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ADVANCES IN SOCIAL HUMANITIES RESEARCH

Analysis of Loss Prevention in Underground Mine's Ore Delivery Operations Through the Implementation of an Integrated Remote Monitoring System on Fire Protection Equipment

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loss prevention, remote monitoring system, fire suppression system, opportunity loss, Prevention-Appraisal-Failure, significance test

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Abstract

Unintended discharges of fire suppression systems (FSS) on underground conveyor systems at PT Freeport Indonesia (PTFI) disrupted single-line ore delivery operations and resulted in substantial opportunity losses. Before this study, most FSS units were not integrated into a centralized remote monitoring platform, causing delays in incident detection, response, and operational recovery. This study examined the contribution of limited remote monitoring capabilities to prolonged downtime and quantified the reductions in operational downtime and opportunity losses associated with integrating FSS status monitoring into the existing AVEVA PI Vision dashboard. A quantitative, quasi-experimental pretest–posttest design was employed to analyze 48 verified discharge events, comprising 29 events in Phase 1 (2022–2023) and 19 events in Phase 2 (2024–2025). Data were obtained from the AVEVA PI System historian and evaluated using the prevention–appraisal–failure (PAF) cost framework. Statistical analyses included paired-samples t-tests and Wilcoxon signed-rank tests involving seven matched conveyor systems. None of the recorded discharges resulted from an actual fire. Mean downtime per event decreased by 37.4%, from 2.967 to 1.857 hours, while the matched-conveyor analysis indicated a 43.6% reduction ($t = 5.2203$, $p = 0.00099$; Wilcoxon $p = 0.0078$; Cohen's $d_z = 1.97$). Annualized failure costs decreased by 53.4%, from approximately USD 22.05 million to USD 10.28 million, with a conservative estimate of USD 4.9 million in annual avoided losses attributable solely to reduced downtime duration. The findings indicated that integrating FSS status monitoring into AVEVA PI Vision was associated with substantial reductions in operational downtime, particularly prolonged outage events, and demonstrated the potential for a financial payback period of several weeks.

INTRODUCTION

In large-scale underground mining operations, safety systems have traditionally been designed primarily to prevent catastrophic incidents. Fire protection systems, in particular, serve as essential safeguards for personnel, critical infrastructure, and operational continuity. However, as mining operations become deeper, more complex, and increasingly capital-intensive, the performance of safety systems must be evaluated not only in terms of regulatory compliance and hazard mitigation but also in relation to operational loss prevention. Although these systems are designed to protect mining operations, their activation under nonfire

conditions may cause substantial production disruptions and associated economic losses (Ackerson, Grannes, Steven G & Green, 1990).

Operational loss prevention encompasses measures to minimize avoidable downtime, reduce the duration of unplanned shutdowns, and limit the financial consequences of operational interruptions. In underground mining, ore delivery networks often consist of interconnected conveyor systems with limited redundancy and buffering capacity. Consequently, an unplanned shutdown at a critical point may interrupt ore flow throughout the connected material handling system, resulting in production losses that cannot necessarily be recovered within the same operating shift. Conveyor systems are essential components of underground ore transportation, and their interconnected configuration makes them particularly vulnerable to cascading operational disruptions (Burduk et al., 2020). Within this context, fire suppression systems (FSS) perform a critical protective function but may also contribute to operational downtime when unintended discharges occur. Such discharges, triggered by equipment malfunctions, mechanical disturbances, or environmental conditions rather than actual fires, can activate conveyor shutdown interlocks and initiate operational recovery procedures.

PT Freeport Indonesia (PTFI), a subsidiary of Freeport-McMoRan Inc. (FCX), operates a major copper and gold mining complex in the highlands of Papua, Indonesia (FCX, 2026b, 2026c). Following the cessation of open-pit mining operations in 2019, underground mining became the primary source of ore production, particularly from the Grasberg Block Cave (GBC), Deep Mill Level Zone (DMLZ), and Big Gossan (BG) mines. According to the Technical Report Summary effective December 31, 2025, GBC contained approximately 472 million metric tons of proven and probable mineral reserves, with average grades of 1.04% copper and 0.66 grams of gold per metric ton. DMLZ contained approximately 350 million metric tons, grading 0.71% copper and 0.53 grams of gold per metric ton, while Big Gossan contained approximately 47 million metric tons, with higher average grades of 2.23% copper and 0.94 grams of gold per metric ton (FCX, 2026a). These substantial mineral reserves underscore the operational and economic importance of maintaining reliable ore delivery systems and minimizing avoidable production interruptions.

Under PTFI's occupational health and safety requirements, enclosed and underground conveyor systems must be equipped with functional FSS integrated with conveyor shutdown interlocks to ensure automatic equipment shutdown when the fire suppression system is activated (PT Freeport Indonesia, n.d.). These safety requirements remain mandatory and were not modified or relaxed in this study. Following each FSS discharge, whether caused by an actual fire or an unintended activation, Fire System Maintenance and Engineering (FSME) personnel were required to conduct physical inspections before authorizing conveyor restart. Unintended discharges resulted from internal equipment-related factors, including FSS component malfunctions and pressure-sensitive diaphragm failures associated with fluctuations in underground water supply pressure, as well as external factors, such as impacts from rock fragments or metallic debris on sprinkler head glass bulbs and damage to fire detection piping. Among the 48 recorded FSS discharge events associated with measurable conveyor downtime between 2022 and 2025, none was attributed to an actual fire. An example of an FSS discharge is presented in Figure 1.



Figure 1. Typical FSS discharge on conveyor (source: PT Freeport Indonesia, 2025)

Before the intervention evaluated in this study, most fire suppression system (FSS) units across PT Freeport Indonesia's (PTFI) underground conveyor network were not integrated into a centralized remote monitoring platform. Notifications of FSS discharges were typically received through conveyor shutdown alarms or radio communications from underground personnel, with reporting delays ranging from several minutes to several hours. The Fire System Maintenance and Engineering (FSME) team was then required to dispatch personnel underground to inspect the affected area and communicate their findings to surface operations before conveyor restart could be authorized. A particularly severe incident occurred at Belt Conveyor 34 (BC34) in the Deep Mill Level Zone (DMLZ) mine on November 16, 2022. The conveyor stopped at 01:24 and resumed operation at 12:35, resulting in approximately 11.18 hours of downtime. Prolonged exposure to discharged suppression water also damaged the conveyor drive motor. This incident resulted in approximately 37,278 metric tons of deferred ore delivery, equivalent to 46.6% of DMLZ's daily production target, with an estimated opportunity loss of USD 4.06 million from a single event.

PTFI had already implemented the AVEVA PI System and AVEVA PI Vision, managed by the Industrial Automation team, to provide real-time operational monitoring of milling processes, crushers, pumps, and energy consumption. However, FSS status data from underground conveyor systems had not been integrated into the existing monitoring dashboards, creating a critical visibility gap within an otherwise data-rich operational environment. The primary operational challenge was therefore not limited to unintended FSS discharges but also involved the information latency following these events, particularly the delay between discharge occurrence, incident detection, and notification of personnel responsible for initiating corrective actions. Accordingly, this study examined the integration of FSS status monitoring into AVEVA PI Vision, as illustrated in Figure 2, as an operational loss prevention strategy intended to improve incident visibility, accelerate response coordination, and reduce conveyor downtime rather than merely as a technological upgrade.

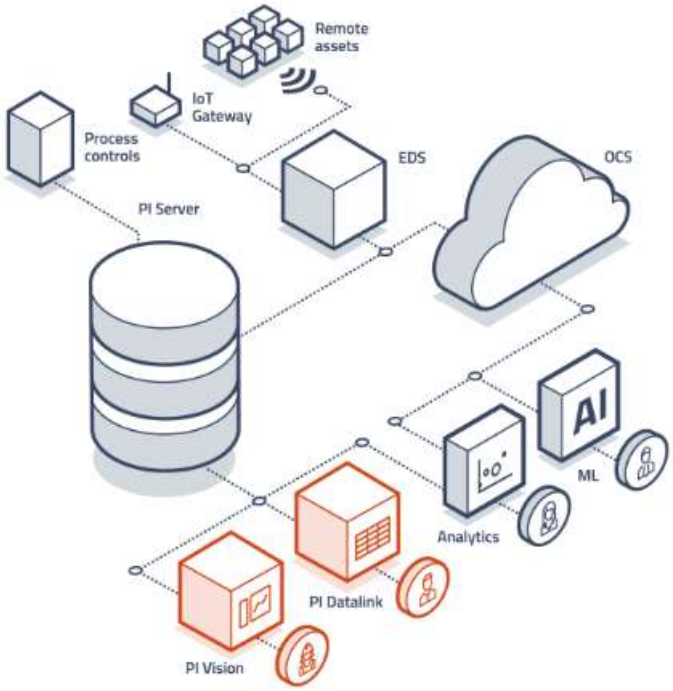


Figure 2. PI Vision monitoring system's schematics

The observation period extended from January 2022 to September 8, 2025. The end date was selected because a mud rush incident at the Grasberg Block Cave (GBC) mine on September 8, 2025, resulted in abnormal operating conditions that were not representative of routine ore delivery operations. The study addressed three research questions: (1) How did the absence of centralized remote monitoring contribute to prolonged response and recovery times following fire suppression system (FSS) activations on underground conveyors? (2) To what extent could integrating FSS status monitoring into AVEVA PI Vision reduce operational downtime and associated opportunity losses, estimated based on the contained copper and gold value of deferred ore delivery? (3) How did AVEVA PI Vision integration affect real-time operational visibility and response times during FSS discharge events? Accordingly, the study aimed to examine the relationship between limited remote monitoring capabilities and prolonged operational recovery, quantify changes in downtime and estimated opportunity losses using the prevention–appraisal–failure (PAF) cost framework, and evaluate improvements in real-time monitoring visibility and operational response following FSS integration into AVEVA PI Vision.

METHOD

This study employed a quantitative approach based on secondary operational data to evaluate whether integrating remote monitoring into fire suppression systems (FSS) reduced the operational and financial consequences of unintended discharges. Identifying the underlying causes of these discharges was beyond the scope of the study. A quasi-experimental before-and-after design was adopted because the conveyor systems constituted fixed, safety-critical infrastructure, and randomly withholding safety-related monitoring or establishing a parallel untreated control group was not feasible (Shadish et al., 2002). The same conveyor systems were compared across two observation phases, as illustrated in Figure 4.

Phase 1 (baseline, without centralized remote monitoring) covered January 2022 through December 2023, during which FSS discharge detection relied on local control panels and field

reports. Phase 2 (post-intervention, with remote monitoring) covered January 1, 2024, through September 8, 2025, during which FSS discharge information was accessible to Fire System Maintenance and Engineering (FSME) supervisors, Oreflow Operations, and Underground Dispatch through a shared AVEVA PI Vision dashboard displaying discharge locations, valve status, conveyor interlock conditions, and event timestamps. The independent variable was the implementation of the remote monitoring system (RMS), while the dependent variables were conveyor downtime duration, disrupted ore delivery volume (metric tons), and estimated opportunity losses (USD). Conveyor configuration and mine location remained unchanged, while operating schedules, ore valuation assumptions, and response procedures were considered when comparing the two phases. Changes to response procedures introduced during Phase 2 were treated as part of the intervention rather than as controlled conditions.

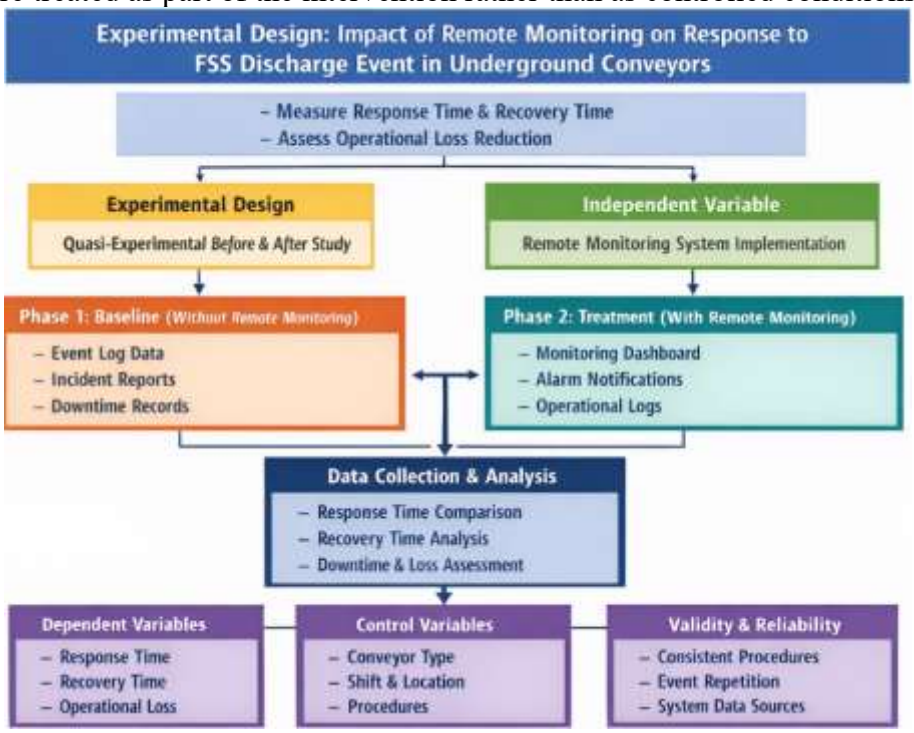


Figure 4. Experimental design

All operational data were retrieved from PT Freeport Indonesia's (PTFI) AVEVA PI System historian using PI DataLink, including fire suppression system (FSS) discharge logs, flow switch activation records, conveyor operating-hour records, and daily ore delivery targets for each mine. Mineral reserve and valuation data were obtained from the relevant company reports (FCX, 2026a, 2026b). Each discharge event was cross-checked against historian-recorded conveyor operating data, and system-generated timestamps were used when discrepancies occurred between historian records and Fire System Maintenance and Engineering (FSME) logs. Four records from 2021 were excluded because consistent conveyor operating-hour data were unavailable. The final verified dataset comprised 48 discharge events, including 29 in Phase 1 and 19 in Phase 2. The measurement definitions are presented in who served as an FSME supervisor and participated in implementing the monitoring system, had a potential conflict of interest. To mitigate measurement bias, downtime was determined using automatically recorded historian data, and the same verification procedures were applied consistently across both phases

Table 4. The researcher,

Variable	Definition	Start point	End point
Downtime duration	Total conveyor stoppage attributable to the FSS event	Verified conveyor stop time	Verified conveyor restart time
Loss (tons)	Ore tonnage not delivered during the stoppage	Same as downtime start	Same as downtime end
Loss (USD)	Value of undelivered ore at fixed mine-specific value	Same as downtime start	Same as downtime end
Discharge cause	Recorded cause: false, operational, or genuine fire	—	—

The analysis proceeds in four sequential steps: descriptive performance comparison (count, mean, median, total and standard deviation of downtime by mine and phase), PAF cost interpretation, opportunity loss quantification, and statistical significance testing. PAF categories are mapped to the cost items of this research in Table 5. Appraisal cost is computed as:

Table 5. PAF cost classification for this research

PAF category	Cost items in this research	Expected change from RMS
Prevention	RMS development and PI Vision FSS integration; SOP revision; FSME training	One-time increase; fixed after implementation
Appraisal	Manual underground inspection trips; verification and coordination per event	Decrease: remote triage reduces trips required
Failure	Conveyor downtime; lost ore delivery; risk of secondary equipment damage	Decrease: shorter stoppages reduce opportunity loss

$$C_A = N \times \tau \times h \times w \tag{4}$$

where N is the number of discharge events in the phase; τ is the proportion of events requiring a physical verification trip (1.00 in Phase 1; 0.60 in Phase 2); h is labor-hours per trip (6, being two technicians for three hours); w is the fully loaded FSME labor rate (approximately USD 5 per labor-hour).

Opportunity loss per event and the annualized failure cost are computed as:

$$L_j = D_j \times Q_m \times V_m ; \quad C_{FA} = (\Sigma L_j) / Y \tag{5}$$

where D_j is the verified downtime of event j (hours); Q_m is the nominal hourly throughput of the affected conveyor, being the daily target divided by twenty-four; V_m is the fixed mine-specific ore value; Y is the observation window (2.000 years for Phase 1; 1.688 years for Phase 2).

Ore values are deliberately held constant across both phases so that any difference in reported loss reflects a difference in tonnage not delivered rather than a movement in metal prices. The avoided failure cost is the difference between the annualized figures, $\Delta C_F = C_{FA1} - C_{FA2}$. A conservative counterfactual isolates the duration effect alone by valuing the Phase 2 events as though each had run for the Phase 1 mean duration:

$$\Delta C_{FC} = \Sigma_j (\bar{x}_1 - D_j) \times Q_m \times V_m \tag{6}$$

Statistical testing is performed on downtime hours rather than monetary loss. Each conveyor that recorded discharge events in both phases forms one matched pair (Field, 2018). The hypotheses are H_0: $\mu_1 = \mu_2$ and H_1: $\mu_2 < \mu_1$, tested one-tailed at $\alpha = 0.05$. Normality of the paired differences is checked with the Shapiro-Wilk test (Shapiro & Wilk, 1965); if normality

is not rejected, the paired sample t-test is the primary test, with the Wilcoxon signed-rank test (Wilcoxon, 1945) reported as a robustness check:

$$d_i = x_{1i} - x_{2i} ; \quad t = \bar{d} / (s_d / \sqrt{n}) , \quad df = n - 1 \tag{7}$$

$$d_z = \bar{d} / s_d ; \quad CI_{95}\% = \bar{d} \pm t_{(\alpha/2,\, df)} \times SE_d \tag{8}$$

$$W^+ = \Sigma R_i \ \ (d_i > 0) \tag{9}$$

where d_i is the difference between Phase 1 and Phase 2 mean downtime for conveyor i; $\bar{d}$ and s_d are the mean and standard deviation of the differences; d_z is Cohen's effect size for paired samples (Cohen, 1988); R_i is the rank of $|d_i|$.

As supporting evidence, an event-level independent-samples comparison is reported using the Welch t-test and the Mann-Whitney U test (Mann & Whitney, 1947), together with a sensitivity check on the valuation reference. After implementation, RMS performance is governed through the Plan–Do–Check–Act cycle.

RESULTS AND DISCUSSION

Overview of FSS Discharge Events

Table 6 summarizes the annual distribution of downtime-bearing discharge events, conveyor downtime, and resulting opportunity loss. Total FSS-related downtime fell from 86.05 hours in Phase 1 to 35.28 hours in Phase 2, and the associated opportunity loss from approximately USD 44.1 million to USD 17.4 million. Part of this reflects the shorter Phase 2 window, so the per-event and annualized comparisons that follow provide a fairer basis; nonetheless, the direction is consistent every year and the step change between 2023 and 2024 is pronounced.

Table 6. FSS discharge events by year and phase

Year	Phase	Events (n)	Downtime (hr)	Loss (tons)	Loss (USD)
2022	Phase 1	14	40.20	164,097	21,345,278
2023	Phase 1	15	45.85	164,812	22,757,326
2024	Phase 2	10	18.43	72,778	10,275,833
2025	Phase 2	9	16.85	49,389	7,076,417
Phase 1 total	**2022–23**	**29**	**86.05**	**328,910**	**44,102,604**
Phase 2 total	**2024–25**	**19**	**35.28**	**122,167**	**17,352,250**

The distribution of events by mine and the classification of discharge causes are shown in Table 7 and Table 8. GBC accounts for the largest share of events in both phases, and all three mines record events in both phases, which allows within-mine before-and-after comparison.

Table 7. Event distribution by area and phase

Area	Phase 1	%	Phase 2	%	Total	%
BG	1	3%	2	11%	3	6%
DMLZ	11	38%	4	21%	15	31%
GBC	17	59%	13	68%	30	63%
Total	**29**	**100%**	**19**	**100%**	**48**	**100%**

Table 8. Classification of FSS discharge causes (2022–2025, n = 48)

Cause category	Events	Share	Typical recorded causes
False discharge – physical impact or damage	27	56%	Metal or rock impact, sprinkler head struck, wire sling, rebar, metal pipe, cable tray, detection line eroded, pipe hit by equipment
Unknown	18	38%	Recorded as Unknown; no fire confirmed in any case
False discharge – system or hydraulic	2	4%	Water pressure fluctuation, foam system fault
Operational (non-fire)	1	2%	Chute plugged
Genuine fire	0	0%	None recorded across the observation period

The classification confirms the research premise decisively: not a single discharge was recorded as a genuine fire. Sixty percent are confirmed false discharges arising from physical and hydraulic mechanisms, predominantly metal debris striking sprinkler head bulbs, and the events recorded as Unknown almost certainly belong to the same category since no fire was identified in any of them. FSS discharges at PTFI are therefore, in practice, a production-continuity problem wearing the clothing of a safety event. Three events anchor the loss analysis: the BC34 incident (11.18 hours, approximately USD 4.06 million), the GBC Conveyor 71 event of 3 October 2023 (6.43 hours, approximately USD 5.79 million), and the GBC Conveyor 71 event of 19 May 2025 annotated as metal impact with the motor soaked (3.63 hours, approximately USD 3.27 million). Together these three events account for approximately USD 13.1 million, or 21% of the total recorded loss across all forty-eight events.

Descriptive Performance Analysis

Table 9 and Table 10 list the verified downtime records for both phases, with every stop and restart time validated against PI Vision conveyor running-hour data.

Table 9. Phase 1 FSS discharge record (2022–2023, n = 29)

Date	Area	Conv	Stop	Run	Down (hr)	Loss (tons)
27-Feb-22	GBC	612	15:22	17:18	1.93	12,083
12-Mar-22	GBC	71	00:52	02:08	1.27	7,917
15-Mar-22	DMLZ	38	02:00	03:16	1.27	4,222
20-Mar-22	GBC	612	07:58	11:04	3.10	19,375
20-Mar-22	GBC	613	08:46	10:20	1.57	9,792
20-Mar-22	GBC	601	19:05	20:54	1.82	3,785
11-Apr-22	DMLZ	508	03:37	05:27	1.83	3,056
18-Jun-22	DMLZ	512	20:12	01:09	4.95	16,500
24-Jun-22	GBC	613	11:53	14:24	2.52	15,729
10-Aug-22	GBC	601	00:47	02:54	2.12	4,410
24-Aug-22	DMLZ	508	07:04	09:36	2.53	4,222
09-Nov-22	GBC	613	16:12	17:43	1.52	9,479
12-Nov-22	GBC	612	02:49	05:25	2.60	16,250
16-Nov-22	DMLZ	34	01:24	12:35	11.18	37,278
05-Jan-23	GBC	601	05:02	09:17	4.25	8,854
23-Jan-23	DMLZ	508	14:25	16:50	2.42	4,028
07-Mar-23	GBC	601	20:14	23:02	2.80	5,833
11-May-23	GBC	612	22:12	00:25	2.22	13,854
04-Jun-23	GBC	612	05:34	08:29	2.92	18,229
13-Jun-23	GBC	602	17:28	20:11	2.72	5,660
02-Aug-23	GBC	612	01:26	04:18	2.87	17,917
26-Aug-23	GBC	613	03:09	05:49	2.67	16,667
04-Sep-23	DMLZ	512	03:45	06:49	3.07	10,222
11-Sep-23	DMLZ	509	23:50	02:04	2.23	3,722
03-Oct-23	GBC	71	17:17	23:43	6.43	40,208
07-Oct-23	BG	522	04:10	08:39	4.48	1,868
15-Oct-23	DMLZ	512	17:00	19:04	2.07	6,889
14-Nov-23	DMLZ	512	17:07	18:55	1.80	6,000
30-Dec-23	DMLZ	508	20:30	23:25	2.92	4,861

Table 10. Phase 2 FSS discharge record (2024 – 8 September 2025, n = 19)

Date	Area	Conv	Stop	Run	Down (hr)	Loss (tons)
15-Jan-24	GBC	603	04:02	05:59	1.95	4,062
17-Feb-24	GBC	601	08:27	10:00	1.55	3,229
11-Mar-24	GBC	601	14:12	15:24	1.20	2,500
03-Sep-24	DMLZ	508	14:59	16:51	1.87	3,111
03-Sep-24	GBC	71	17:01	21:46	4.75	29,687
07-Sep-24	GBC	612	20:57	22:19	1.37	8,542
24-Sep-24	GBC	612	08:48	10:37	1.82	11,354
12-Oct-24	GBC	603	06:25	08:03	1.63	3,403
15-Oct-24	DMLZ	508	07:57	09:35	1.63	2,722
20-Dec-24	GBC	613	11:15	11:55	0.67	4,167
29-Jan-25	DMLZ	508	08:47	10:41	1.90	3,167
12-Feb-25	GBC	71	02:47	03:53	1.10	6,875
28-Feb-25	GBC	601	14:08	15:47	1.65	3,437
06-Mar-25	BG	522	05:13	06:42	1.48	618
08-Mar-25	GBC	603	23:41	01:39	1.97	4,097
30-Apr-25	DMLZ	512	19:26	20:47	1.35	4,500
19-May-25	GBC	71	02:59	06:37	3.63	22,708
20-Jun-25	GBC	603	23:10	00:37	1.45	3,021
01-Sep-25	BG	522	13:43	16:02	2.32	965

Mean downtime per event by mine is compared in Table 11. Every mine improved: at GBC mean downtime fell from 2.67 to 1.90 hours (28.6%), at DMLZ from 3.30 to 1.69 hours (48.8%), and at Big Gossan from a single 4.48-hour event to a Phase 2 mean of 1.90 hours. In aggregate, mean downtime per event fell 37.4%, from 2.97 to 1.86 hours. An improvement appearing simultaneously at three operationally distinct mines is difficult to explain by local circumstance and points to the common change in monitoring capability.

Table 11. Mean downtime per FSS discharge event by mine and phase

Mine	P1 n	P1 mean (hr)	P2 n	P2 mean (hr)	Reduction (hr)	Change
GBC	17	2.665	13	1.903	0.762	−28.6%
DMLZ	11	3.297	4	1.688	1.609	−48.8%
Big Gossan	1	4.483	2	1.900	2.583	−57.6%
Aggregate	**29**	**2.967**	**19**	**1.857**	**1.110**	**−37.4%**

Beyond the change in average duration, the distribution of event severity shifted markedly (Table 12 and Figure 5). The proportion of events exceeding three hours fell from 24% to 11%, the longest event shortened from 11.18 to 4.75 hours, and the median fell from 2.53 to 1.63 hours, confirming that the improvement is not driven solely by the removal of outliers. The standard deviation fell by 52.7%, indicating that FSS response became not only faster but substantially more predictable, which has independent operational value because a stoppage of known short duration can be absorbed into shift planning.

Table 12. Shift in event severity and predictability between phases

Severity metric	Phase 1	Phase 2	Change
Events exceeding 3 hours downtime	7 of 29 (24%)	2 of 19 (11%)	−56%
Longest single event (hr)	11.18	4.75	−58%
Median downtime (hr)	2.533	1.633	−36%
Standard deviation of downtime (hr)	1.945	0.920	−53%

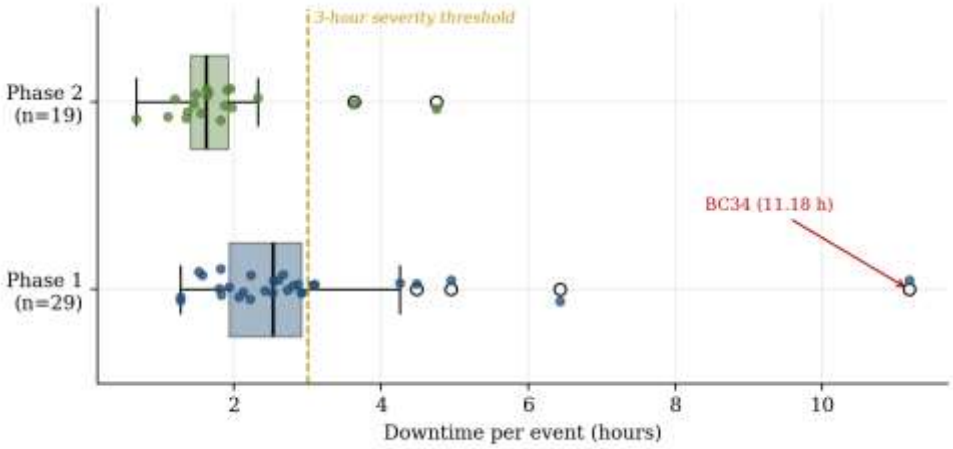


Figure 5. Distribution of FSS discharge downtime by phase

Prevention–Appraisal–Failure Cost Analysis

The PAF analysis applies fixed ore values and throughput (Table 2) identically to both phases, so that valuation affects only the absolute scale of reported figures. Because the actual project prevention cost is pending from Project Controls, the analysis derives the break-even prevention cost rather than assuming a value. Phase 1 prevention cost is taken as zero, and the appraisal assumptions are listed in Table 13.

Table 13. Appraisal-cost assumptions

#	Assumption	Basis
B1	Each Phase 1 discharge requires one full underground verification trip before restart authorization	Workflow description
B2	FSME appraisal effort per Phase 1 event: 2 technicians × 3 hours = 6 labor-hours	Normal response before RMS
B3	In Phase 2, remote triage via PI Vision removes the need for an immediate physical trip in an estimated 40% of events	Normal response after RMS
B4	FSME fully loaded labor rate	IDR 88,717/hour ≈ USD 5/hour

Failure cost by mine and phase is presented in Table 14. Total failure cost fell from approximately USD 44.10 million to USD 17.35 million, and average failure cost per discharge fell from approximately USD 1.52 million to USD 0.91 million, a reduction of 39.9%. All three mines contributed: GBC per-event cost fell from USD 1.91 million to USD 1.19 million,

DMLZ from USD 1.00 million to USD 0.37 million, and Big Gossan from USD 0.54 million to USD 0.23 million.

Table 14. Failure cost by mine and phase

Mine / Phase	Events	Downtime (hr)	Failure cost (USD)	Cost per event (USD)	Mean hr/event
GBC#1	17	45.30	32,550,000	1,914,706	2.665
GBC#2	13	24.73	15,420,000	1,186,154	1.903
DMLZ#1	11	36.27	11,009,000	1,000,818	3.297
DMLZ#2	4	6.75	1,471,500	367,875	1.688
BG#1	1	4.48	543,604	543,604	4.483
BG#2	2	3.80	460,750	230,375	1.900
Total Phase 1	**29**	**86.05**	**44,102,604**	**1,520,779**	**2.967**
Total Phase 2	**19**	**35.28**	**17,352,250**	**913,276**	**1.857**

Normalizing for the unequal length of the two windows gives the annualized comparison in Table 15. FSS-related failure cost fell from approximately USD 22.05 million per year to USD 10.28 million per year, an avoided failure cost of approximately USD 11.77 million per year, or 53.4%. The counterfactual estimate, which values the nineteen Phase 2 events as though each had run for the Phase 1 mean of 2.967 hours, gives approximately USD 8.32 million in additional loss over the Phase 2 window, or roughly USD 4.9 million per year. Read together, roughly 40% of the avoided loss comes from events being shorter and the remainder from there being fewer of them.

Table 15. Annualized failure cost, Phase 1 versus Phase 2

Annualized metric	Phase 1	Phase 2	Change
Events per year	14.50	11.26	−22.4%
Downtime hours per year	43.03	20.91	−51.4%
Failure cost per year (USD)	22,051,302	10,281,772	−53.4%

Appraisal effort is compared in Table 16. Verification labor falls by an estimated 62.1% in absolute terms and by 55.1% on an annualized basis, driven by fewer events overall and by remote triage removing the trip requirement for a share of events. Each avoided trip is also one fewer instance of personnel entering an area following an uncontrolled water release, a safety dividend that appears on no cost line.

Table 16. Appraisal-effort comparison

Appraisal metric	Phase 1	Phase 2	Change
Discharge events	29	19	−34.5%
Events requiring physical verification	29 (100%)	~11 (60%)	−18
Verification labor-hours (6 h/event)	174	~66	−62.1%
Annualized labor-hours	87.0	~39.1	−55.1%

The break-even thresholds in Table 17 show that, even on the conservative counterfactual basis, avoided failure cost of approximately USD 4.9 million per year means that any

implementation cost below that figure repays itself within a single year; at an illustrative cost of USD 500,000, payback is approximately 37 days. The total PAF cost shift in Table 18 matches the theoretical prediction of the model: a modest, one-time increase in prevention expenditure coincides with a reduction in failure cost of approximately USD 11.77 million per year. Appraisal and failure costs fell by almost identical proportions, 55.1% and 53.4%, because both are driven by event frequency and duration, but failure cost is roughly fifty thousand times larger, so it carries the business case.

Table 17. Break-even prevention cost thresholds

Break-even basis	Avoided failure cost (USD)	Payback if cost = USD 500k
Annualized (includes frequency effect)	~11,769,531 / yr	~16 days
Counterfactual, duration effect only (conservative)	~4,927,000 / yr	~37 days
Observed total (Phase 1 – Phase 2)	~26,750,354	—

Table 18. Total PAF cost shift, annualized across all mines

PAF category	Phase 1 (annualized)	Phase 2 (annualized)	Direction and interpretation
Prevention (C_P)	~0	One-time RMS cost	Increase by design; low, being an extension of an existing platform
Appraisal (C_A)	USD 435 (87.0 hr)	USD 196 (39.1 hr)	Decrease of ~55%; fewer and faster verification trips
Failure (C_F)	USD 22.05M / yr	USD 10.28M / yr	Decrease of ~53%, or ~USD 11.77M avoided per year
Total	**≈ USD 22.05M / yr**	**≈ USD 10.28M / yr + C_P**	**Materially lower in Phase 2 under any plausible prevention cost**

Statistical Significance Testing

Seven conveyors across all three mines recorded discharge events in both phases, forming seven matched pairs (Table 19). All seven show a reduction in mean downtime, with an average reduction of 1.316 hours per event, a 43.6% improvement; not one conveyor regressed.

Table 19. Paired conveyor-level comparison

Mine	Conveyor	P1 events	P1 mean (hr)	P2 events	P2 mean (hr)	Reduction (hr)
GBC	71	2	3.850	3	3.161	0.689
GBC	601	4	2.746	3	1.467	1.279
GBC	612	6	2.606	2	1.592	1.014
GBC	613	4	2.067	1	0.667	1.400
DMLZ	508	4	2.425	3	1.800	0.625
DMLZ	512	4	2.971	1	1.350	1.621
BG	522	1	4.483	2	1.900	2.583
Mean	**—**	**25**	**3.021**	**15**	**1.705**	**1.316**

The Shapiro-Wilk test on the seven paired differences returned $W = 0.908$ with $p = 0.384$, so normality is not rejected and the paired t-test is applicable (Table 20). The raw event durations in both phases depart sharply from normality, as expected for a duration variable

bounded below at zero, while differencing produces a more symmetric distribution because the skew common to both series partially cancels.

Table 20. Shapiro-Wilk normality test results

Data series tested	W	p	Conclusion at α = 0.05
Paired differences d_i (n = 7)	0.9084	0.3847	Normality not rejected; paired t-test valid
Phase 1 event durations (n = 29)	0.6681	0.00000076	Right-skewed (p < 0.001)
Phase 2 event durations (n = 19)	0.7599	0.00032	Right-skewed (p < 0.001)

Applying Equation 7, the sum of differences is 9.211 hours, so $\bar{d}$ = 1.3159 hours, s_d = 0.6669 hours, SE_d = 0.2521 hours and t = 5.2203 on 6 degrees of freedom. The critical one-tailed value at α = 0.05 is 1.9432, and the associated probability is p = 0.000988 one-tailed. The effect size is d_z = 1.97, which is very large under the conventional benchmarks of Cohen (1988). The 95% confidence interval is 1.3159 ± 2.4469 × 0.2521, from 0.699 to 1.933 hours, so even at the lower bound RMS is associated with a saving of approximately forty-two minutes per discharge event. In the Wilcoxon test all seven differences are positive, giving W^+ = 28, the maximum attainable for n = 7, with p = $(1/2)^7$ = 0.0078 (Table 21). The agreement between a parametric and a non-parametric test means the conclusion does not depend on the distributional assumption.

Table 21. Paired significance test results (n = 7 conveyor pairs)

Test	Statistic	p (one-tailed)	Decision (α = 0.05)	Effect size
Paired sample t-test	t = 5.2203	0.00099	Reject H_0	Cohen's d_z = 1.97 (very large)
Wilcoxon signed-rank	W^+ = 28.0	0.0078	Reject H_0	—

An independent-samples comparison treating each of the forty-eight discharges as a separate observation was also performed (Table 22). The Mann-Whitney U test gives U = 430.5 against a maximum of 551, with p = 0.00054, and the Welch t-test gives t = 2.6538 on approximately 42.6 degrees of freedom, p = 0.0056, with Cohen's d = 0.684 based on a pooled standard deviation of 1.6232 hours. The individual mine-level comparisons also reach significance: GBC at p = 0.041 and DMLZ at p = 0.043, while Big Gossan is not tested independently because three events cannot support a meaningful test.

Table 22. Comparison of analysis levels

Analysis level and test	P1 mean (hr)	P2 mean (hr)	Statistic	p (one-tailed)
Paired, conveyor level – t-test (primary)	3.021	1.705	t = 5.2203, df = 6	0.00099
Paired, conveyor level – Wilcoxon	3.021	1.705	$W^+ = 28.0$	0.0078
Event level – Mann-Whitney U	2.967	1.857	U = 430.5	0.00054
Event level – Welch t-test	2.967	1.857	t = 2.6538, ν ≈ 42.6	0.0056
Event level – GBC only, Welch	2.665	1.903	t = 1.802	0.041
Event level – DMLZ only, Welch	3.297	1.688	t = 1.894	0.043

Because every operational and statistical finding is expressed in hours, it is wholly unaffected by the valuation reference (Table 23). Only the absolute dollar magnitude of avoided loss depends on it, proportionally, leaving the 53.4% reduction unchanged. Had year-specific valuations been used, rising metal prices between 2022 and 2025 would have valued Phase 2 tonnage more highly and understated the measured benefit.

Table 23. Sensitivity of findings to the ore valuation reference

Finding	Basis	Result	Valuation-dependent?
Mean downtime reduction per event	Hours	−37.4%	No
Paired conveyor reduction	Hours	−43.6%	No
Paired t-test significance	Hours	p = 0.00099	No
Wilcoxon significance	Hours	p = 0.0078	No
Mann-Whitney significance	Hours	p = 0.00054	No
Annualized downtime reduction	Hours	−51.4%	No
Variance reduction	Hours	−52.7%	No
Avoided failure cost	USD	~11.77M / yr	Scale only

With respect to the first research question, the Phase 1 record shows a mean of 2.967 hours, a standard deviation of 1.945 hours and a maximum of 11.18 hours, with almost a quarter of events exceeding three hours. That dispersion is the signature of a process in which the time to awareness is itself variable and uncontrolled. The BC34 incident illustrates the mechanism described in the loss prevention literature: information latency does not merely delay the response, it allows a manageable deviation to escalate into a larger failure (Manuele, 2011; Tannous, 2021).

With respect to the second research question, annualized failure cost fell by approximately USD 11.77 million, or 53.4%. The fall in event frequency from 14.50 to 11.26 per year is more plausibly attributable to the maintenance attention accompanying the rollout

than to monitoring itself, so the conservative business case rests on roughly USD 4.9 million per year attributable to duration reduction alone. Even on that basis, set against a prevention cost consisting of extending an already-deployed platform, the investment repays itself within weeks, consistent with the PAF proposition of Juran and Godfrey (1999).

With respect to the third research question, mean downtime per event fell by 37.4% in aggregate and by 43.6% on the paired conveyor-level basis, and five separate tests across two analysis levels converge on the same conclusion. The mechanism is chiefly the compression of the long tail: real-time visibility appears to act less by improving the best-case response, which was already reasonable, than by preventing the worst-case one. This is consistent with Duarte et al. (2022) and Zhang et al. (2023), who identify faster detection and surface-based characterization of abnormal conditions as the principal benefits of integrated monitoring, and with Burduk et al. (2020), who show that stoppage duration governs the delivery consequence in series conveyor systems. Because none of the forty-eight discharges was a genuine fire, the correct management response is to invest in the speed of the verification loop rather than to reduce detection sensitivity, which would compromise the safety function described by Bałaga et al. (2023) and Rowland et al. (2011).

The findings also have long-horizon implications. On Phase 1 performance, each FSS-protected conveyor carries an annualized failure exposure of approximately USD 1.84 million, against approximately USD 0.86 million on Phase 2 performance. As the conveyor network expands with the planned Parallel Conveyor (ParCon) and Redundant Conveyor (ReCon) projects, that exposure scales accordingly, as shown in Table 24. If the protected network grows from twelve to twenty conveyors, the difference of roughly USD 19.7 million per year is the value of ensuring that expansion is accompanied by monitoring rather than following it. The implementation roadmap to the end of PTFI's operating license in 2061 is summarized in Table 25.

Table 24. FSS failure-cost exposure as the conveyor network expands (USD million per year)

Protected network	Unmanaged (Phase 1 performance)	Managed with RMS (Phase 2 performance)
12 conveyors	22.1	10.3
16 conveyors	29.4	13.7
20 conveyors	36.8	17.1
24 conveyors	44.1	20.6

Table 25. Implementation roadmap summary

Horizon	Period and focus	Key actions	Success measure
Horizon 1	2026–2028 Consolidate	Close assumption gaps; formalize KPI reporting; rationalize alarms and escalation SOP in line with IEC 62682	FSS KPIs in monthly Oreflow report; verified business case on actual cost
Horizon 2	2028–2035 Scale	Complete retrofit coverage; embed RMS as ParCon/ReCon design standard	100% of operating FSS units monitored; monitoring in commissioning criteria
Horizon 3	2035–2061 Sustain	Three-yearly re-baselining; predictive analytics	Mean downtime per discharge held at or below

	development; grade-decline review	1.9 hours through license end

Several limitations bound the findings. The primary statistical result rests on seven conveyor pairs; the appraisal figures rest on working assumptions awaiting FSME validation; ore values are indicative of in-situ recoverable metal and do not account for smelting terms or refining charges; and the quasi-experimental design cannot fully exclude other contemporaneous changes in FSME practice as contributing causes. The findings reflect PTFI's specific orebody, conveyor configuration and FSS design and may not transfer directly to operations that differ materially in these respects.

CONCLUSION

This study concluded that integrating fire suppression system (FSS) status monitoring into PT Freeport Indonesia's (PTFI) existing AVEVA PI Vision platform was associated with improved operational loss prevention, consistent with the prevention–appraisal–failure (PAF) cost framework. Across 48 verified FSS discharge events, none of which resulted from an actual fire, prolonged baseline downtime indicated that delayed incident detection and notification may have contributed substantially to operational recovery times. Following implementation, mean downtime per discharge decreased from 2.967 to 1.857 hours (37.4%), with reductions observed across all seven matched conveyor systems. The improvement was statistically significant in both parametric and nonparametric analyses ($t = 5.2203$, $p = 0.00099$; Wilcoxon $p = 0.0078$), with a very large effect size. Annualized failure costs decreased from approximately USD 22.05 million to USD 10.28 million, while the conservative estimate of annual avoided losses attributable solely to shorter downtime durations was approximately USD 4.9 million. These findings suggested a potential investment payback period of several weeks, subject to the underlying implementation costs and savings assumptions. The observed reduction in prolonged shutdown events further indicated that improved monitoring visibility may have reduced detection and response delays. Based on these findings, Oreflow Operations should incorporate FSS-related downtime and its variability into operational performance indicators. Fire System Maintenance and Engineering (FSME) should standardize remote incident triage procedures, strengthen sprinkler head protection, and establish consistent discharge-cause classifications. The Industrial Automation team should maintain FSS monitoring tags according to the same data quality and reliability standards applied to other operational process tags. PTFI should also consider incorporating centralized FSS monitoring into the design requirements for the Parallel and Redundant Conveyor projects and extending this approach to other interlocked safety systems, including gas detection, ventilation, and dust suppression systems. Future research should examine a longer observation period with a larger matched sample, collect incident detection, notification, and dispatch timestamps to distinguish individual response stages, and investigate predictive models of unintended FSS discharges using detection-line pressure data.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to the conduct of the research, preparation, or publication of this article.

AUTHOR CONTRIBUTIONS

All authors contributed to the preparation of this article. The first author, Musta'an Mahfud, was responsible for the conceptualization of the study, data collection and analysis,

interpretation of the results, and manuscript preparation. The other authors contributed to the review, editing, and final approval of the manuscript.

GENERATIVE AI STATEMENT

The authors declare that no generative artificial intelligence was used in the preparation of this article.

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