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A Process Safety Framework for Reducing Operational Hazards During Facility Modifications, Equipment Replacement, and Commissioning

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Abstract

A disproportionate share of process safety incidents occurs during non-routine work: modifications, equipment replacement, tie-ins, start-up and commissioning. This study develops a quantified process safety framework for such work and applies it to a representative 28-activity brownfield project that replaces a separator, hot-taps a new compressor into a live header and upgrades a safety instrumented system. Each activity's hazard rate is combined with the failure probabilities of its barriers. These probabilities rise with the number of simultaneous high-risk tasks and with proximity to live plant. Five framework elements were evaluated alone and in all 32 combinations: isolation management, risk-based permit to work, enhanced pre-startup review, safety instrumented system bypass management with start-up alarm rationalization, and contractor competence assurance. Inputs are representative literature values, not project data. Commissioning and start-up carried 61 percent of baseline risk, and start-up with bypassed protection alone carried 51 percent. Bypass management with alarm rationalization cut fatality-equivalent risk by 58 percent at a net saving. Four low-cost elements together cut it by 78 percent at roughly zero net cost after avoided incident costs. Adding all five reached 80 percent and reduced peak daily risk by 92 percent. Risk-aware scheduling added only 2 to 4 percent at the assumed concurrency effect, but 24 percent when that effect was quadrupled. Bypass management ranked first in 93 percent of uncertainty samples.

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1. Introduction

Process plants are most dangerous when they are changing. Analyses of incident databases show that a large share of process safety incidents occurs during maintenance, modification, shutdown and start-up rather than during steady operation ^[1-3]. The United States Chemical Safety and Hazard Investigation Board has devoted a safety digest to incidents during start-ups and shutdowns ^[2], the Environmental Protection Agency has issued an enforcement alert on the risk of chemical accidents during process start-up ^[4] and the Center for Chemical Process Safety has published guidelines for process safety during transient operating modes ^[3]. Studies of maintenance-related major accidents in the 21st century ^[5], maintenance as a source of major accidents in petroleum process plants ^[6] and the root causes of hydrocarbon leaks on offshore installations ^[7] show that work on equipment is a recurring trigger of loss of containment. The Piper Alpha disaster of 6 July 1988, in which a pump was restarted

while its pressure safety valve had been removed under a permit that was not communicated across shifts, remains the defining example^[8].

The hazards of non-routine work arise from the combination of several conditions that are absent in steady operation. Isolations must be made and verified before equipment is opened^[9, 10]; permits to work must control hot work, line breaking, confined space entry and lifting near live plant^[11–13]; simultaneous operations (SIMOPS) place construction crews close to hydrocarbon systems^[14, 15]; new equipment must be checked by pre-startup safety review (PSSR) before hydrocarbons are introduced^[16, 17]; and safety instrumented systems (SIS) are often bypassed during commissioning and start-up and not always restored^[18, 19]. Alarm floods during start-up overwhelm operators at the moment when their response matters most^[20–22]. Investigations of the Formosa Plastics vinyl chloride explosion of 23 April 2004^[23], the Williams Geismar reboiler rupture of 13 June 2013^[24], the Esso Longford gas plant accident of 25 September 1998^[25] and the BP Texas City isomerization unit start-up of 23 March 2005^[26] illustrate how these conditions combine.

Guidance exists for each element of control, but the elements are rarely evaluated together in a quantified way that shows which ones matter most for a given project and how they interact with the schedule. Process hazard analysis methods such as HAZOP and layer of protection analysis (LOPA) are typically applied to the steady-state design^[27–29], and dynamic risk assessment methods have been developed mainly for operations rather than for projects^[30–32]. Studies of permit-to-work effectiveness^[33–35], lockout and tagout^[36–38], confined spaces^[39, 40], turnaround management^[41–43] and contractor safety^[44–47] each address part of the problem.

This paper develops and demonstrates a quantified process safety framework for modifications, equipment replacement and commissioning. It makes four contributions. First, it represents a brownfield project as a network of activities whose hazard rates and barrier failure probabilities depend on activity type, SIMOPS concurrency and proximity to live plant, producing a daily risk profile. Second, it evaluates five framework elements individually and in all combinations for risk reduction, cost and schedule effect. Third, it applies risk-aware scheduling to reduce concurrency of high-risk tasks. Fourth, it tests the robustness of the conclusions to parameter uncertainty. Section 2 reviews the literature, Section 3 describes the framework and model, Section 4 presents results, Section 5 discusses implications and Section 6 concludes.

2. Literature Review

This section reviews the evidence on incidents during non-routine operations, hazard identification and risk assessment methods, permit to work and isolation, SIMOPS and construction near live plant, start-up, commissioning and alarm management, safety instrumented systems during non-routine work, human and organizational factors in maintenance, dynamic risk and resilience, and turnaround planning. It draws on accounts of why major accidents continue to occur^[48, 49] and on the history of process safety^[50], which emphasize that the lessons of past accidents are repeatedly forgotten^[51, 52]. It also reflects regulatory perspectives on human factors and major hazards^[53, 54], root-cause and thematic analysis of major incidents^[55], conceptual accounts of human error causation in high-risk construction

and industrial activities^[56] and trends in international process safety research^[57].

2.1. Incidents During Non-Routine Operations

Incident analyses consistently identify maintenance, start-up and shutdown as high-risk phases. The hazards of transient operations have been reviewed^[1], and incidents that define process safety include many in these phases^[58]. Analyses of maintenance management deficiencies^[59], maintenance-induced accidents and piping problems^[60], maintenance safety management in the chemical industry^[61], ageing assets at Dutch major hazard sites^[62], accidents triggered by electrical failures^[63], LPG loading and unloading^[64] and common causes of major losses in onshore oil, gas and chemical facilities^[65] add detail. Statistical analyses of incident databases in Greece^[66, 67], France^[68], South Korea^[69, 70], China^[71–78], Sri Lanka^[79], the fuel ethanol industry^[80], chemical plants and transport^[81] and wastewater facilities^[82, 83] reveal recurring contributors, including equipment failures^[84, 85], process safety management element failures^[86], corrective actions^[87], hierarchy of controls in CSB reports^[88] and key issues in accident reports^[89]. Data mining and text analysis of incident databases^[90–94], failure knowledge databases^[95], reactive chemistry incidents^[96], shutdowns and management of change^[97–99], accident precursors^[100], relationships between major hazard and occupational accidents^[101], accident frequency prediction^[102], occupational risks in maintenance^[103], ergonomics in petrochemical maintenance^[104], the Tianjin Port explosion^[105], the Dalian tank farm fire^[106], the Buncefield explosion^[107], the Deepwater Horizon blowout^[108], comparisons of major industrial disasters^[109], management and technical factors^[110], learning from major accidents for design^[111] and design life cycle accident prevention^[112] complete the picture. Hot work remains a leading cause of fatalities in and around tanks^[113, 114], and mechanical sparks are an ignition source^[115]. Near-miss and hazard observation data can reveal these contributors before they produce an accident^[116], provided that proactive hazard recognition and reporting systems are in place to capture them^[117].

2.2. Hazard Identification and Risk Assessment

HAZOP is the principal hazard identification method in process plants^[29], and research has sought to improve it^[27], automate it^[118–122], combine it with dynamic simulation^[123, 124], apply it to oil production units^[125], fuel terminals^[126], health, safety and environment engineering^[127], multi-criteria decision making^[128], reactors^[129, 130], and FMEDA integration^[131]. LOPA determines whether protection layers are sufficient^[28, 132–134], often combined with HAZOP and SIL determination^[135]. Bow-tie methods^[136–138], baseline risk assessment tools^[139], semi-quantitative prioritization^[140], generic leak frequencies^[141], risk assessment of aromatic units^[142], risk assessment of construction during operation^[143] and power plant construction risk^[144] extend the toolkit. Risk-based process engineering frameworks have been proposed to strengthen reliability across natural gas infrastructure systems^[145], and hazard identification and risk control practices in construction projects have been reviewed systematically^[146]. Few of these methods are applied specifically to the sequence of activities in a modification project.

2.3. Permit to Work, Isolation and Confined Spaces

Permit-to-work systems are the main administrative barrier for non-routine work. Guidance from the UK Health and Safety Executive [11], reviews of permits in the process industries [12], offshore approaches [147, 148], transaction processing [149], effectiveness narratives [33], efficiency indicators [34], performance questionnaires [35], their contribution to accidents [13], lessons from incidents [150], safety management integration [151], human factors in control of work [152, 153] and digital transformation [154] have been studied. Isolation of hazardous energy through lockout and tagout is regulated [10] and has been studied in terms of fatal injuries [37], standard effects [155], situation awareness [36], alternative methods [156, 157], verification [158], self-audit tools [159, 160], written programmes [161], procedures [38], moving-parts accidents [162] and sawmills [163]. Confined space entry is regulated [164, 165] and has been studied for contributory factors [40, 166, 167], incident rates [168], rescue [169–171], comprehensive management [39, 172, 173], holistic approaches [174] and fatality surveillance [175]. Sharing awareness among maintenance crews [176] and the gap between safety documents and worker perception [177] show the limits of paperwork alone.

2.4. Simultaneous Operations, Construction Near Live Plant and Contractors

SIMOPS risk assessment has been developed for industrial sites [14], LNG bunkering [178], process plant expansions on operating sites [15] and construction activities during operation [143]. Contractors carry out much of the work in modifications and turnarounds, and their role in process safety [44], PSM for managing contractors [45], governance-oriented models of contractor safety performance in multi-contract projects [47], safety risk governance in multi-contractor projects [179], institutionalizing life-preserving safety practices across project-based organizations [180], interorganizational complexity [181] and European lessons on accidents involving contractors [46] have been examined. Risk pathway and risk management models have also been proposed for lifting and rigging in heavy industrial construction [182] and for heavy lifting and crane installation [183], operations that recur in equipment replacement. Organizational models integrating human factors and safety management [184–187], organizational and human factors in quantitative risk analysis [188], behavioural safety and major hazards [189], systems thinking and reliability culture [190], high reliability principles [191], organizational learning [192–194], management safety walkthroughs [195], near-miss archives [196], investigation guidelines [197], catastrophic incident warning signs [198] and internal audits [199, 200] provide the organizational context.

2.5. Start-Up, Commissioning and Alarm Management

Start-up concentrates hazards. Loss prevention at the start-up stage [17], PSSR performance and close-out [16], frameworks for managing transitions [201], and start-up procedures in novel plants [202] have been studied. Alarm management is critical during transitions, with surveys and reviews [203–205], lifecycle management [206], rationalization and suppression [207, 208], chatter quantification [209], dynamic strategies for transitions [21], chronicle-based management in start-up and shutdown [20], temporal pattern learning [210], diagnosis [211], superalarms [212], flood reduction [22], alarm database analysis [213, 214] and simulation of operator behaviour [215]. Operator

training simulators [216, 217], workforce safety training models [218], virtual reality [219, 220], performance indicators [221], situation awareness [222–224], operator efficiency [225], decision support including human factors [226] and the reasons control systems fail [227] bear on start-up performance.

2.6. Safety Instrumented Systems During Non-Routine Work

Functional safety standards IEC 61508 and IEC 61511 govern SIS design and management, including management of bypasses and modifications [228–230]. Reliability data [231], reliability models [232], loss of safety assessment [233], new protection layers [234], SIL determination and calculation [235], multiphase dynamic Bayesian networks [236], cascading failures [237], reachability-based architecture assessment [238], testing strategies for final elements [239, 240], degradation [241], condition-based activation [242], demand-caused failures [243], partial tests [244], demand rate and imperfect proof tests [245], Markov simplifications [246], requirements for operation and maintenance [19], proof testing as a key performance indicator [247], maintenance on safety systems under change management [248] and the prevalence of undetected bypasses [18] show that SIS integrity depends on how bypasses and tests are managed during non-routine work.

2.7. Human Factors in Maintenance and Modification

Human error in maintenance has been reviewed [249–251] and studied in power plants [252], petroleum facilities [253], factories [254] and safety-critical organizations [255]. Human reliability analysis methods have been mapped [256] and reviewed for application [257], linked to task analysis [258], extended with Bayesian networks [259], applied to maintenance [260] and construction critical controls [261], and supported by guidance on safety critical task analysis [262, 263], qualitative human reliability assessment [264] and human factors assessment techniques [265, 266]. HFACS and related models have been applied to chemical accidents [267–274], and systemic accident models such as STAMP and 24Model have been compared [275–277]. Conceptual models of incident prevention in industrial maintenance environments [278], the recurrence mechanisms of unsafe behaviours in high-hazard worksites [279] and behavioural safety programmes for large workforces [280] address the same problem from the organizational side. Activity theory [281], normal accidents in refineries [282] and Korean PSM experience [283] complete the picture.

2.8. Dynamic Risk, Resilience and Maintenance Planning

Dynamic risk management updates risk as conditions change [30, 31, 284, 285], using real-time analysis of safety systems [32], Bayesian updating [286], multistate Bayesian networks for barrier degradation [287], managed pressure drilling [288], dynamic economic risk [289], digital twins [290] and continuous hazard monitoring systems [291]. Risk-based maintenance has been applied to power plants [292], gas regulating stations [293, 294], offshore processing [295] and maintenance scheduling [296], and risk assessment in maintenance decisions has been reviewed [297], as have Bayesian networks for inspection and maintenance [298]. Resilience engineering [299–301] has been applied to process systems [302–309], loss of containment prediction [310], health and safety management [311], Natech accidents [312] and barrier management [313], and reliability engineering faces new challenges [314]. Turnaround maintenance has been studied for practices [41], integration [42], scheduling [43] and spare parts [315], and a computerized

maintenance management system (CMMS) concept has been proposed for optimizing preventive and corrective maintenance of static mechanical equipment ^[316]. Holistic control of process safety risks ^[317], global regulations ^[318], asset integrity ^[319], reliability and integrity management of fired heaters, boilers and furnaces in upstream oil and gas ^[320] and reliability-centred design of mechanical components using FEA and DFMEA ^[321] provide additional context.

2.9. Research Gap

The literature provides strong evidence that non-routine work concentrates risk and offers methods for each barrier, but it rarely quantifies the risk of a modification project activity by activity, evaluates combinations of controls against cost and schedule, or uses scheduling as a risk control ^[1, 14, 43]. Risk-based maintenance scheduling has been proposed for operating plants ^[295, 296], and SIMOPS assessments have been developed qualitatively ^[14], but the joint effect of barrier quality, concurrency and sequencing on the risk profile of a project has not been demonstrated. The framework presented next addresses this gap by combining an activity-level risk model with control elements whose effects can be compared on a common scale of risk, cost and schedule, and by treating the sequence of work itself as a control.

3. Framework and Methods

This section describes the framework, the representative project, the activity risk model, the framework elements, the economic evaluation, the risk-aware scheduling method and the uncertainty analysis. The risk model follows the logic of

LOPA and bow-tie analysis, in which the frequency of a consequence is the initiating event frequency multiplied by the probabilities of failure of independent protection layers ^[28, 133, 136], extended so that barrier failure probabilities depend on the conditions of each project day, in the spirit of dynamic risk assessment ^[30, 31, 287] and of data-driven occupational safety risk control in large energy infrastructure projects ^[322]. All parameter values are representative values chosen within ranges reported in the literature cited; they are not data from a specific project, and the results demonstrate the framework and the relative value of its elements rather than estimate the risk of any particular project.

3.1. Framework Structure

Figure 1 shows the framework. A modification project passes through six phases: preparation, removal, installation, tie-in, testing, and commissioning and start-up. Five control elements act across these phases: integrated isolation management with independent verification (E1), a risk-based permit to work with a SIMOPS matrix (E2), enhanced PSSR and commissioning readiness with helium leak testing (E3), SIS bypass management and start-up alarm rationalization (E4), and contractor competence assurance and supervision (E5). A quantification layer converts activity hazards and barrier performance into a daily risk profile, and a sixth element, risk-aware scheduling (E6), re-sequences work to reduce the concurrency of high-risk tasks. The elements correspond to recognized good practice for isolation ^[9, 10], permits ^[11, 12], start-up readiness ^[16, 17], SIS and alarm management ^[18, 207, 230] and contractor management ^[44, 45].

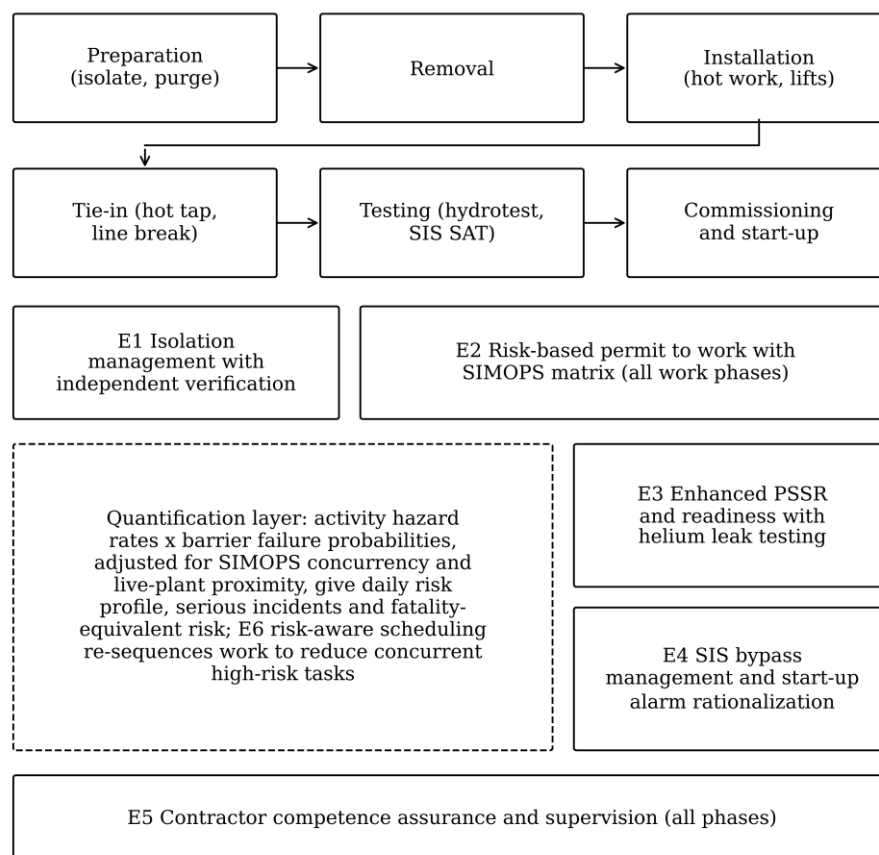


Fig 1: Process safety framework for modifications, equipment replacement and commissioning: project phases, control elements and quantification layer.

3.2. Representative Project

The project replaces a separator, installs a new compressor skid tied into a live gas header by a hot tap, and replaces the SIS cabinet, at an operating onshore facility. It comprises 28 activities in three areas: area A, the compressor area adjacent to live plant; area B, the separator area; and area C, the control room and equipment room (Table 1). Durations range from

one to six days and the earliest-start schedule takes 32 days. The activity types reflect the operations whose hazards are documented in the literature, including isolation and purging [9, 99], line breaking [60], hot work [113, 114], crane lifts near live equipment [15, 183], hot tapping [24], pressure testing, SIS testing [247], hydrocarbon introduction and start-up [2, 3].

Table 1: Activities of the representative brownfield project.

No.	Activity	Area	Type	Duration (d)	Predecessors
1	Isolation planning and permit set-up	C	admin	2	None
2	Isolate and depressurize separator	B	isolation	1	1
3	Purge and gas-free separator	B	purge	1	2
4	Isolate compressor tie-in header	A	isolation	1	1
5	Erect scaffolding, separator area	B	height	3	1
6	Erect scaffolding, compressor area	A	height	2	1
7	Disconnect separator piping	B	line_break	2	3, 5
8	Remove old separator by crane	B	lift	1	7
9	Cut out old piping	B	hot_work	3	7
10	Remove old control panels	C	electrical	2	1
11	Set new separator by crane	B	lift	1	8
12	Weld new separator piping	B	hot_work	6	9, 11
13	Set new compressor skid by crane	A	lift	1	6
14	Weld compressor piping near live plant	A	hot_work_live	6	13
15	Install new SIS cabinet and wiring	C	electrical	5	10
16	Install field instruments and cables	B	electrical	4	12, 14
17	Hot tap tie-in to live header	A	hot_tap	1	4, 14
18	Tie-in separator to process piping	B	line_break	2	12
19	Hydrotest separator piping	B	pressure_test	2	18
20	Hydrotest compressor piping	A	pressure_test	2	17
21	Leak test and reinstate flanges	A	line_break	2	19, 20
22	Loop checks and SIS site acceptance test	C	functional_test	4	15, 16
23	Pre-startup safety review	C	admin	2	21, 22
24	De-isolate and nitrogen purge	B	purge	1	23
25	Introduce hydrocarbons to separator	B	hc_intro	1	24
26	Start new compressor and ramp up	A	startup	2	25
27	Remove SIS bypasses and proof test	C	sis_proof	1	26
28	Handover to operations	C	admin	1	27

3.3. Activity Risk Model

For activity i of type k on day d , the frequency of a serious incident is the initiating event frequency multiplied by the failure probabilities of the barriers relevant to that type:

$$s_{i,d} = f_k \prod_{b \in B_k} p_b(\mathbf{E}, c_{i,d}, a_i) \quad (1)$$

where f_k is the initiating event frequency per activity-day, B_k is the set of barriers, and p_b is the probability of failure on demand of barrier b , which depends on the set of framework elements $\mathbf{E}$, the SIMOPS concurrency $c_{i,d}$ and the area a_i . For barriers whose effectiveness depends on the surrounding work, namely SIMOPS control, gas testing, fire watch and exclusion zones, the failure probability increases with concurrency and with proximity to live plant:

$$p_b = p_b^0 (1 + \kappa c_{i,d}) \gamma_{a_i} \quad (2)$$

where p_b^0 is the base failure probability, κ is the degradation per concurrent high-risk task (0.5, reduced to 0.2 by the SIMOPS matrix of E2), $c_{i,d}$ is the number of other high-risk tasks in the same area plus half of those in the adjacent work area, and γ_{a_i} is 1.5 in area A next to live plant and 1 elsewhere, reflecting the evidence that SIMOPS and work near live plant degrade barriers [14, 143]. Each serious incident has a fatality-equivalent consequence q_k , and the project risk is

$$S = \sum_i \sum_{d \in D_i} s_{i,d}, \quad \text{PLL} = \sum_i \sum_{d \in D_i} q_k s_{i,d} \quad (3)$$

where D_i is the set of days on which activity i is performed, S is the expected number of serious incidents and PLL is the potential loss of life in fatality equivalents. Table 2 lists the parameters. During start-up the SIS is assumed to be bypassed with probability 0.5 without bypass management, consistent with reports that bypasses frequently remain in place undetected [18, 19]; with E4 this falls to 0.05.

Table 2: Activity hazard parameters: initiating events per activity-day, barriers with base failure probabilities, and fatality equivalents per serious incident.

Activity type	Initiating events per day	Barriers and base failure probabilities	Fatality equivalent
Isolation	0.006	isolation verification 0.1; permit 0.1	0.10
Purging	0.006	gas test 0.05; permit 0.1	0.10
Line breaking	0.012	isolation integrity 0.05; gas test 0.05; permit 0.1	0.15
Hot work	0.020	gas test 0.05; SIMOPS control 0.1; fire watch 0.2	0.20
Hot work near live plant	0.030	gas test 0.05; SIMOPS control 0.2; fire watch 0.2	0.25
Crane lift	0.004	lift plan 0.1; exclusion zone 0.2	0.30
Work at height	0.004	fall protection 0.05	0.20
Electrical work	0.002	lockout 0.05	0.20
Hot tap	0.040	hot tap procedure 0.05; pressure monitoring 0.1	0.30
Pressure test	0.004	exclusion zone 0.1; test procedure 0.1	0.20
SIS functional test	0.004	bypass management 0.2	0.10
Hydrocarbon introduction	0.060	PSSR line-up check 0.3; leak test 0.3; operator response 0.3	0.25
Start-up	0.040	SIS active 0.5 (bypass unmanaged); operator response 0.2	0.30
SIS bypass removal and proof test	0.006	test procedure 0.1	0.10

3.4. Framework Elements

Table 3 defines the effect of each element on barrier failure probabilities and its cost per project. E1 reduces isolation verification and integrity failures by 70 percent and gas test failures by 50 percent, reflecting independent verification of isolations^[36, 38, 158]. E2 halves permit failures and reduces the SIMOPS degradation factor from 0.5 to 0.2 by prohibiting incompatible concurrent tasks^[11, 14, 34]. E3 reduces PSSR line-up failures by 60 percent and leak-test failures by 70 percent through structured readiness reviews and helium leak testing of new joints, at the cost of one day^[16, 17]. E4 reduces

the probability that the SIS is bypassed during start-up from 0.5 to 0.05, halves operator response failures during hydrocarbon introduction and start-up through alarm rationalization, and reduces bypass management failures during SIS testing by 70 percent^[18, 20, 207]. E5 reduces the failure probability of all barriers that depend on human performance by 30 percent through competence assurance and supervision^[44, 45, 47]. Costs are marginal per-project costs; schedule extension is valued at USD 0.15 million per day of deferred production, and avoided serious incidents at USD 20 million each, including repair, response and lost production.

Table 3: Framework elements, their effects in the model and their cost per project.

Element	Effect on barrier failure probabilities	Cost per project (USD M)	Schedule effect
E1 Isolation management with independent verification	Isolation verification and integrity x 0.3; gas test x 0.5	0.08	None
E2 Risk-based permit to work with SIMOPS matrix	Permit x 0.5; SIMOPS degradation factor 0.5 to 0.2	0.05	None
E3 Enhanced PSSR and readiness with helium leak testing	PSSR line-up x 0.4; leak test x 0.3	0.15	One day
E4 SIS bypass management and start-up alarm rationalization	SIS bypassed at start-up 0.5 to 0.05; operator response x 0.5; bypass management x 0.3	0.06	None
E5 Contractor competence assurance and supervision	Human-dependent barriers x 0.7	0.12	None

3.5. Risk-Aware Scheduling and Uncertainty Analysis

Risk-aware scheduling (E6) delays the start of activities beyond their earliest start, within their float and an allowed extension of the project, to reduce concurrency. The delays were optimized by simulated annealing over integer start-day offsets, minimizing PLL subject to the precedence constraints and a maximum project duration, a heuristic approach consistent with turnaround scheduling practice^[43, 296, 315]. Extensions of 0, 2 and 4 days were evaluated, and the value of scheduling was tested for SIMOPS degradation factors from 0.25 to 2.0. Parameter uncertainty was assessed by multiplying each initiating event frequency by an independent lognormal factor with an error factor of 3 and each barrier failure probability by a factor with an error factor of 2, and drawing 1,000 samples; for each sample the baseline and full-framework risks and the element giving the largest

single risk reduction were recorded^[286, 287, 289].

4. Results

This section reports the baseline risk profile and its sources, the effects of individual elements and their combinations, the effect of risk-aware scheduling and the robustness of the results to parameter uncertainty. Because the inputs are representative, the distribution of risk across phases and the ranking of elements are more informative than absolute values, consistent with the use of LOPA and bow-tie quantification for comparing options rather than predicting outcomes^[133, 136]. The baseline corresponds to execution of the earliest-start schedule with the base barrier probabilities in Table 2 and none of the framework elements. All comparisons use the same activity network and parameter values, so differences between cases reflect only the elements and schedules applied.

4.1. Baseline Risk Profile

The baseline project had an expected 0.020 serious incidents and a PLL of 4.68×10^{-3} fatality equivalents over 32 days. Figure 2 shows the daily risk profile. Risk was low during preparation and removal, rose during installation when hot work near live plant coincided with other high-risk tasks in area A, and peaked sharply during start-up on days 28 and 29, at 1.2×10^{-3} per day, about sixteen times the average daily risk of the installation phase. By phase, commissioning and start-up accounted for 61 percent of PLL, installation for 22 percent, testing for 8 percent, preparation for 5 percent,

removal for 3 percent and tie-in for 1 percent. Figure 3 shows the contributions by activity type: start-up with a 50 percent chance of bypassed SIS protection accounted for 51 percent of PLL, hot work near live plant for 16 percent, hydrocarbon introduction for 9 percent and SIS functional testing for 7 percent. Isolation, purging and line breaking, each protected by two or three barriers, contributed less than 1 percent together. This concentration in start-up reflects the CSB and EPA findings on start-up incidents ^[2, 4] and the Texas City experience ^[26].

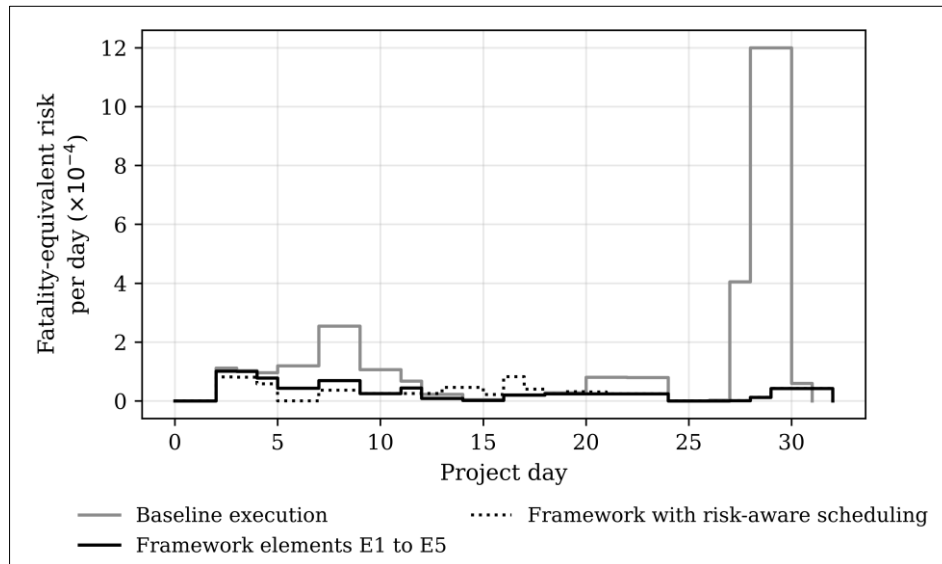


Fig 2: Daily fatality-equivalent risk over the project for baseline execution, the framework elements E1 to E5, and the framework with risk-aware scheduling.

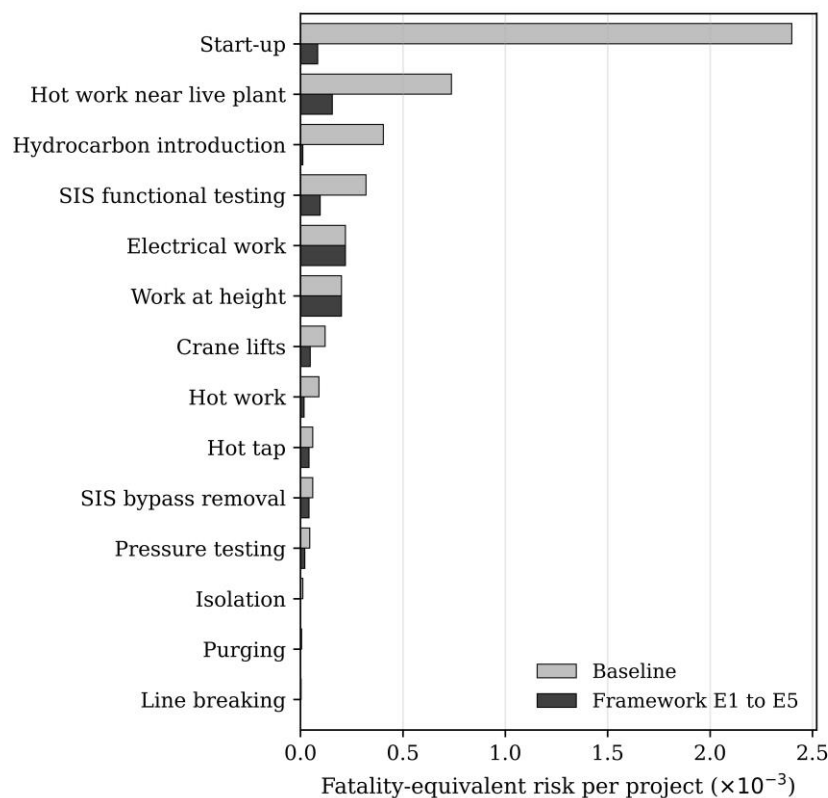


Fig 3: Fatality-equivalent risk per project by activity type for baseline execution and with framework elements E1 to E5.

4.2. Framework Elements and Combinations

Table 4 reports the effects of individual elements and selected combinations, and Figure 4 shows all 32 combinations. SIS bypass management with start-up alarm rationalization (E4) was by far the most effective single element, reducing PLL by 58 percent and serious incidents by 53 percent for USD 0.06 million, a net saving of USD 0.15 million after avoided incident costs. Contractor competence assurance (E5) reduced PLL by 28 percent. Isolation management (E1), risk-based permits (E2) and enhanced PSSR (E3) each reduced PLL by 8 to 9 percent; E3 was the least cost-effective because it extended the schedule. The cost-efficient frontier rose

steeply to E4, then to E2 with E4 (66 percent reduction), E1, E2 and E4 (71 percent) and E1, E2, E4 and E5 (78 percent, at a net cost of USD 0.02 million after avoided incidents). Adding E3 to these four raised the reduction to 80 percent at a further USD 0.30 million. With all five elements, the peak daily risk fell from 1.2×10^{-3} to 1.0×10^{-4} , a 92 percent reduction, and the risk profile became nearly flat (Figure 2), with installation rather than start-up the largest remaining phase. These results support the emphasis on SIS bypass control in functional safety standards^[228, 230] and on barrier management during transient operations^[3, 287].

Table 4: Effects of framework elements and selected combinations.

Elements	PLL (x 10^{-3})	Serious incidents	Duration (d)	Cost (USD M)	PLL reduction (%)	Net cost after avoided incidents (USD M)	Cost per serious incident averted (USD M)
None	4.68	0.0200	32	0.00	0	0.00	
E4	1.97	0.0093	32	0.06	58	-0.15	5.6
E5	3.38	0.0151	32	0.12	28	0.02	24.5
E1	4.25	0.0181	32	0.08	9	0.04	43.7
E2	4.31	0.0184	32	0.05	8	0.02	32.2
E3	4.32	0.0185	33	0.30	8	0.27	210.4
E2 + E4	1.61	0.0077	32	0.11	66	-0.13	9.0
E1 + E2 + E4	1.35	0.0067	32	0.19	71	-0.08	14.3
E1 + E2 + E4 + E5	1.03	0.0053	32	0.31	78	0.02	21.2
E1 to E5	0.94	0.0049	33	0.61	80	0.31	40.7

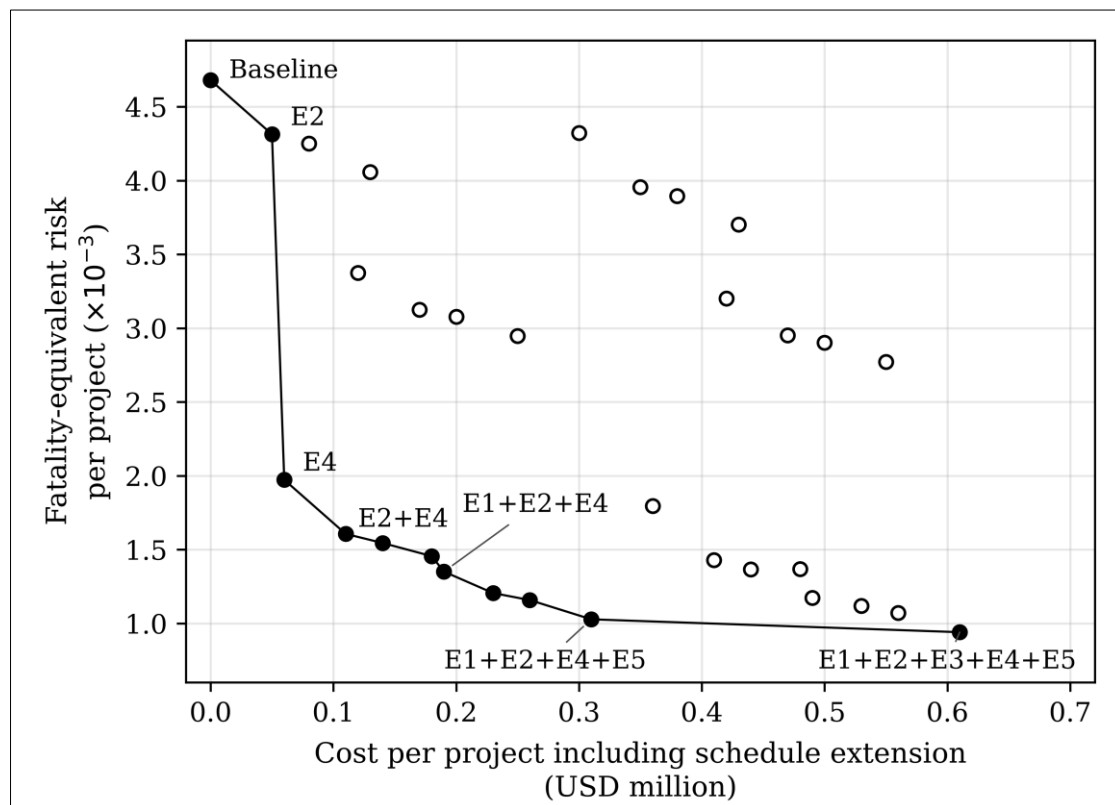


Fig 4: Fatality-equivalent risk and cost per project for all 32 combinations of framework elements; filled markers and the line show the cost-efficient frontier.

4.3. Risk-Aware Scheduling

Risk-aware scheduling had a modest effect at the assumed SIMOPS degradation factor. Without the framework elements, rescheduling within the 32-day duration reduced PLL by 3.7 percent, mainly by separating hot work near live plant from other high-risk tasks in area A. With all framework

elements, which already include the SIMOPS matrix, rescheduling reduced PLL by 1.9 percent at no extension and by 3.1 and 3.6 percent with extensions of 2 and 4 days, and it reduced the peak daily risk of the project by 19 percent. The value of scheduling depends strongly on how much concurrency degrades barriers (Figure 5b): for degradation

factors of 0.25, 0.5, 1.0 and 2.0 per concurrent task, rescheduling without extension reduced PLL by 1.4, 3.4, 9.5 and 24.4 percent. Where SIMOPS interactions are strong, as in congested brownfield sites [14, 15], sequencing becomes a significant control.

4.4. Robustness to Parameter Uncertainty

Figure 5a shows the effect of parameter uncertainty. The baseline PLL had a median of 5.8×10^{-3} with a 90 percent

range from 2.8×10^{-3} to 14.7×10^{-3} , and the full framework a median of 1.3×10^{-3} with a range from 0.7×10^{-3} to 2.3×10^{-3} . The relative reduction ranged from 62 to 90 percent with a median of 79 percent, so the framework reduced risk substantially across the plausible range. E4 gave the largest single-element reduction in 93 percent of samples, E5 in 4 percent and E1 in 3 percent, so the priority of SIS bypass management and start-up alarm rationalization is robust to the uncertainty in the inputs [286, 287].

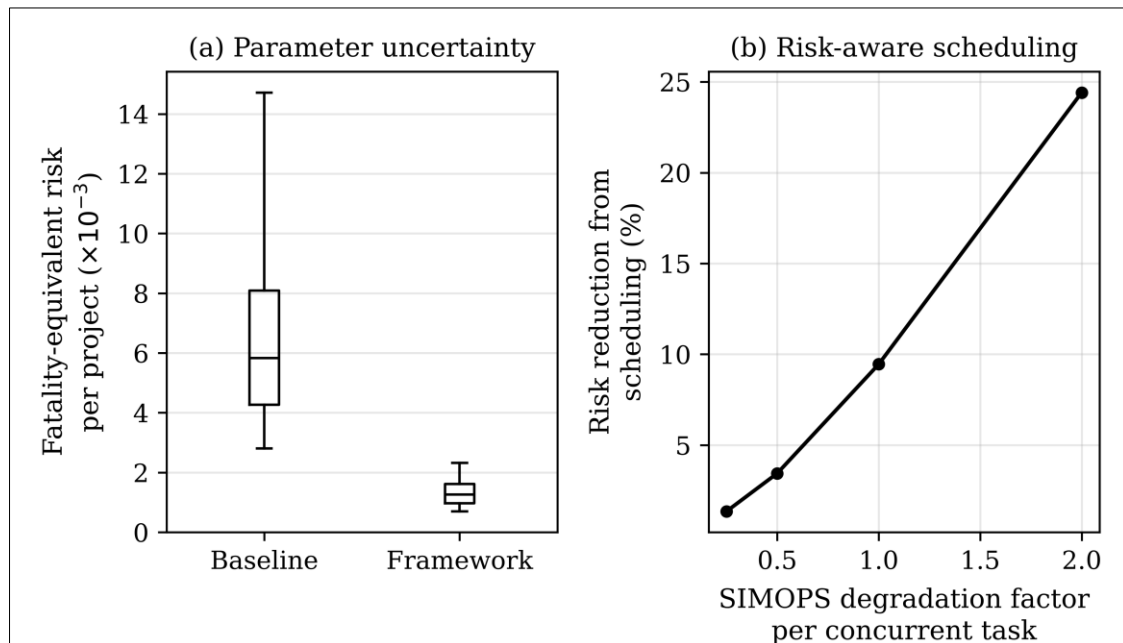


Fig 5: (a) Fatality-equivalent risk per project under parameter uncertainty for baseline and framework (box shows quartiles, whiskers 5th and 95th percentiles) and (b) risk reduction from risk-aware scheduling as a function of the SIMOPS degradation factor.

5. Discussion

This section interprets the findings, draws implications for project and operations teams, considers how the framework can be applied to real projects and sets out the limitations of the study. The discussion is framed by the observation that major accidents continue to occur during non-routine work despite long-established guidance [48, 50, 51], and by the systems view that the controls for such work are interdependent barriers rather than separate procedures [136, 137, 184]. It also considers how the findings relate to the organizational conditions, such as contractor management and learning from incidents, on which the effectiveness of every control depends [44, 192].

5.1. Principal Findings

Three findings stand out. First, the risk of a modification project is concentrated in time and in a few activities. In the representative project, the two start-up days carried more than half of the project's fatality-equivalent risk, and the start-up peak was about sixteen times the average daily risk of installation. This concentration matches incident evidence that start-up and other transient operations generate a disproportionate share of serious process safety events [1, 2, 4], and it implies that controls should be targeted at the transition from construction to operation rather than spread evenly across the project.

Second, the most valuable control in the model was not a work control such as permits or isolation but the management of SIS bypasses and alarms during start-up. Because the SIS

is the last automated barrier and its bypass during commissioning removes it entirely, restoring it before hydrocarbons are introduced removed more risk than any other element and paid for itself through avoided incidents. This reflects reports that bypassed protection is common and often undetected [18], the requirements of IEC 61511 for bypass management [230] and the role of alarm floods in start-up incidents [20, 21]. Isolation, permits and contractor competence remained valuable, particularly for the hot work near live plant that dominated installation risk, and four low-cost elements together cut risk by 78 percent at roughly zero net cost.

Third, scheduling is a conditional control. At a moderate concurrency effect, re-sequencing work reduced risk by only a few percent once a SIMOPS matrix was in place, but when concurrency degraded barriers strongly, re-sequencing reduced risk by a quarter. The value of risk-aware scheduling therefore depends on site congestion and the strength of SIMOPS interactions, which are rarely quantified in practice [14, 15].

5.2. Implications for Practice

For project and operations teams, the results suggest a sequence of actions. The first is to build a daily risk profile for each modification project from its activity schedule, using the barrier logic of LOPA and bow-tie analysis [28, 136, 138], so that high-risk days are visible before work begins. The second is to treat SIS bypass management, start-up alarm rationalization and operator readiness as a commissioning

deliverable with the same status as mechanical completion^[19, 207, 216]. The third is to apply risk-based permits with an explicit SIMOPS matrix and independent verification of isolations, which are inexpensive and reduce risk across all phases^[11, 34, 36]. The fourth is to assure the competence of contractors who perform hot work, lifting and tie-ins near live plant^[44-46]. The fifth is to use scheduling to separate high-risk tasks where the site is congested, especially hot work near live plant, so that productivity is balanced against safety compliance rather than traded for it^[15, 43, 323].

For organizations, the framework provides a basis for learning across projects. Incident databases and investigation reports can be used to calibrate initiating event frequencies and barrier failure probabilities by activity type^[66, 80, 90], near-miss archives can reveal barrier degradation^[116, 196], and dynamic risk tools, continuous hazard monitoring and digital twins can update the daily profile as work progresses^[31, 290, 291]. Human factors critical task analysis can strengthen the human-dependent barriers that dominate several activity types^[262-264].

5.3. Application to Real Projects

The framework requires an activity schedule with areas and activity types, a library of initiating event frequencies and barrier failure probabilities, and estimates of SIMOPS interactions. Generic leak frequencies^[141], SIS reliability data^[231], human reliability methods^[256, 257, 259] and incident statistics^[84, 85] can supply initial values, and Bayesian updating can refine them as site experience accumulates^[286, 287]. Dependencies between barriers, such as shared reliance on the same supervisor or permit, can be represented with Bayesian networks^[268, 269] or STAMP-based analyses^[277]. For turnarounds with hundreds of activities, the scheduling heuristic can be replaced by constraint programming or mixed-integer formulations used in turnaround scheduling^[43, 315].

5.4. Limitations

The study has several limitations. All parameters are representative values rather than data from a specific project, so absolute risks should not be transferred without calibration. Barriers were treated as independent, which overstates the benefit of layering where common causes such as fatigue or supervision failures affect several barriers at once^[184, 188]. The effects of framework elements were represented as fixed multipliers on barrier failure probabilities, whereas their real effectiveness depends on implementation quality and culture^[189, 191]. The SIMOPS model used a simple linear degradation with concurrency, and the value of scheduling is sensitive to it. Consequences were expressed as fatality equivalents and an average incident cost, without modelling escalation to neighbouring units. Finally, the model covers a single project; organizational learning across projects, which could change barrier performance over time, was not represented^[192, 194, 324].

6. Conclusion

This study developed a quantified process safety framework for modifications, equipment replacement and commissioning, combining an activity-level risk model, five control elements and risk-aware scheduling, and applied it to a representative brownfield project at an operating facility.

The risk of the project was concentrated in commissioning and start-up, and above all in starting new equipment with safety instrumented protection bypassed. Managing those bypasses and rationalizing start-up alarms removed more than half of the project's risk at a net saving, and together with isolation management, risk-based permits with a simultaneous-operations matrix and contractor competence assurance reduced risk by about four fifths at roughly zero net cost. Enhanced pre-startup review added a further reduction at higher cost. Risk-aware scheduling added little where concurrency effects were moderate but became significant where they were strong. The priority of bypass management held across the range of parameter uncertainty.

For facilities planning modifications, the results support building a daily risk profile for each project, treating safety system and alarm readiness as a commissioning deliverable, applying risk-based permits and independent isolation verification throughout, assuring contractor competence and using scheduling where sites are congested. Further work should calibrate the framework with incident and project data, represent dependencies between barriers and extend it to multi-project turnarounds.

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