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Process Safety Management and Management of Change Effectiveness in Mature Oil and Gas Production Operations

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Abstract
Mature oil and gas operations make more brownfield changes each year while their staff shrink, straining management of change (MOC). This study develops a system dynamics model of MOC effectiveness. Five types of change flow through capture, hazard review and pre-startup safety review. Any hazard that escapes becomes a latent condition, which persists until audits, near-miss learning, process hazard analysis revalidation or maintenance remove it, or until it releases a process safety event. Inputs are representative literature values, not site data. With reviewers declining 4 percent and changes growing 3 percent a year, reviewer load doubled over ten years. Review effectiveness fell from 0.80 to 0.52, and the expected annual rate of process safety events rose from 3.2 to 5.3. Sixteen intervention portfolios were evaluated. Strengthening audits and near-miss learning was the most cost-effective single measure, averting 16.4 events for USD 1.2 million. Better change capture without added reviewer capacity was undermined by reviewer overload; pairing capture with added capacity averted a third more events than the sum of their separate effects. All four interventions together cut expected events by 70 percent, a benefit-cost ratio of 3.3. A quarterly audit of 20 MOC records detected a fall in review quality within a year with 80 percent probability. Over three years, event counts detected it with only 28 percent probability.

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1. Introduction

Process safety management (PSM) has been the principal regulatory and organizational response to major accidents in the process industries since the late 1980s. In the United States, the Occupational Safety and Health Administration standard on process safety management of highly hazardous chemicals sets out fourteen elements that covered facilities must implement [1], and the Environmental Protection Agency Risk Management Program addresses accidental releases to the public and environment [2, 3]. In Europe, the Seveso III directive establishes comparable requirements for major-accident hazards [4]. Industry frameworks such as the Center for Chemical Process Safety (CCPS) risk-based process safety guidelines [5], the Energy Institute high-level framework [6] and the International Association of Oil and Gas Producers (IOGP) process safety fundamentals [7] have extended these requirements into management systems that emphasize commitment, hazard understanding, risk management and learning. Bibliometric and scientometric analyses show that process safety research has grown rapidly and diversified across these themes [8, 9].

Management of change (MOC) is the PSM element that ensures that modifications to equipment, chemicals, technology, procedures and organization are reviewed for their hazards before they are implemented [1, 10]. Its importance was established by the Flixborough disaster of 1974, in which a temporary bypass installed without engineering review failed and released cyclohexane [11], and it has been reaffirmed by many later accidents. Investigations of the Texas City refinery explosion [12, 13], the Macondo blowout [14], the Longford gas plant explosion [15], the Williams Olefins reboiler rupture [16], the Philadelphia Energy Solutions refinery fire [17] and the Husky Superior refinery explosion [18] all identified failures to recognize or properly assess changes. Analysis of chemical industry accidents has attributed a substantial share to deficiencies in MOC [19], and practitioner reviews of incidents and audits have found recurring weaknesses in MOC practice [20, 21].

Mature oil and gas production operations present conditions that place particular stress on MOC. As fields age, brownfield modifications multiply: separators are re-rated, compression is added or removed, water handling is expanded, controls are upgraded and equipment is replaced, and ageing pressure vessels must be reassessed for fitness for service [22–25]. At the same time, declining production and margins create pressure to reduce engineering and operations staff, to outsource and to restructure, and organizational change has been shown to affect safety outcomes in the petroleum industry [26–28]. Knowledge is lost as experienced workers retire [29], and creeping changes accumulate that individually seem minor [30, 31]. These conditions resemble the drift towards the boundary of safe performance that Rasmussen described [32] and the incubation of disasters described by Turner [33]. Upstream process safety event data show that the oil and gas production sector continues to experience significant process safety events [34–36].

Although the importance of MOC is widely accepted, quantitative evidence on how MOC effectiveness responds to the conditions of mature operations, and on which interventions offer the best return, is limited. Existing studies describe what a good MOC system looks like [21, 37], how to audit it [38], how its action items should be scoped [39] and how MOC quality relates to performance [40], but they rarely model the dynamic interaction between change volume, reviewer capacity, review quality and the accumulation of latent hazards. System dynamics has been applied to safety management systems [41], construction safety culture [42, 43], behavioural safety [44] and near-miss reporting [45], but not, to the author's knowledge, to MOC in mature production operations. This paper develops such a model and uses it to answer four questions. How does MOC effectiveness evolve when change volume grows and reviewer capacity declines? Which PSM and MOC interventions are most cost-effective, alone and in combination? Which parameters most influence process safety outcomes? And how quickly can deterioration in MOC be detected by leading indicators compared with lagging event counts? Section 2 reviews the literature, Section 3 presents the model, Section 4 the results and Section 5 the discussion, and Section 6 concludes.

2. Literature Review

This section reviews the literature on which the model is built: PSM regulation, frameworks and effectiveness; process safety indicators; MOC design and failures; organizational change, drift and normalization of deviance; organizational accident models and learning from incidents; and quantitative and system dynamics models of safety management. The review draws on the observation that major accidents in the process industries arise from combinations of technical, human and organizational causes [46–48], and on reviews of risk analysis methodologies for industrial plants and work sites, which classify the qualitative, semi-quantitative and quantitative methods available for assessing such causes [49, 50]. It also reflects the systematic review evidence that safety management practices rely on indicators whose selection and use remain contested [51].

2.1. Process Safety Management Regulation and Effectiveness

Regulatory PSM frameworks differ in scope and enforcement. The OSHA PSM standard [1] and its enforcement in petroleum refineries, which produced lessons on recurring citations [52], the EPA Risk Management Program and its accident epidemiology [2, 3], and the Seveso directives and their implementation in different countries [4, 53, 54] have been studied. The COVID-19 pandemic tested safety management in Italian Seveso establishments [55]. Calls have been made for an international standard for process safety management [56], for corporate governance guidance for senior leaders [57] and for PSM approaches suited to upstream oil and gas [58]. Lessons from Bhopal have been used to strengthen PSM elsewhere [59], and a pesticide plant explosion yielded further PSM lessons [60].

The effectiveness of PSM systems has been assessed through quality evaluations in industrial corporations [61], systematic reviews of hazard identification and risk control practices [62], analyses of interrelations between PSM elements [63], strategies for sustaining process safety performance [64] and predictions of effectiveness for managing low-probability events [65]. Internal auditing of process safety and QHSE performance [66, 67], the relationship between audit findings and operational discipline [68], the limitations of auditing as verification [69], warning flags for organizations [70], survey-based measurement systems [71] and the persistent problem that early warning signals are noticed but not acted upon [72] show that compliance does not guarantee effectiveness. Risk analysis has been proposed as the basis of safety management systems [73], risk-based process engineering frameworks have been proposed to strengthen reliability across complex natural gas infrastructure [74], including in small enterprises with major hazards [75], and cause-consequence analyses of Seveso accidents have informed system design [76]. Process safety leadership [57, 77], competence assessment [78], workforce safety training [79] and education [80] are recognized as conditions for effective PSM.

2.2. Process Safety Indicators

Indicators are used to monitor PSM effectiveness. API RP 754 defines Tier 1 and Tier 2 process safety events as lagging indicators and Tier 3 and Tier 4 as leading indicators [81], IOGP Report 456 provides an equivalent framework for oil and gas [82] and CCPS publishes leading and lagging metrics [83]. The debate on process safety indicators that followed the Texas City accident [84–87] and later work on organizational risk indicators [88], the use of indicator information [89], instantaneous measurement of plant safety [90], barrier-status indicators [91] and leading indicators for oil storage and pipelines [92] show both the promise and the difficulty of measuring process safety. Upstream event data compiled by

IOGP have been analysed to identify learning opportunities [34–36, 93].

2.3. Safety Culture, Leadership and Climate

PSM operates within an organizational culture. Reviews of safety culture [94, 95], safety climate [96] and HSE culture in the petroleum industry [97, 98], maturity models [99–101], including an organizational learning-based maturity model for continuous safety performance improvement [102], and their critique show the breadth of the field. Studies in petrochemical and oil and gas settings have examined culture factors and risk perception [103], cross-cultural organizational factors in refineries [104], perceived safety culture [105], culture assessment [106], resilience safety culture [107], safety climate and mindful practices [108], safety leadership and performance [109–111], leadership practices for compliance [112], safety management practices and behaviour [113] and the role of safety climate in implementing safety management systems [114]. The Texas City investigation and subsequent analyses identified cultural causes [13, 115], and process safety culture pathologies, including normalization of deviance, have been described [116]. Conceptual models have also linked leadership-driven safety culture transformation in large workforces [117], the frequency and coverage of management safety walkthroughs [118] and the institutionalization of life-preserving safety practices across project-based organizations [119] to safety culture outcomes.

2.4. Management of Change

The CCPS guidelines define the scope of MOC, the types of change it should cover and the steps of review, authorization, implementation and closeout [10]. Practitioner studies discuss how to manage MOC [37], why it is sometimes neglected [120], what a good system looks like [21], how to ensure that MOC action items are correctly scoped [39], how to benchmark MOC practices across the process industries [121] and how to implement effective MOC in upstream oil and gas [122]. Quality implementation of MOC and its relation to performance [40], methods for auditing MOC programmes in oil and gas [38] and lessons from incidents and audits [20] have been reported. Process modelling has been used to analyse the business flow of MOC across the plant life cycle [123], to support logical PSM [124], to identify the information required for risk assessment in MOC [125] and to support MOC with HAZOP logs [126]. Case histories of process safety failures include many involving change [127, 128].

Organizational change is a particularly difficult category. Kletz argued that changes in organization, staffing and responsibilities can be as hazardous as changes in equipment [129], and studies have assessed process operation staffing arrangements [130] and the impacts of mergers, downsizing and reorganization on PSM [131]. Creeping changes, which accumulate gradually without triggering MOC, have been analysed by Goff and colleagues [30, 31, 132], and atypical accident scenarios can emerge from changes to process conditions [133]. Accidents in which change management failed include the Shell Moerdijk explosions [134], the BP Grangemouth incidents [135], the Buncefield depot explosion [136] and the Williams Geismar reboiler rupture, in which an isolated standby reboiler was overpressured [16, 137].

2.5. Organizational Change, Staffing and Psychosocial Factors

Research in the Norwegian petroleum sector and elsewhere has examined how restructuring and downsizing affect safety. Studies show ways to identify and manage psychosocial risks during restructuring [26], the moderating role of change process healthiness [27], links between psychosocial risks and hydrocarbon leaks [28, 138], action errors and violations on offshore rigs [139], safety climate on the Norwegian continental shelf [140, 141] and safety, reliability and worker satisfaction during change [142]. Broader reviews address the causes and effects of downsizing [143], restructuring and employee well-being [144], organizational change and mental health [145], downsizing and work conditions [146], responses to external shocks [147], job insecurity and safety outcomes [148], and work intensification and organizational safety performance [149]. Outsourcing in mature fields increases reliance on contractors, and governance-oriented models of contractor safety performance in multi-contract projects [150, 151] address the interfaces that restructuring creates. Fatigue [152], heat stress in extreme operating environments [153] and stress and situation awareness in drilling crews [154] complete the picture. Human factors contributions to offshore accidents have long been recognized [155].

2.6. Drift, Normalization of Deviance and Organizational Accidents

Rasmussen's model of migration towards the boundary of acceptable performance under pressures of efficiency and workload [32] has been formalized and extended [156, 157], and Dekker described drift into failure as an emergent property of complex systems [158, 159]. Vaughan's analysis of the Challenger launch decision introduced the normalization of deviance [160], and related analyses of Challenger and Columbia [161–163], repeated failures in high-risk technologies [164], learning failures as root causes [165] and disaster dynamics [166, 167] show how organizations accept growing risk. Normalization of deviance has been studied in oil and gas, including the role of rig leadership [168] and the Ocean Ranger [169], in process safety [170–172], construction [173], healthcare [174, 175], and nuclear power [176], and a conceptual framework has described the mechanisms through which unsafe behaviours recur in high-hazard worksites [177]. Models of production versus protection [178], frameworks for balancing productivity and safety compliance in high-risk drilling [179], drift and adjustment in rule compliance [180, 181], and high-reliability organizing [182] provide complementary perspectives.

Organizational accident models provide the theoretical basis for treating MOC failures as latent conditions. Reason's distinction between active failures and latent conditions [48, 183, 184] and his account of organizational accidents [47] underpin the stock of latent conditions in the model. Systems approaches include STAMP [185, 186], applied to well control [187], pipelines [188, 189], process industries [190, 191], maritime incidents [192] and other domains [193], and reviewed [194, 195]; the functional resonance analysis method (FRAM) [196], reviewed and extended [197–199], and applied [200–203]; and AcciMap [204, 205], applied to building collapses [206], low-income settings [207] and near misses [208]. Comparisons of

systemic methods [209–213], their use in practice [214–216], the organizational ceiling of investigations [217, 218], anti-dualist models [219], hybrid Reason-based approaches [220], accident causation reviews [221–223], loss of responsibility [224], rail safety management [225], mine safety [226] and the complexity of failure [227] complete the landscape. Root cause and accident investigation methods have been compared [228, 229], root-cause and thematic analysis for major incident management has been reviewed [230], the effect of accident models on investigations examined [231, 232], and the challenges of investigation data identified [233]; the systemic analysis of the 2015 Aliso Canyon gas leak [234] illustrates their application.

2.7. Learning from Incidents and Near Misses

Learning from incidents is the mechanism by which latent conditions are revealed and removed. Studies have examined how organizations learn from incidents [235, 236], efficient learning [237], methods to assess the effectiveness of the learning cycle [238], critical steps and propensity to learn [239, 240], experience feedback [241], organizational learning in high-hazard industries [242], multilevel learning [243], practical applications [244], systemic constraints [245], maturity of investigations [246], lessons from accidents [247, 248], the dilemma between learning and liability [249], learning from normal accidents to high reliability [250] and situation awareness and organizational learning [251]. Kletz's work on learning from accidents remains influential [128], and reflections on Piper Alpha [252] and Texas City [253] ask what has really been learned.

Near-miss management extends learning to events without consequences. Near-miss reporting as a safety tool [254, 255], near-miss management in the chemical process industry [256], its effectiveness [257], industry-wide reviews [258, 259], workers' near-miss experiences and reports [260, 261], game-theoretic analysis [262], the utilization of near-miss and hazard observation data [263], proactive hazard recognition and reporting systems [264], weak signals [265], unsafe acts and conditions [266], near misses from Seveso inspections [267] and accident surveys in downstream oil [268] show both the potential and the limits of near-miss systems. Incident data analysis using natural language processing and Bayesian networks [269], taxonomies of oil and gas process safety events [270], analyses of incident investigation data across industries and in U.S. chemical plants [271, 272] and analyses of operational events [273] provide evidence on contributing factors. Accident analyses in China [274–279], domino accidents [280], vapour cloud explosions [281], West Fertilizer [282] and drill crew situation awareness [283] add further lessons.

2.8. Quantitative Models of Safety Management

Quantitative methods for modelling organizational factors include fuzzy Bayesian networks [284], uncertainty handling in fault trees [285], dynamic Bayesian safety assessment of gas stations [286], dynamic risk assessment of the Texas City accident [287] and of process faults [288], fuzzy HAZOP of gas wellheads [289], expert judgement [290] and realistic frequency assumptions in QRA [291]. Barrier management in offshore oil and gas [292, 293], barrier diagrams [294], state-of-the-art reviews [295], mechanical integrity and barrier alarms [296] and operational safety economics [297] link organizational factors to technical barriers. Human reliability analysis methods such as SPAR-H [298–301], HEART [302], CREAM [303], NARA [304] and their reviews [305–308], together with skills-rules-knowledge [309], human barriers [310], performance shaping factor dependence [311], refinery-specific methods [312], offshore causal models [313, 314], integration with process hazard analysis [315], maintenance optimization [316] and conceptual frameworks of human error causation in high-risk construction and industrial activities [317], address the human contribution. Conceptual models of data-driven occupational safety risk control in large energy projects [318] and risk pathway models for lifting, rigging and crane installation [319, 320] show how hazards, controls and organizational factors can be linked in a structured way for specific high-risk activities.

System dynamics, which represents feedback, accumulation and delay [321], has been applied to the Westray mine disaster [322], traffic safety policy [323], construction safety culture and attitudes [42, 43], production pressure in construction [324], behavioural safety in chemical plants [44], the Bhopal safety management system [41] and near-miss reporting in complex systems [45]. These studies show that stock-and-flow models can capture the accumulation of latent hazards and the feedback between workload and safety performance that static models miss.

2.9. Mature-Field Operations and Research Gap

Late-life operations raise specific issues: the ageing of onshore fields [22], life extension of production facilities [23], asset management guidelines [24], decommissioning safety [325, 326], risk from maintenance and modification work on major process equipment [327], incident prevention in maintenance engineering [328], integrity management of ageing fired heaters, boilers and furnaces in upstream service [329], operational discipline and conduct of operations [330, 331], shift handover [332–335] and knowledge retention with an ageing workforce [29]. The literature has therefore established that MOC failures contribute to major accidents, that organizational change and workload affect safety, that latent conditions accumulate and that learning removes them. What it lacks is a quantitative model that connects these mechanisms in the setting of mature production operations, evaluates interventions jointly and compares leading and lagging indicators of MOC deterioration [41, 45, 156]. The model presented next is designed to fill that gap.

3. Methods

This section describes the model structure, the representative operation and its parameters, the interventions evaluated, the global sensitivity analysis and the indicator detection experiment. The model is a stock-and-flow system dynamics model in the tradition of Sterman [321], in which the stock is the number of latent conditions present in the facility, following Reason's concept of latent conditions that lie dormant until combined with triggering events [47, 48]. Its inflows are the hazards introduced by changes that escape the MOC process, and its outflows are removal of latent conditions by detection and the release of process safety events. Similar structures have been used to model safety management systems and drift [41, 44, 156]. All parameter values are representative values chosen from ranges reported in the literature cited; they are not data from a specific operation, and the results demonstrate the behaviour of the model rather than estimate outcomes for any facility.

3.1. Model Structure

Figure 1 shows the model structure. Changes arrive in five categories: technical permanent changes, temporary changes, emergency changes, organizational changes and setpoint and software changes, following the scope of change recommended in MOC guidance [10, 129]. Each change has a probability of creating a latent hazard if it is implemented without effective review. A change is first captured by the MOC process with a probability that depends on its category; uncaptured changes, including creeping and unrecognized organizational changes, pass directly to the stock of latent conditions if hazardous [30, 131]. Captured changes are reviewed for hazards with an effectiveness that falls when reviewer load exceeds capacity, reflecting the effect of work intensification on safety performance [130, 149]. Hazards missed at review may be caught at pre-startup safety review (PSSR) and closeout. Captured temporary changes that remain in place beyond their expiry create further hazards [20, 21]. Latent conditions are removed by audits, near-miss reporting and investigation, process hazard analysis (PHA) revalidation and routine rectification during maintenance, or release a process safety event [5, 66, 256, 328]. Mature-operation pressures increase change volume and reduce reviewer staffing over time.

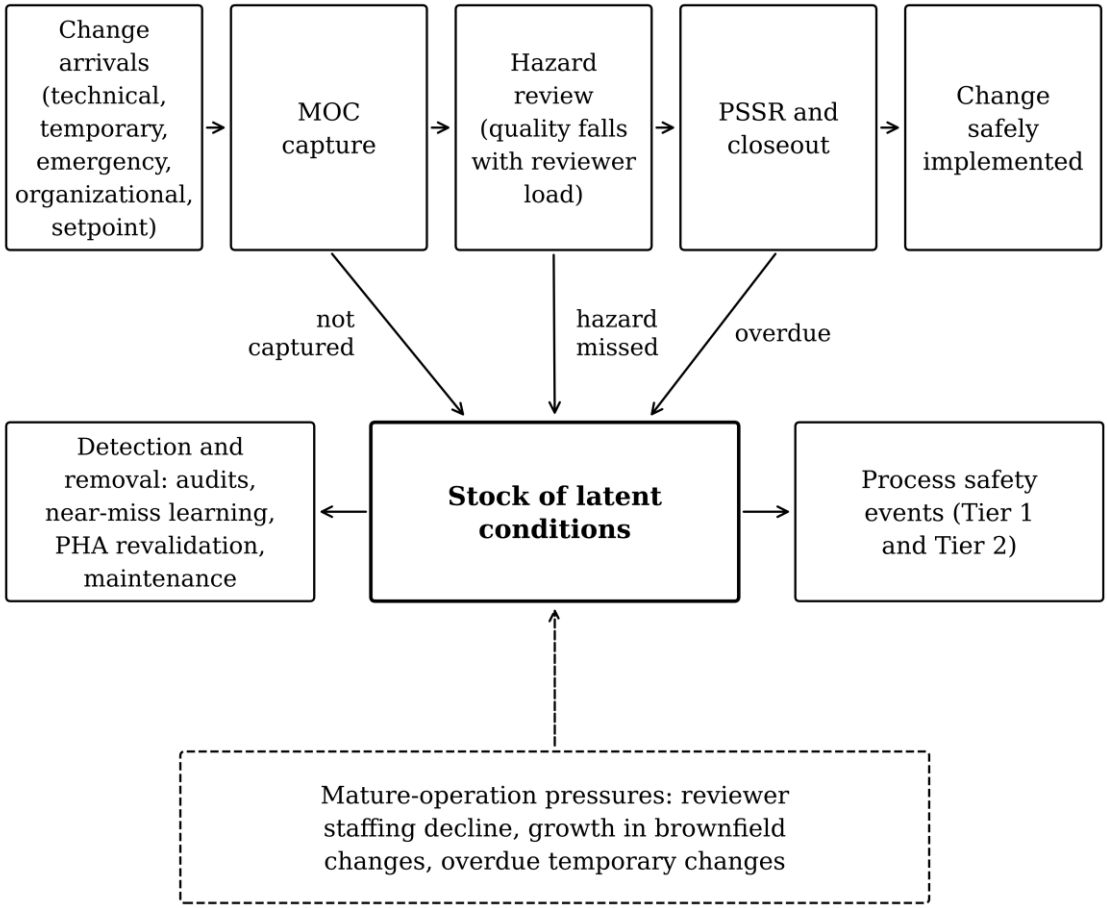


Fig 1: Stock-and-flow structure of the management of change and process safety model.

Change arrivals of category k in month t grow with brownfield activity, and reviewer staffing declines with cost reduction:

$$A_k(t) = A_{k,0}(1+g_A)^{t/12}, \qquad N_r(t) = N_{r,0}(1-d_r)^{t/12} \tag{1}$$

The reviewer load is the effort demanded by captured changes relative to reviewer capacity, and review effectiveness declines as a power of the overload [149, 324]:

$$L(t) = \frac{\sum_k A_k(t)\, q_k\, e_k}{N_r(t)\, c}, \qquad q_{\text{rev}}(t) = q_{\text{rev},0}\left[\min\left(1, \frac{1}{L(t)}\right)\right]^{\gamma} \tag{2}$$

where q_k is the capture probability, e_k the review effort per captured change in effort units, c the capacity per reviewer per month and γ the elasticity of review quality to overload. The probability that a hazardous change of category k escapes the MOC process is

$$m_k(t) = (1-q_k) + q_k[1-q_{\text{rev}}(t)]\left(1-q_{\text{pssr}}\right) \tag{3}$$

And New Latent Conditions Arrive at Rate

$$N(t) = \sum_k A_k(t)\, h_k\, m_k(t) + A_T(t)\, q_T\, o\, h_o \tag{4}$$

where h_k is the probability that a change is hazardous, q_{pssr} the PSSR detection probability, and the last term represents captured temporary changes left beyond expiry, with o the overdue fraction and h_o the probability that an overdue temporary change is hazardous. The stock of latent conditions X evolves as

$$X(t+1) = [X(t) + N(t) - r\,X(t)][1 - \pi(t)], \qquad r = \mu + \nu\,\rho_r\,\rho_i + \frac{a}{12} + m_r \tag{5}$$

where μ is the monthly probability that a latent condition releases a process safety event, ν the monthly near-miss rate per latent condition, ρ_r the reporting probability, ρ_i the probability that investigation identifies and removes the condition, a the annual fraction removed by audits and m_r the monthly fraction removed by routine maintenance. $\pi(t)$ is the fraction removed at five-yearly PHA revalidation, equal to the PHA detection probability multiplied by documentation accuracy in months 60 and 120 and zero otherwise, which reflects the dependence of PHA on accurate records of past changes [10, 124]. Expected process safety events are $I(t) = \mu X(t)$, of which a fraction ϕ are Tier 1 events in the API RP 754 classification and the remainder Tier 2 [81, 82]. The MOC effectiveness index is the fraction of hazardous changes that are neutralized:

$$E(t) = 1 - \frac{N(t)}{\sum_k A_k(t)\,h_k + A_T(t)\,q_T\,h_o} \tag{6}$$

The model starts from the steady state of the baseline parameters and runs monthly for ten years.

3.2. Representative Operation and Parameters

The representative operation is a mature onshore production asset with gathering, separation, compression, water handling and storage, operated by a team that includes three full-time equivalent MOC reviewers at the start of the horizon. Table 1 gives the change-type parameters and Table 2 the system parameters. Change volumes, about 230 per year at the start, are consistent with practitioner descriptions of MOC workload in operating facilities [20, 21, 122]. Capture probabilities are lowest for organizational changes, which are often not recognized as requiring MOC [120, 129, 131], and for setpoint and temporary changes [20, 38]. Review effectiveness at capacity of 0.80 and PSSR detection of 0.40 reflect evidence that MOC reviews miss a substantial share of hazards [19, 40]. The annual decline in reviewers of 4 percent and growth in changes of 3 percent represent cost pressure and brownfield activity in mature fields [22, 26]. Near-miss rates, reporting and investigation parameters reflect studies of near-miss management in the process industries [257, 259, 263, 268], and audit and PHA parameters reflect evidence on audit and revalidation effectiveness [66–68]. Costs of process safety events, USD 2.5 million for a Tier 1 event and USD 0.3 million for a Tier 2 event, include repair, lost production and response, consistent with analyses of operational safety economics [297].

Table 1: Change-type parameters.

Change type	Arrivals per month at start	Probability hazardous if unmanaged	Capture probability	Review effort per change
Technical permanent	10.0	0.20	0.92	1.0
Temporary	4.0	0.25	0.75	0.6
Emergency	1.5	0.35	0.70	0.8
Organizational	0.8	0.30	0.30	1.2
Setpoint and software	3.0	0.15	0.60	0.4

Table 2: System parameters of the baseline mature operation.

Parameter	Symbol	Value
Review effectiveness at or below capacity	$q_{\text{rev},0}$	0.80
Elasticity of review quality to overload	γ	0.8
PSSR and closeout detection	q_{pssr}	0.40
Reviewers at start, capacity per reviewer	$N_{r,0}$, c	3.0 FTE, 5 effort units per month
Annual decline in reviewers	d_r	4 percent
Annual growth in change arrivals	g_A	3 percent
Overdue temporary changes, probability hazardous	o, h_o	0.30, 0.30
Event release probability per latent condition	μ	0.006 per month
Near-miss rate, reporting, investigation removal	ν, ρ_r, ρ_i	0.06 per month, 0.40, 0.50
Annual audit removal fraction	a	0.10
PHA revalidation detection, documentation accuracy	p_{PHA}, D	0.40, 0.75
Routine maintenance removal	m_r	0.005 per month
Tier 1 share of events	ϕ	0.15
Cost of Tier 1 and Tier 2 events		USD 2.5 million, USD 0.3 million

3.3. Interventions

Four interventions were evaluated (Table 3), each grounded in recommendations from the literature. P1, a change capture programme, extends MOC coverage through training, clearer triggers and an MOC system that flags organizational, temporary and setpoint changes [123, 126, 129]; structured training models are a recognized means of operational risk reduction [79], and cross-functional education has been associated with fewer errors in the work of engineering teams [336]. P2 restores reviewer capacity by adding one reviewer, halting the decline in staffing and introducing risk-tiered triage, in which half of the changes are classified as low risk and receive a streamlined review requiring 30 percent of the standard effort [21, 39, 125]. P3 enforces expiry of temporary changes through tracking and escalation [20, 21]. P4 strengthens the detection of latent conditions through more effective

audits and improved near-miss reporting and investigation [66, 256, 257, 264]. Annual costs are representative estimates of staff time, systems and training. All sixteen combinations of the four interventions, including the baseline, were evaluated.

Table 3: Interventions evaluated.

Code	Intervention	Parameter changes	Annual cost (USD k)
P0	Baseline mature operation	None	0
P1	Change capture programme	Capture probabilities 0.97, 0.92, 0.90, 0.75, 0.85	150
P2	Reviewer capacity and risk-tiered triage	4.0 FTE, no decline, triage of low-risk changes	200
P3	Temporary change expiry enforcement	Overdue fraction 0.05	60
P4	Audit and near-miss learning	Audit removal 0.30, reporting 0.70, investigation 0.70	120

3.4. Global Sensitivity Analysis

To identify the parameters that most influence outcomes, eighteen parameters were varied simultaneously over the ranges in Table 4 using Latin hypercube sampling with 3,000 samples, and partial rank correlation coefficients (PRCC) between each parameter and the ten-year expected count of process safety events were computed [285, 290]. PRCC measures the monotonic association between a parameter and the output after removing the linear effects of the other parameters on ranks, and is widely used for global sensitivity analysis of system dynamics and risk models [285, 321]. Latin hypercube sampling ensures that each parameter range is covered evenly with far fewer samples than simple random sampling, and the ten-year expected event count was chosen as the output because it integrates both the inflow and the removal of latent conditions.

Table 4: Parameter ranges for the global sensitivity analysis.

Parameter	Range	Parameter	Range
Capture, technical	0.80 to 0.99	Overdue temporary changes	0.05 to 0.50
Capture, temporary	0.55 to 0.95	Event release probability	0.004 to 0.009 per month
Capture, emergency	0.50 to 0.95	Near-miss reporting	0.2 to 0.8
Capture, organizational	0.10 to 0.80	Investigation removal	0.3 to 0.8
Capture, setpoint	0.40 to 0.90	Audit removal	0.05 to 0.35 per year
Review effectiveness at capacity	0.60 to 0.95	PHA revalidation detection	0.2 to 0.6
PSSR detection	0.2 to 0.6	Documentation accuracy	0.50 to 0.95
Overload elasticity	0.4 to 1.2	Reviewers at start	2.0 to 4.5 FTE
Annual decline in reviewers	0 to 8 percent	Annual growth in changes	0 to 6 percent

3.5. Indicator Detection Experiment

The final analysis compares how quickly a deterioration in MOC review quality can be detected by a leading indicator and by a lagging indicator. In the experiment, review effectiveness drops from 0.80 to 0.60 at time zero, with change volume and staffing held constant. The leading indicator is a quarterly audit in which n completed MOC records are independently re-reviewed and scored as adequate or inadequate, consistent with MOC audit methods [38, 66]. A Beta(1,1) prior on review quality is updated with the cumulative results, and an alarm is raised when the posterior probability that quality is below 0.70 exceeds 0.90:

$$q \mid x_{1:j} \sim \text{Beta}\left(1 + \sum_{i \le j} x_i,\ 1 + \sum_{i \le j} (n - x_i)\right), \quad \text{alarm if } \Pr\left(q < 0.70 \mid x_{1:j}\right) > 0.90 \quad (7)$$

where x_i is the number of adequate records in quarter i. The lagging indicator is the cumulative count of Tier 1 and Tier 2 process safety events, with an alarm when it exceeds the 90th percentile of the Poisson distribution of the cumulative count expected without deterioration, in line with the use of event counts as lagging indicators [81, 89]. Each indicator was simulated 4,000 times over twelve quarters with deterioration, and its false alarm probability was estimated by simulating the same procedure without deterioration.

4. Results

This section reports the baseline dynamics of the mature operation, the effects of single interventions and portfolios, the global sensitivity analysis and the indicator detection experiment. Results are expected values over the ten-year horizon unless stated otherwise. Because the parameters are representative, the relative effects of interventions and the qualitative dynamics are more informative than the absolute numbers of events, in keeping with the use of system dynamics models for policy analysis rather than point prediction [41, 321, 322]. Where portfolios are compared, the same initial stock of latent conditions is used so that differences reflect the interventions alone, and costs are undiscounted totals over the decade.

4.1. Baseline Dynamics of the Mature Operation

Figure 2 and Table 5 show the baseline. Reviewer load rose from 0.86 of capacity at the start to 1.72 at year ten, crossing capacity after about two years. Once reviewers were overloaded, review effectiveness fell steadily from 0.80 to 0.52. The MOC effectiveness index, the share of hazardous changes neutralized, fell from 0.69 to 0.58, and new latent conditions rose from 19.2 per year in year one to 33.5 per year in year ten. The stock of latent conditions grew from about 44 to 54, and the expected rate of process safety events rose from 3.2 per year in year one to 5.3 per year in year ten. The PHA revalidations at years five and ten produced visible step reductions in the stock and the event rate, but the stock rebuilt within two years because the inflow continued to grow. Over ten years the baseline produced 39.3 expected events, of which 5.9 were Tier 1, with an expected loss of USD 24.8 million. A counterfactual without staffing decline or change growth produced 32.6 events, so the pressures of mature operation added 6.7 events, or 20 percent, over the decade. These dynamics reproduce in quantitative form the drift

towards the boundary of safe performance described by Rasmussen [32] and the incubation of hazards described by Turner and by Dekker [33, 158].

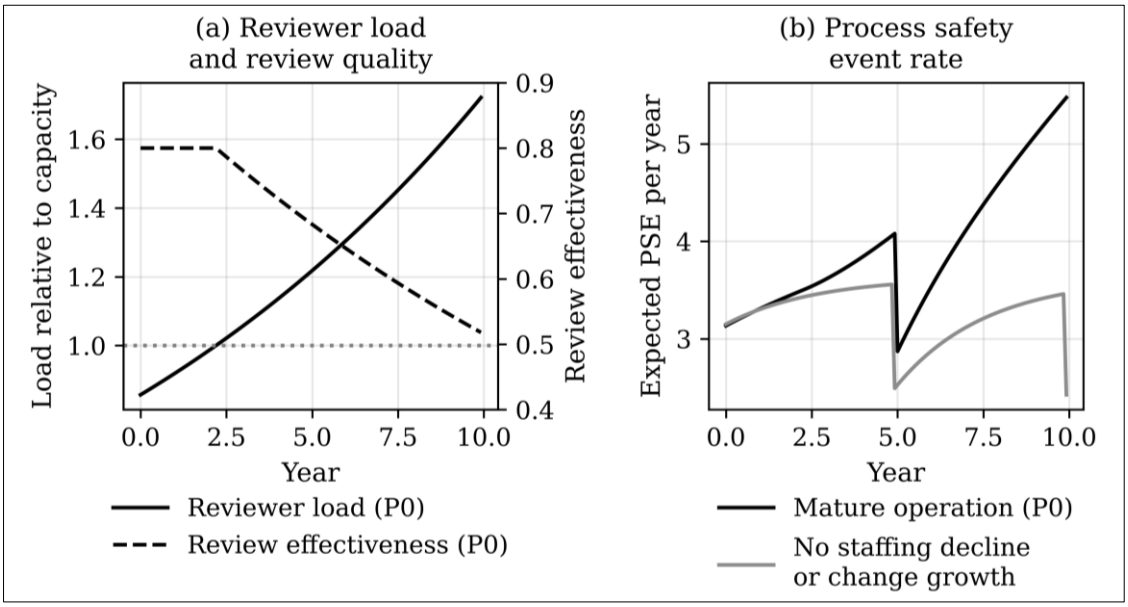


Fig 2: Baseline dynamics of the mature operation: (a) reviewer load and review effectiveness and (b) expected process safety event rate compared with a counterfactual without staffing decline or change growth.

Table 5: Baseline mature operation in year 1 and year 10.

Measure	Year 1	Year 10
Reviewer load relative to capacity	0.86	1.72
Review effectiveness	0.80	0.52
MOC effectiveness index	0.69	0.58
New latent conditions per year	19.2	33.5
Stock of latent conditions	44	54
Expected process safety events per year	3.2	5.3

Figure 3b shows the sources of latent conditions. In year one, temporary changes were the largest source, contributing 7.4 of 19.2 new latent conditions per year, followed by technical permanent changes with 4.6. By year ten, technical permanent changes had more than doubled to 10.8, because the growth in their volume combined with the collapse in review effectiveness, and temporary changes had risen to 11.6. Organizational changes contributed 2.2 latent conditions per year in year one despite their low volume, because most were not captured by MOC.

4.2. Single Interventions

Figure 3a and Table 6 compare the single interventions. Strengthening audits and near-miss learning (P4) was by far the most effective, reducing ten-year expected events from 39.3 to 22.9, a reduction of 16.4 events or 42 percent, for USD 1.2 million, a benefit-cost ratio of 8.6. It worked by draining the stock of latent conditions, which fell to 29 by year ten instead of rising to 54. The change capture programme (P1) averted 5.1 events, but its effect was limited by a mechanism that is easy to overlook: by routing more changes into MOC without adding reviewers, it raised reviewer load to 1.97 of capacity by year ten and reduced review effectiveness to 0.46, below the baseline. Reviewer capacity and triage (P2) kept load at 0.56 of capacity and review effectiveness at 0.84 throughout and averted 4.8 events, but at the highest cost. Temporary change expiry enforcement (P3) averted 4.0 events for only USD 0.6 million, a benefit-cost ratio of 4.2. The weak response to P1 mirrors the finding of studies of work intensification that adding demands without resources degrades the quality of safety-critical work [149, 337].

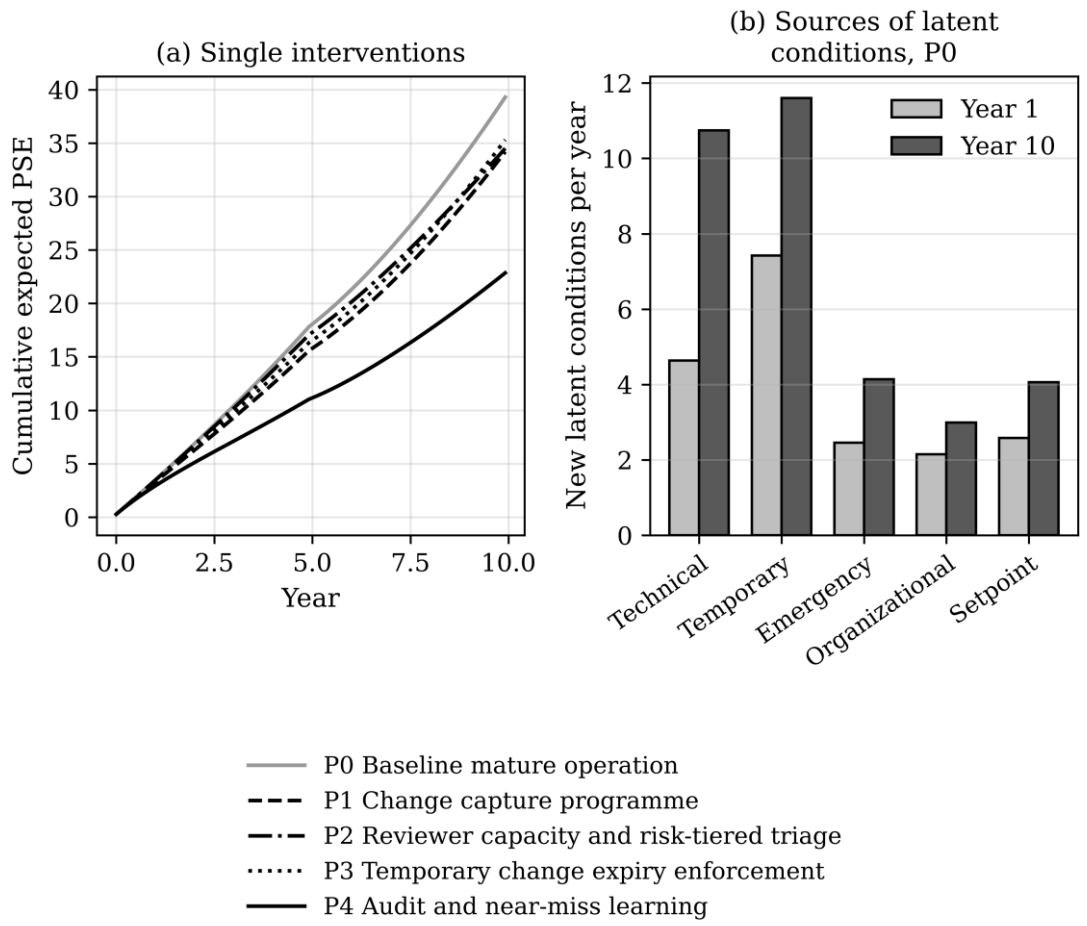


Fig 3: (a) Cumulative expected process safety events under single interventions and (b) sources of new latent conditions in year 1 and year 10 of the baseline.

4.3. Intervention Portfolios

Table 6 reports all sixteen portfolios and Figure 4 plots expected events averted against cost. Every portfolio had a benefit-cost ratio above 1, ranging from 1.5 for P2 alone to 8.6 for P4 alone. The cost-efficient frontier consists of P3, P4, P3 and P4, P1 and P4, P2 and P4, P1 with P3 and P4, P1 with P2 and P4, and all four. Every frontier portfolio from P4 onwards contains P4, confirming that removing latent conditions is the foundation of a cost-effective programme in a mature operation. The interaction between capture and capacity is strongly synergistic: P1 and P2 together averted 13.3 events, against 9.9 for the sum of their separate effects, because capacity allows the additional captured changes to be reviewed effectively. All four interventions together reduced ten-year expected events from 39.3 to 11.9, or 70 percent, and Tier 1 events from 5.9 to 1.8, for USD 5.3 million, averting USD 17.3 million of expected losses, a benefit-cost ratio of 3.3. The MOC effectiveness index under the full portfolio was 0.86 throughout the horizon. These results support the view that PSM elements interact and must be strengthened together [63, 64].

Table 6: Ten-year results of intervention portfolios.

Portfolio	Expected events	Tier 1 events	Expected loss (USD M)	Cost (USD M)	Events averted	Benefit-cost ratio
P0	39.3	5.9	24.8	0.0	0.0	
P1	34.2	5.1	21.5	1.5	5.1	2.1
P2	34.5	5.2	21.7	2.0	4.8	1.5
P3	35.3	5.3	22.2	0.6	4.0	4.2
P4	22.9	3.4	14.4	1.2	16.4	8.6
P1+P2	26.0	3.9	16.4	3.5	13.3	2.4
P1+P3	29.3	4.4	18.5	2.1	10.0	3.0
P1+P4	19.9	3.0	12.5	2.7	19.4	4.5
P2+P3	30.5	4.6	19.2	2.6	8.8	2.1
P2+P4	19.8	3.0	12.5	3.2	19.5	3.8
P3+P4	20.5	3.1	12.9	1.8	18.8	6.6
P1+P2+P3	21.1	3.2	13.3	4.1	18.2	2.8
P1+P2+P4	14.8	2.2	9.3	4.7	24.5	3.3
P1+P3+P4	17.0	2.6	10.7	3.3	22.3	4.3
P2+P3+P4	17.4	2.6	11.0	3.8	21.9	3.6
P1+P2+P3+P4	11.9	1.8	7.5	5.3	27.4	3.3

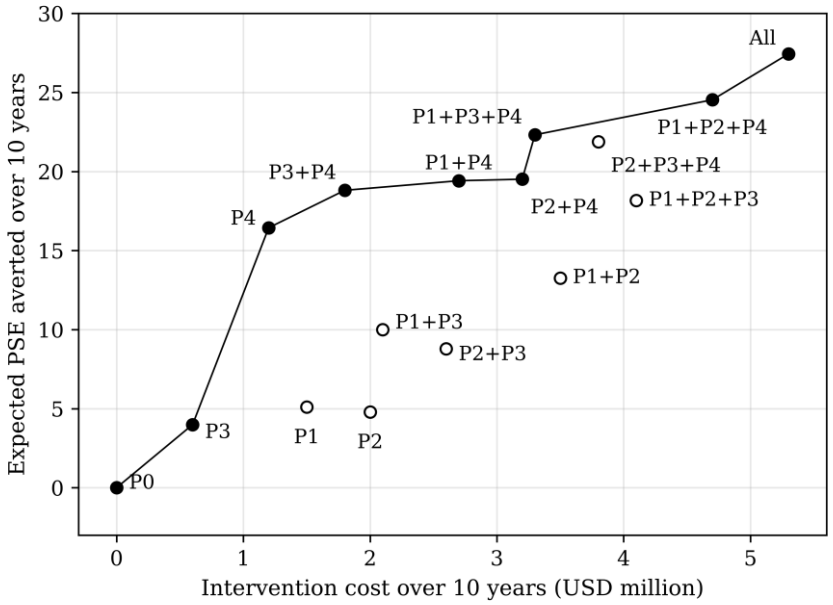


Fig 4: Expected process safety events averted over ten years against intervention cost for all sixteen portfolios; filled markers and the line show the cost-efficient frontier.

4.4. Global Sensitivity Analysis

Across the 3,000 Latin hypercube samples, the ten-year expected number of events had a mean of 33.2, with a 90 percent range from 17.2 to 55.2. Figure 5 shows the PRCC values. The event release probability per latent condition had the strongest positive association (0.91), as expected, since it scales the conversion of latent conditions into events. The strongest protective parameters were audit removal of latent conditions (-0.85), near-miss reporting (-0.78) and review effectiveness at capacity (-0.75), followed by investigation removal (-0.67), reviewer staffing (-0.62) and PSSR detection (-0.59). Growth in change volume (0.70) and the overdue fraction of temporary changes (0.62) were the strongest harmful parameters after the release probability. Capture probabilities had moderate associations, from -0.40 for technical changes to -0.22 for organizational changes, and PHA revalidation detection (-0.20) and documentation accuracy (-0.13) the weakest. The ranking is consistent with the portfolio results and indicates that, within the ranges studied, the detection and removal of latent conditions and the quality of hazard review matter more than incremental improvements in capture [40, 89, 257].

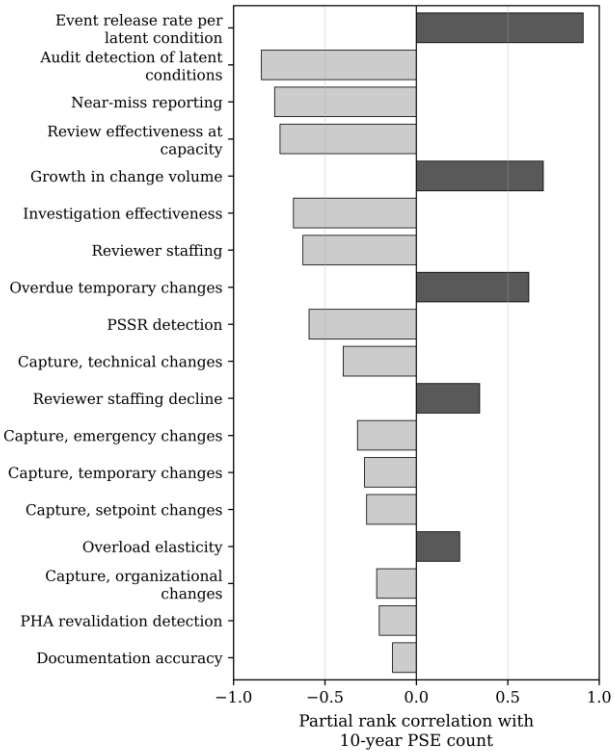


Fig 5: Partial rank correlation coefficients between model parameters and the ten-year expected number of process safety events.

4.5. Leading and Lagging Indicators

Table 7 and Figure 6 report the detection experiment. A quarterly audit of 20 MOC records detected the fall in review quality from 0.80 to 0.60 within four quarters with probability 0.80 and within eight quarters with probability 0.95, with a false alarm probability over twelve quarters of 0.02. With 40 records per quarter, detection within four quarters rose to 0.94; with 5 records it fell to 0.58 and false alarms rose to 0.09. The lagging indicator performed poorly: because latent conditions accumulate gradually, the expected event rate rose from about 0.80 to only about 1.0 per quarter over three years, and the cumulative event count detected the deterioration within twelve quarters with probability 0.28, while raising false alarms with probability 0.23. This quantifies the argument that lagging process safety event counts are too sparse and too delayed to monitor the health of PSM elements, and that leading indicators based on the quality of element execution are needed [84, 90, 92].

Table 7: Probability of detecting a fall in MOC review quality from 0.80 to 0.60.

Indicator	Within 4 quarters	Within 8 quarters	False alarm within 12 quarters
Audit, 5 records per quarter	0.58	0.73	0.09
Audit, 10 records per quarter	0.68	0.84	0.03
Audit, 20 records per quarter	0.80	0.95	0.02
Audit, 40 records per quarter	0.94	1.00	0.00
Cumulative process safety event count	0.16	0.22	0.23

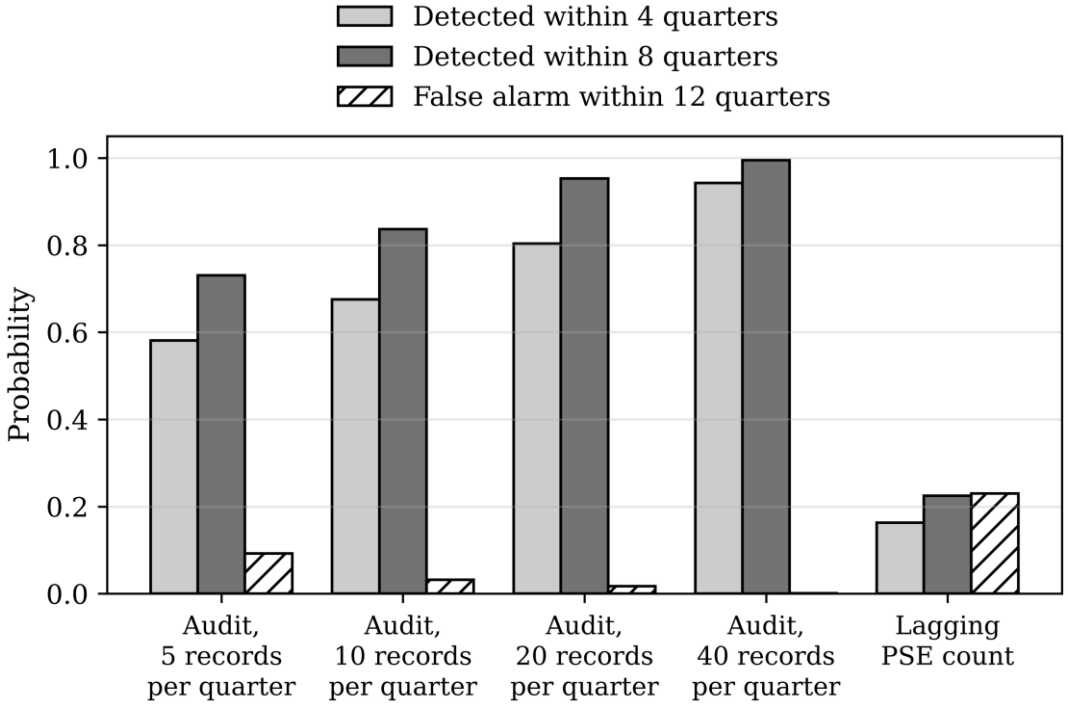


Fig 6: Probability of detecting a fall in MOC review quality and of false alarms for audit-based leading indicators and a lagging event count.

5. Discussion

This section interprets the findings in relation to the literature, draws implications for operators and regulators of mature production operations, considers how the model could be calibrated and used in practice, and sets out its limitations. The discussion is framed by the organizational accident perspective, in which serious events result from latent conditions created by decisions and processes remote from the point of failure [47, 48, 184], and by the systems view that safety emerges from the control of interactions across organizational levels [32, 185, 186]. It also takes account of evidence that organizations frequently fail to act on early warnings [70, 72, 165].

5.1. Principal Findings

Three findings stand out. First, in a mature operation in which changes grow and reviewers decline, MOC effectiveness erodes gradually and the stock of latent conditions builds, so that the event rate rises by about two thirds over a decade even though no single decision appears to weaken the MOC system. This is the quantitative signature of drift into failure [156, 158, 159] and of the normalization of deviance, in which progressively degraded practice comes to be accepted [116, 160, 177]. Studies of restructuring and downsizing in the petroleum industry report associations between organizational change and safety outcomes [26–28], and the model provides a mechanism, reviewer overload, through which such associations can arise.

Second, the most cost-effective intervention in the model is not at the front of the MOC process but at its back: strengthening audits, near-miss reporting and investigation so that latent conditions are found and removed. This reflects the stock-and-flow structure: in a mature operation, a large stock of latent conditions has already accumulated from past changes, and front-end improvements only reduce the rate at which it grows. It is consistent with the emphasis that the learning-from-incidents literature places on the learning cycle [237–239] and with evidence on the effectiveness of near-miss management systems [256, 257, 259]. It also implies that audits should be designed to find latent conditions in the field,

not only to verify paperwork, a distinction emphasized in critiques of auditing [66, 68, 69].

Third, front-end improvements interact. Capturing more changes without adding review capacity worsens review quality and partly defeats its purpose, whereas capture and capacity together are synergistic. This result illustrates why PSM elements must be considered as a system [5, 63] and why risk-tiered triage, which concentrates scarce review effort on the changes that matter most, is valuable [21, 39]. It also cautions against responding to an MOC audit finding of poor coverage simply by widening the scope of MOC without considering the effect on reviewers.

5.2. Implications for Operators and Regulators

For operators of mature production assets, the results suggest a sequence of actions. The first is to treat reviewer capacity as a process safety resource, monitoring MOC backlog, review time and reviewer load as leading indicators, and to examine the effect of any staffing reduction on MOC through the organizational MOC process itself [129–131]. The second is to strengthen the detection of latent conditions through field-verified audits, management safety walkthroughs with adequate frequency and coverage [118], improved near-miss reporting and investigations that look beyond immediate causes, using systemic methods and root-cause and thematic analysis where appropriate [209, 211, 228, 230]. The third is to enforce the expiry of temporary changes, which is cheap and has a high benefit-cost ratio, and which addresses one of the most common MOC weaknesses found in audits [20, 21]. The fourth is to extend MOC capture to organizational and setpoint changes, but only together with triage or additional capacity. Operational discipline and conduct of operations provide the cultural foundation for these measures [330, 331], and attention to shift handover and knowledge retention addresses the specific vulnerabilities of an ageing workforce [29, 332, 335].

For regulators and industry bodies, the detection experiment supports a shift in emphasis from lagging event counts to leading indicators of element execution. API RP 754 and IOGP Report 456 already define Tier 3 and Tier 4 indicators [81, 82], and the results show that a modest audit sample of 20 MOC records per quarter can detect a material fall in review quality within a year with high probability, whereas event counts would take years and give frequent false alarms. Regulatory inspection that samples MOC records for quality, rather than checking only that procedures exist, would exploit this sensitivity [52, 53, 267]. Industry event data sharing remains valuable for identifying common causes [34, 93, 271], but it cannot substitute for site-level monitoring of PSM element health.

5.3. Calibration and Use in Practice

The model is intended as a decision-support tool that can be calibrated to a specific operation. Change volumes and categories can be obtained from MOC system records, capture probabilities from audits that compare field changes with MOC records, review effectiveness from independent re-review of samples [38, 40], near-miss rates and reporting from incident databases [261, 263] and release probabilities from incident investigations that trace events to latent conditions [269, 271, 272]. Bayesian networks and fuzzy methods can be used to combine sparse data with expert judgement [284, 290], and dynamic risk assessment can update estimates as new data arrive [286–288]. Barrier management frameworks provide a structure for linking latent conditions to specific barriers [292, 293, 295], and human reliability methods can refine the treatment of review and PSSR performance [298, 302, 303]. Operational safety economics provides the basis for valuing interventions [297].

The model can be extended in several directions. Safety culture and leadership could be represented as slowly varying stocks that influence capture, reporting and review quality, as in system dynamics models of construction safety culture [42, 43]. Production pressure could be linked to deferral of audits and investigations, as in models of production versus protection and of the balance between productivity and safety compliance [178, 179, 324]. Accident models such as STAMP, FRAM and AcciMap could inform the structure of the model for specific facilities [194, 197, 205]. Human reliability analysis could be used to estimate the effect of fatigue and workload on reviewers [152, 154, 300].

5.4. Limitations

The study has several limitations. All parameters are representative values chosen from the literature rather than data from a specific operation, so the absolute numbers of events and the benefit-cost ratios should not be transferred without calibration [291, 321]. The model treats latent conditions as homogeneous, whereas in practice they differ greatly in severity, and a single release probability and Tier 1 share were applied to all. The intervention costs are representative estimates. The model omits feedback from events to organizational behaviour, such as the temporary improvement in vigilance that often follows a serious incident [247, 249], and from culture to all parameters [94, 95]. The detection experiment considered a single, step deterioration in review quality, whereas real deterioration is often gradual and multidimensional. Finally, the model is deterministic in its expected values; event counts were treated as Poisson only in the detection experiment, and parameter uncertainty was addressed through the global sensitivity analysis rather than full probabilistic simulation [285, 290].

6. Conclusion

This study developed a system dynamics model of management of change and process safety management effectiveness in mature oil and gas production operations. Changes flow through capture, hazard review and pre-startup safety review; hazards that escape accumulate as latent conditions until they are removed by audits, near-miss learning, process hazard analysis revalidation and maintenance, or release process safety events.

In a representative mature operation with declining reviewer staffing and growing change volume, reviewer load doubled over ten years, review effectiveness fell from 0.80 to 0.52 and the expected rate of process safety events rose from about three to more than five per year, with the pressures of mature operation adding a fifth to the events expected over the decade. Strengthening audits and near-miss learning was the most cost-effective single intervention. Extending change capture without adding review capacity was undermined by reviewer overload, while capture and capacity together were strongly synergistic. A portfolio of all four interventions reduced expected events by 70 percent with a benefit-cost ratio of 3.3. A quarterly audit of MOC record quality detected a fall in review quality far sooner and more reliably than process safety event counts.

For mature operations, the results support treating reviewer capacity as a process safety resource, prioritizing the detection and removal of latent conditions, enforcing the expiry of temporary changes and monitoring MOC through audits of execution quality. Further work should calibrate the model with MOC, audit and incident data from operating facilities, represent the heterogeneity of latent conditions and add feedback from culture, leadership and events.

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