past incidents lead to tangible performance gains.

4.3. *Challenges and Opportunities*

While the above indicators offer clear benefits for guiding integrated process safety and process security efforts, expert interviews shed light on key barriers and potential strategies for implementing them.

One key challenge involves resource constraints. Many organizations operate under tight budgets and may not prioritize preventive or resilience-focused measures, especially those requiring both financial and human capital. Demonstrating the long-term return on investment through cost-benefit analyses can help shift such perceptions and increase upper-management support (Ylönen et al. 2022).

Another challenge stems from procedural inertia and resistance to change (Le Coze 2019). Updating emergency response protocols or integrating lessons learned into everyday processes often encounters reluctance from personnel who are accustomed to established routines. Strengthening leadership support, involving staff in shaping new protocols, and offering cross-functional training can boost acceptance, ensuring that changes are effectively implemented and sustained over time.

Technological and analytical gaps also pose significant hurdles, particularly for indicators that require real-time condition monitoring or advanced data analytics (Sultana et al. 2019). Organizations without a robust digital infrastructure may struggle to deploy and interpret these metrics fully. However, a phased approach to technology adoption, along with strategic partnerships with technology providers, can facilitate incremental progress, allowing organizations to build capacity gradually.

A final challenge is the inconsistent application of lessons learned. Ascension indicators rely on systematically capturing and utilizing insights gained from disruptions, yet many organizations lack formal processes for consolidating these lessons (Leveson 2015). Establishing centralized knowledge repositories, conducting regular debriefs, and embedding post-incident reviews into standard practice can close this gap and help institutionalize continuous improvement. By proactively addressing these multifaceted challenges, organizations can harness the full potential of the proposed performance indicators, ultimately achieving stronger and more adaptive risk management in both process safety and security.

5. Conclusion and Future Research

This study proposes a structured set of resilience-oriented performance indicators (PIs) integrating process safety and process security risk management in the chemical process industry. Guided by the four resilience capabilities (Anticipation, Absorption, Adaptation, and Ascension), the indicators form a comprehensive framework for anticipating disruptions, maintaining operational stability under stress, adapting to evolving threats, and recovering effectively through continuous learning. By classifying these PIs into Management, Process, and Result types, the framework transforms theoretical resilience concepts into practical metrics for industry stakeholders.

Although expert insights played a key role in developing these indicators, further empirical validation in real-world industrial contexts is needed to confirm their utility and adaptability. Additional research could examine how these metrics scale across different organizational structures, regulatory environments, and geographic regions. A deeper analysis of how multiple disruption types interact and how the various resilience capabilities can reinforce one another would also strengthen the framework's robustness. While the paper adopts a strict alignment between capability and indicator type, real-world applications may require some flexibility in assigning certain indicators to specific groups, depending on organizational needs and evolving contexts.

Looking ahead, future studies should pilot the proposed indicators in operational settings to gauge their effectiveness, refine their design, and develop practical guidance for data collection, measurement standards, and performance thresholds. Such efforts would support broader adoption by demonstrating tangible benefits, clarifying implementation steps, and offering insight into potential barriers. By operationalizing resilience engineering principles through these integrated performance indicators, this research offers a viable path for organizations to enhance both process safety and process security in a rapidly evolving industrial landscape.

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