



Design of Monitoring Dashboard for Mining Pump with Design Thinking and Acceptance Analysis with Technology Acceptance Model

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Abstract

PT SBS is a pump manufacturing company that conducts Factory Acceptance Tests (FAT) prior to field deployment. Current FAT procedures require personnel to physically enter hazardous zones generating three fundamental problems: high occupational safety risks, low data validity from human and parallax error, and limited information transparency for customers. This research designs a SCADA-based monitoring system using Design Thinking as the design methodology and the Technology Acceptance Model extended with TAM3 external variables as the technology acceptance evaluation framework. Design Thinking was applied through five stages (Empathize, Define, Ideate, Prototype, Test) using Node-RED, while acceptance evaluation utilized questionnaires from 60 PT SBS workshop employees analyzed via PLS-SEM using SmartPLS 4. Design Thinking produced a SCADA dashboard eliminating the requirement for operators to enter hazardous zones during testing. TAM evaluation confirmed all 26 indicators are valid ($AVE > 0.50$) and reliable ($\alpha > 0.80$). The model explains 72.1% of Actual Usage variance. Attitude Toward Using is the sole direct predictor of Actual Usage ($\beta = 0.849$; $f^2 = 0.882$, large effect), fully mediated by PU ($\beta = 0.454$; $p = 0.000$) and PEOU ($p = 0.005$). Technology Self-Efficacy is the strongest predictor of PEOU among external variables ($\beta = 0.494$; $p = 0.000$), followed by Perceived Enjoyment ($\beta = 0.270$; $p = 0.004$). Perception of External Control and Technology Anxiety were not significant. This research concludes that integrating Design Thinking and TAM produces a system well-accepted across all user levels, with occupational safety motivation as the primary driver of actual usage.

Introduction

Domestic coal consumption is primarily used for power generation (coal-fired power plants), followed by the cement, textile, paper, and other industries. This demonstrates that the mining and coal industries play a vital role in the economy. Coal mining companies generally employ open-cut mining systems. A problem with this open-cut mining system is that, after the mining process is complete, post-mining backfilling should be carried out; however, this is often neglected, leaving behind abandoned mine pits. Post-mining pits, also known as voids, left behind without proper planning for their utilization, have the potential to cause adverse environmental impacts (Said, 2021; Devrath et al., 2025; Mhlono, 2023; Cacciuttolo &

Atencio, 2023). Mine dewatering is an effort or method to prevent, drain, and remove water present in or flooding a specific area. This effort is undertaken to prevent or reduce disruptions to mining operations caused by excessive water, particularly during the rainy season. This activity is carried out to prevent disruption of mining operations, especially during the rainy season, which results in excessive water accumulation (Adnyano, 2020; Mardonova & Han, 2023; Rodríguez et al., 2023; Gu et al., 2025). Mine dewatering activities involve pumping, which is used to transfer a certain volume of water from one location to another. In the mining process, water accumulates in the excavation area and must be moved to a higher elevation. This process prevents water from flowing naturally, necessitating artificial removal methods such as pumping (Gautama, 2019). Therefore, the selection, design, and operation of pumps are critical to the success of the dewatering process (Said et al., 2026; Werbinska-Wojciechowska & Rogowski, 2025; Pirouzi et al., 2025; Morton, 2025).

PT. SBS is a company engaged in the manufacture of pumps to meet these mine dewatering needs. The pumps produced by PT. SBS must meet these needs and ensure optimal performance. Therefore, it is crucial to conduct monitoring during the FAT (Factory Acceptance Test) process to verify the pumps' performance and quality. However, the performance tests are currently conducted by PT. SBS at its Balikpapan branch still relies on manual methods, specifically periodic performance checks performed by operators. This inevitably leads to various biases, such as human error, inaccuracies in data collection, delayed responses to emergencies, time-consuming performance analysis, and limited visibility of information for potential customers due to restricted access. It also increases workplace safety risks, as operators must be physically present near the testing unit to record data. The pump testing process involves rotating mechanical components (such as impellers and couplings), high-pressure fluids, and high-voltage motors; thus, this direct exposure is highly dangerous and prone to fatal accidents (Widajati, 2025). Manual testing methods in heavy industrial environments pose significant safety risks. Operators who must be physically present near the test machine are directly exposed to mechanical hazards, such as the risk of being struck, pinched, or cut by moving machine parts, as well as electrical hazards like electric shock or burns. In addition to the risk of acute accidents, the manual data recording process itself is a hazardous manual task that can cause musculoskeletal disorders (MSDs) due to body postures or repetitive activities (Deros et al., 2017; Odebiyi & Okafor, 2023; Benharkat et al., 2026; Ogedengbe et al., 2023).

Therefore, the author has undertaken innovation and digitalization efforts by developing a SCADA (Supervisory Control and Data Acquisition) based monitoring system so that the entire testing process can be conducted comprehensively, as well as more easily and safely. Innovation through the SCADA system is crucial in modern manufacturing due to its ability to control industrial processes and monitor, collect, and process data in real time. This system enables companies to transition to data-driven decision-making (Nuruzzaman, 2025; Eso & Eseosa, 2022; Sverko et al., 2022; Enam et al., 2025). Furthermore, SCADA directly contributes to improved product quality and productivity by detecting anomalies, reducing human error through automation, and minimizing the risk of workplace accidents, thereby enhancing workplace safety (Rut et al., 2020; Enam et al., 2025; Hasso, 2025; Sharma, 2024; Mohammad et al., 2025). To analyze the developed system innovation, the author employs the Technology Acceptance Model (TAM) and Design Thinking. In this study, TAM serves as the theoretical framework to assess how SCADA-based dashboard designs are accepted by end-users in manufacturing or monitoring system environments. The primary focus is on understanding how interface design aspects influence users' perceptions of the system's ease of use and utility, as well as how these perceptions contribute to the intention to use the dashboard. Based on this, the developed system design can be more user-centered and have a greater chance of being widely adopted. The Design Thinking method is increasingly being applied to ensure that the developed dashboard is truly user-centered. Applying the Design

Thinking methodology through five stages (Empathize, Define, Ideate, Prototype, Test) to design a user-based web dashboard. This approach ensures that specific user needs, identified through interviews and observations in the Empathize stage, serve as the primary foundation for prototype development. (Wahyudi, 2025) Implementation of TAM in the context of strategic dashboard design within the small and medium-sized enterprise (SME) sector. This study uses TAM to evaluate users' perceptions of design features such as metric visualization, indicator iconography, and intuitive navigation. The results indicate that ease of use (PEOU) and perceived utility (PU) are significantly influenced by the dashboard's visual quality and interactivity. (Vasnier et al., 2020). Although prior studies have examined Design Thinking in dashboard development (Kurniawan, 2020; Yulius & Pratama, 2022) and TAM-based evaluation of SCADA or dashboard systems separately (Setiawan, 2020; Vasnier et al., 2020), these two streams have rarely been integrated within a single empirical pipeline, and never within a safety-critical, mandatory-adoption industrial setting. Vasnier et al. (2020) applied TAM to strategic business dashboards used voluntarily by white-collar SME staff, while Setiawan (2020) evaluated SCADA acceptance without a structured design methodology preceding the measurement stage. This study addresses both gaps simultaneously: Design Thinking is used not merely as a design philosophy but as an empirically linked generative process whose outputs (interface features informed by user pain points) are subsequently subjected to formal quantitative validation via TAM3-extended PLS-SEM. Furthermore, unlike the majority of TAM literature which examines voluntary technology adoption among office-based or highly-educated populations this study evaluates acceptance among vocationally-educated technical workers (84% non-university background) under a mandatory adoption regime tied to occupational safety procedures. This combination of context, population, and adoption condition constitutes the primary novelty of this research, and yields findings such as the near total collapse of external control based determinants (PEC, TA) that are unlikely to emerge in conventional voluntary-adoption TAM studies.

In SCADA based dashboard systems, the perception of usefulness is closely related to users' ability to monitor, detect issues early, and make decisions based on real-time data visualizations. Meanwhile, the perception of ease of use refers to navigation, system response speed, and the readability of visual elements (Rut et al., 2020). This study is relevant to the development of industrial dashboards such as SCADA, as users both operators and technicians require clear, fast, and easily understandable information to make data-driven decisions within control systems. By adapting the Design Thinking Method and the Technology Acceptance Model (TAM) as an evaluation framework, this research will identify which design areas need to be addressed to ensure that the developed technology truly aligns with the needs and preferences of end-users.

Methods

Research Approach

This study aims to design an interactive monitoring dashboard using the Design Thinking method and then analyze the acceptance levels of this monitoring dashboard system at PT SBS for implementation in the company's business processes using an integrated approach that incorporates the Technology Acceptance Model (TAM). In Design Thinking, five methods will be used in the monitoring dashboard design process: empathize, define, ideate, prototype, and test. The level of technology acceptance will be measured using the TAM model to determine the ease of use and benefits of the technology. The Extended TAM 3 approach will be used, incorporating several external factors that can influence technology readiness and acceptance, including Technology Self-Efficacy (TSE), Perception of External Control (PEC), Technology Anxiety (TA), and Perceived Enjoyment (PE). Data collection will be conducted via questionnaires administered to technology users, specifically workshop employees.

Instrument Development and Measurement

The measurement instrument was constructed by adapting validated indicators from prior Extended TAM3 literature rather than developing items independently. The core TAM constructs (Perceived Usefulness, Perceived Ease of Use, Attitude Toward Using, Actual Usage) and the four external determinants (Technology Self-Efficacy, Perception of External Control, Technology Anxiety, Perceived Enjoyment) were adapted from Venkatesh and Bala's (2008) original TAM3 instrument, with item wording contextualized to the SCADA dashboard and mine-dewatering pump testing setting used in this study. Each construct was measured using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree), consistent with the response format commonly applied in TAM-based technology acceptance research. The number of items per construct is reported in Table 1: Perceived Usefulness (6 items), Perceived Ease of Use (4 items), Attitude Toward Using (4 items), Actual Usage (4 items), Technology Self-Efficacy (2 items), Perception of External Control (2 items), Technology Anxiety (2 items), and Perceived Enjoyment (2 items), totaling 26 core indicators. As the item pool was drawn from a previously validated instrument rather than newly developed, a separate small-scale pilot test was not conducted prior to full distribution. Content validity was assumed to be inherited from the source instrument. We acknowledge this as a methodological limitation, as pilot testing can still surface context-specific wording or comprehension issues even when items originate from validated sources. To partially compensate, the psychometric adequacy of the adapted items was empirically reverified through the outer model assessment reported in this study: all 26 indicators achieved factor loadings above 0.70 and construct AVE values above 0.50, providing empirical confirmation of convergent validity within this specific respondent population despite the absence of a formal pilot phase. Regarding sample adequacy, this study surveyed the full population of PT SBS workshop personnel involved in pump testing (N = 60), constituting a census rather than a probability sample.

For PLS-SEM specifically, minimum sample size is commonly evaluated using the ten-times rule (Hair et al., 2019) or the more precise inverse square root method (Kock & Hadaya, 2018), both benchmarked against the maximum number of predictors pointing at any single endogenous construct in the structural model. In this study, PEOU receives the largest number of incoming paths (four: TSE, PEC, TA, PE), yielding a minimum recommended sample size of 40 under the ten-times rule. The achieved sample of 60 respondents therefore exceeds this threshold. We further note that because the sample represents a full population census rather than a subset, sampling-based generalizability concerns are reduced, though the findings remain bound to this specific organizational context and should not be generalized to other populations without replication.

Respondent Profile

The study involved a total of 60 respondents drawn from the full population of PT SBS workshop staff engaged in pump repair, maintenance, and testing activities. The demographic profile of this sample is highly relevant to the design decisions documented in this chapter. Eighty percent of respondents were Operators and Mechanics, representing the primary user group of the proposed SCADA system. Educational backgrounds were predominantly vocational: 67% held SMK (vocational high school) qualifications and 17% held diploma degrees, totaling 84% with non-university educational backgrounds. The remaining 16% held undergraduate or postgraduate degrees and were concentrated in QC Staff and Managerial roles. In terms of age distribution, 42% of respondents fell within the 25–35 year bracket, while approximately 12% were above 45 years of age a sub-group classified as potential digital immigrants with elevated susceptibility to technology anxiety. Work experience

distribution showed 37% with one to five years of experience and 33% with six to ten years, confirming that the majority of respondents possess substantive hands-on familiarity with pump testing procedures. This demographic composition directly shaped design priorities: the dominance of vocational-background operators necessitated an interface emphasizing visual simplicity, icon-based indicators, and minimal text-dependent navigation over complex analytical dashboards.

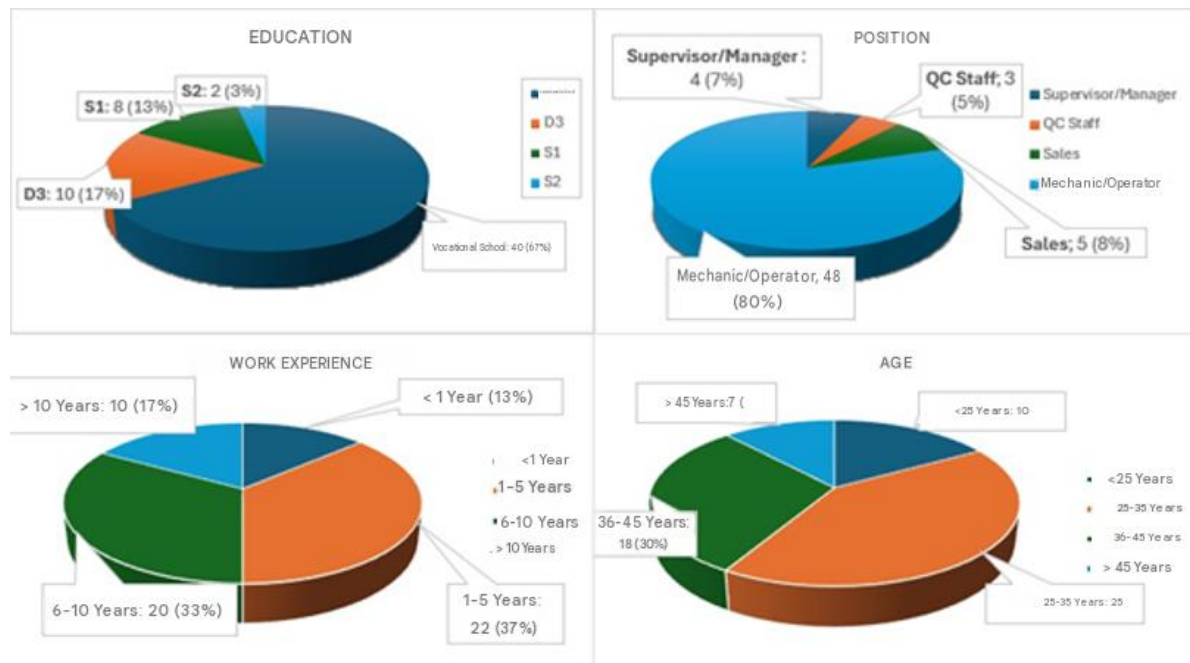


Figure 1. Correspondent Profile

Dashboard Design

This research focuses on the design process and evaluation of user interfaces, without covering the development process or the integration of actual company data. Data collection was conducted through observation and User Journey Mapping of the pump testing process at PT. SBS. The design process was carried out using the Node-Red platform, while survey and interview results were analyzed descriptively to identify user needs and preferences.

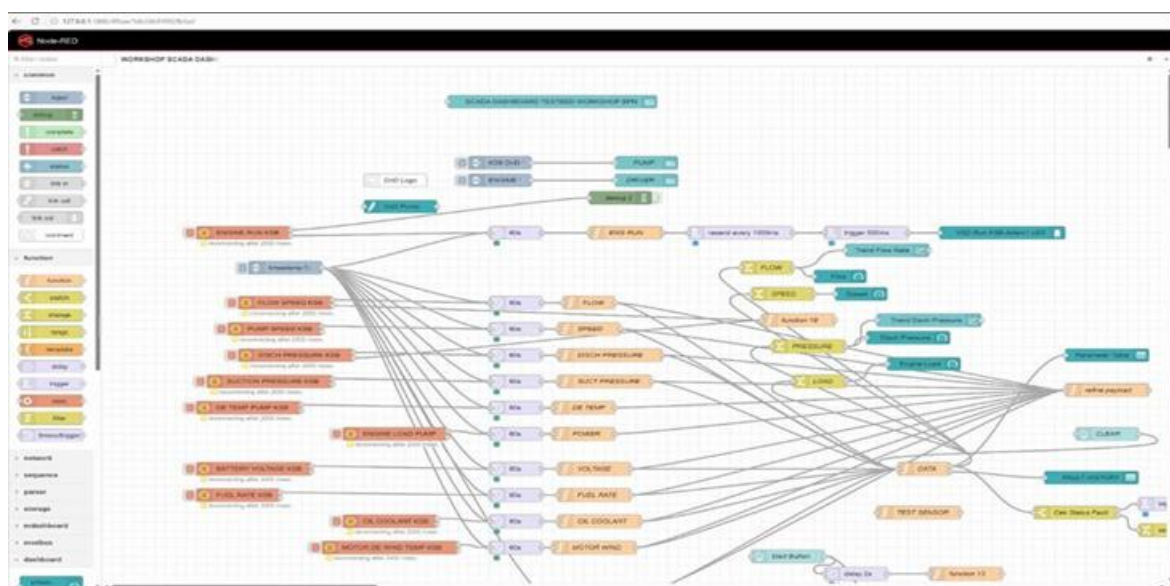


Figure 2. Node-Red Programming

The design process encompasses the five phases of the Design Thinking method: empathize, define, ideate, prototype, and test. The empathize phase focuses on understanding the problem and defining user needs using user journey mapping; the define phase formulates the core problem using the “How Might We” approach, the ideate phase generates alternative design solution. Then prototype phase produces visual designs in the form of wireframes and high-fidelity mockup, finally the test phase is conducted through usability testing to assess the design’s effectiveness and comfort. It should be clarified that the Node-RED prototype shown in Figure 2 was connected to live sensor and PLC data from an actual pump unit during the testing phase, enabling realistic validation of the dashboard's real-time monitoring capability. However, consistent with the study's stated scope, this implementation remained at the design-validation stage: it was not integrated into PT SBS's permanent operational infrastructure, company-wide data systems, or formal IT governance processes, and therefore should be understood as a functional proof-of-concept rather than a deployed production system. Full-scale deployment, including integration with company data systems and formal IT security review, falls outside the scope of this study and is noted as a direction for future work.

Questionnaire Form Design

The research questionnaire was used as the primary instrument for collecting data on employees’ readiness and acceptance of the SCADA monitoring dashboard for pump performance monitoring and control systems. The questionnaire was designed to capture employees’ perceptions regarding their readiness to use the dashboard and their acceptance of its implementation in operational activities. The target respondents were all 60 PT.

SBS employees directly involved in pump operation, repair, maintenance, and testing, as they have direct experience with the processes and systems relevant to the implementation of the SCADA monitoring dashboard. The questionnaire items were developed based on the indicators of the research variables and were structured to reflect the respondents’ perceptions and experiences as potential users of the system. Responses were measured using a Likert scale, with each item providing ordered response options from low to high levels of agreement. Before being used for the main analysis, the questionnaire was assessed for validity and reliability to ensure that the measurement items adequately represented the intended research constructs and produced consistent responses. The 26 core questionnaire items measured eight variables drawn from the Extended TAM3 framework: Perceived Usefulness, Perceived Ease of Use, Attitude Toward Using, Actual Usage, Technology Self-Efficacy, Perception of External Control, Technology Anxiety, and Perceived Enjoyment, with item counts per variable detailed in Table 1. All items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Instrument validity and reliability were established empirically through convergent validity, discriminant validity, and internal consistency reliability testing, with full procedures and results reported in the Instrument Development and Measurement and Outer Model Assessment sections.

Table 1. Frequency Distribution of Variables

Factor	Indicator	Question	Mean	SD
<i>Perceived of Usefulness</i>	PU 1	Scada helps me finish my work quickly	4.233	0.697
	PU 2	Using SCADA improves the quality of my work	4.266	0.709
	PU 3	Using the SCADA dashboard boosts my productivity	4.316	0.724
	PU 4	Using SCADA increases my efficiency	4.366	0.662
	PU 5	Using SCADA makes my work	4.267	0.709

		easier		
	PU 6	Overall, the SCADA dashboard is very helpful for my work	4.308	0.743
<i>Perceived Ease of Use</i>	PEOU 1	Learning to use SCADA was easy for me	4.183	0.724
	PEOU 2	Scada is easy to understand	4.233	0.721
	PEOU 3	It's easy for me to master using Scada	4.251	0.750
	PEOU 4	Overall, Scada is easy to use	4.252	0.704
<i>Attitude Toward Using</i>	ATU 1	Using Scada is a better way to improve systems	4.252	0.728
	ATU 2	Using Scada is always enjoyable	4.366	0.758
	ATU 3	Scada has a positive impact on productivity	4.302	0.696
	ATU 4	Overall, I enjoy using Scada	4.251	0.772

Data Processing Method



Figure 3. Output SmartPLS4

This study employs two distinct, complementary evaluation instruments that should not be conflated. Dashboard usability was assessed qualitatively during the Design Thinking Test phase through direct task-based observation of user interaction with the prototype, focusing on interface-level concerns such as navigability, readability, and task completion ease. In contrast, user readiness and acceptance were assessed quantitatively through the Extended TAM3 questionnaire administered after the design process was finalized, focusing on psychological and behavioral constructs such as perceived usefulness, ease of use, and actual usage intention. While usability findings informed iterative design refinement within the Design Thinking cycle, the TAM questionnaire results reported in the Outer and Inner Model Assessment sections represent a separate, formal acceptance evaluation of the finalized design, analyzed independently via PLS-SEM. This distinction ensures that interface-level usability feedback and construct-level acceptance measurement are not treated as equivalent

or interchangeable forms of evidence. Descriptive analysis of the questionnaire data is conducted to determine respondent demographics, followed by an analysis of user technology usage, validity and reliability tests, and the relationships between variables.

Subsequently, an analysis of the factors influencing the level of technology acceptance will be performed. Outer and inner model testing is conducted to determine the validity and reliability of the model, as well as the relationships among the research variables. If the results are not satisfactory, improvements will be made during the design phase. If the level of technology acceptance is sufficiently high, the findings will be used to inform managerial implications and recommendations for future technological improvements. The software Smart PLS 4.0 is used for data processing.

Results and Discussion

Design Thinking : Empathize and Define

Field observation identified three critical pain points. First the hazardous zone exposure analog HMI design required operators to stand within 1 meter of pumps operating at high RPM and pressure, constituting a hazardous manual task with significant ergonomic risk. Second, visual ergonomic limitations vibrating and dust-covered analog gauges induced parallax error and increased cognitive load, forcing operators to simultaneously maintain physical balance and read precision data. Third, workflow inefficiency data recording every 30 minutes required a minimum of eight operator trips per four-hour testing session, generating non-value-added activity and physical fatigue.

Table 2. User Journey Mapping

Stage	Action	Needs	Painpoints	Solution	User Feeling
Preparation	The operator / QC prepares a paper record sheet and walks toward the test bench area.	Ensure that all materials are available and ready for testing.	Manual process, requires carrying many physical files, noisy location.	The digital checklist is integrated into the system.	(Netral)

User Journey Map analysis showed that operator emotional experience declined sharply during the Data Logging phase, where fear and anxiety were dominant affective states. This finding directly informed the HMW problem statements. HMW1 targeted safety by eliminating the need for physical zone entry. HMW2 targeted data integrity through automated digital acquisition. HMW-3 targeted operational efficiency through remote control capability. The translation from observed user needs to concrete design requirements followed a direct traceability chain. Each pain point identified during the Empathize phase was mapped to a specific design requirement: the hazardous zone exposure pain point translated into a requirement for remote, zone-free monitoring; the parallax error and cognitive load pain point translated into a requirement for high-contrast digital readouts replacing analog gauges; and the workflow inefficiency pain point translated into a requirement for automated, continuous data acquisition eliminating manual recording trips. These requirements were then formally reframed as "How Might We" statements (Table 2) to guide the Ideate phase, ensuring that every feature ultimately implemented in the prototype could be traced back to a specific, empirically observed user need rather than being design-team assumptions.

Table 3. HMW Idea Mapping

How Might We (HMW)	Solution Idea	Feature Technical of Dashboard SCADA
HMW 1 (Safety): How can we provide transparent access and streamline reporting?	Virtually relocate observation points to the control room using an intuitive digital interface.	Safety Control Room: A dedicated room for viewing test data in real time and providing control access
HMW 2 (Data Integrity): How to improve data accuracy and eliminate manual recording?	Automatically acquire data directly from machine sensors (PLC) without human intervention.	• Real-time Data: Digital parameter & gauge display Interactive line charts to monitor data fluctuations.
HMW 3 (Efficiency & Trust): How to facilitate real-time monitoring and control without entering hazardous zones?	Simplify pump unit control processes and provide remote control functions from the control room	• Remote Control Remote Control Provide access to start/stop and adjust the speed of pump units remotely

Each Design Thinking phase produced a distinct, traceable output that fed directly into the next phase. The Empathize phase produced a documented set of three critical pain points and a User Journey Map identifying the Data Logging stage as the point of peak user distress. The Define phase translated these pain points into three formal "How Might We" problem statements, each targeting a specific dimension: safety, data integrity, and operational efficiency. The Ideate phase converted each HMW statement into a corresponding solution concept and dashboard feature, as summarized in Table 3. The Prototype phase then materialized these feature concepts into a functioning Node-RED interface integrating twelve real-time pump and engine parameters. Finally, the Test phase validated the prototype against real users and yielded two additional iterative features (Fault History and Trend Data), closing the design loop with direct evidence of user-driven refinement.

Design Thinking : Ideate Prototype and Testing

The prototype was developed using Node-RED, a flow-based visual programming capable of interfacing with industrial sensors, PLCs, and web-based visualization layers. The initial prototype integrated twelve engine and pump parameters flow rate, pump speed (RPM), discharge pressure, suction pressure, bearing temperature (DE), engine load, voltage, current, motor winding temperature, run hours, oil pressure, and cooling temperature previously distributed across physically separated analog instruments, into a single unified digital interface. Five core features were implemented, Remote Monitoring UI providing consolidated single-screen parameter visualization, Remote Start/Stop enabling engine initiation and shutdown commands from the Control Room, Speed Adjuster (RPM Control) providing stepped RPM adjustment for flow rate optimization, real-time Digital Gauge elements replacing analog dials with high-contrast digital readouts, and a structured Parameter Table displaying all twelve parameters with current values.

The final dashboard adopts a single-screen monitoring architecture, consolidating 12 previously dispersed analog parameters into one digital interface accessible from the Control Room. This design directly addresses the cognitive load and physical safety issues identified

in the Empathize phase, consistent with the Design Thinking principle that interface complexity should match the mental model of the end user. Two iterative features Fault History and Trend Data were added based on direct user feedback during the Testing phase, where QC Engineers identified the need for pressure and flow trend visualization, and operators identified the absence of threshold warning indicators.



Figure 4. Monitoring Dashboard

The Test phase was conducted as a formal usability testing session involving eight participants, comprising one supervisor, two QC Engineers, and five Operators who had direct prior experience with the manual FAT procedure. Participants were assigned three representative testing tasks reflecting real operational scenarios, such as initiating a remote start/stop sequence, reading real-time parameter values from the digital gauges, and reviewing the trend chart to identify an anomalous reading. Feedback gathered during this session directly informed the two iterative features described above (Fault History and Trend Data), evidencing a closed feedback loop between usability testing and design refinement

Outer Model Assessment

The measurement model was evaluated using three established criteria (Hair et al., 2019). convergent validity, internal consistency reliability, and discriminant validity. Convergent validity was confirmed as all 26 indicator loadings exceeded the 0.70 threshold (range: 0.760–0.944) and all construct AVE values exceeded 0.50 (range: 0.714–0.856), indicating that each construct explains more than half of its indicators' variance. Reliability was assessed via Cronbach's alpha and composite reliability; seven of eight constructs exceeded 0.79 on both measures, indicating high internal consistency. PEC was the sole exception, with Cronbach's alpha of 0.635 marginally acceptable per conventional thresholds ($\alpha > 0.60$) attributable to its two item measurement structure, which is inherently more sensitive to response variance than the four item constructs used elsewhere in the model. Discriminant validity was assessed through cross-loading analysis, confirming that each indicator loaded more strongly on its intended construct than on any other

Table 4. Outer Model Assessment Results

Construct	Loading Range	AVE	Cronbach's α	Composite Rel.	Status
PU	0.760 – 0.885	0.714	0.920	0.925	Valid & Reliable
PEOU	0.868 – 0.902	0.796	0.915	0.905	Valid & Reliable
ATU	0.854 – 0.899	0.761	0.895	0.897	Valid & Reliable
AU	0.828 – 0.915	0.766	0.898	0.903	Valid & Reliable
TSE	0.922 – 0.928	0.856	0.831	0.832	Valid & Reliable
PEC	0.832 – 0.878	0.732	0.635	0.644	Valid & Reliable
TA	0.909 – 0.909	0.827	0.791	0.791	Valid & Reliable
PE	0.808 – 0.944	0.772	0.726	0.902	Valid & Reliable

Inner Model Assessment

The structural model was evaluated using coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2), and path significance via bootstrapping (5,000 resamples). The model demonstrates strong predictive validity, explaining 72.1% of AU variance ($R^2 = 0.721$), 72.1% of PEOU variance, 67.5% of PU variance, and 60.3% of ATU variance. The substantial explanatory power across all four endogenous constructs is unlikely to stem from a single cause and is best understood as the joint product of two factors. First, from a theoretical standpoint, the model benefits from the fact that AU is explained through a single, dominant mediating pathway (ATU) rather than being split across multiple competing direct predictors parsimonious structural configurations of this kind tend to yield higher R^2 relative to models with more diffuse causal structures, a pattern consistent with prior TAM literature on strongly mediated adoption models (Davis, 1989). Second, the study setting itself likely contributed to the high explanatory power, the sample is drawn from a single organization with a homogeneous respondent population using one specific, mandatorily-adopted system.

This homogeneity reduces unexplained variance that would typically arise from heterogeneous user roles, voluntary adoption conditions, or cross-organizational differences common in multi-site TAM studies. Consequently, the high R^2 values should be interpreted as reflecting strong model fit within this specific organizational and demographic context, rather than as unconditional evidence of the Extended TAM3 framework's explanatory power in general. All Q^2 values exceeded zero (AU = 0.597, PEOU = 0.659, PU = 0.696, ATU = 0.534), confirming predictive relevance across all endogenous constructs. Model fit was assessed using SRMR and NFI following Hu and Bentler's (1998) guidelines.

The estimated model's SRMR of 0.066 falls within the acceptable range (< 0.08 – 0.10). The NFI value of 0.714 falls below the conventional 0.90 threshold applied in covariance-based SEM (CB-SEM). While it is methodologically accurate that SRMR and NFI originate from CB-SEM and are treated as supplementary rather than primary criteria in PLS-SEM (Hair et al., 2019), this methodological distinction should not be read as fully absolving the lower NFI value of interpretive weight. We therefore treat the below-threshold NFI as a genuine limitation of the model rather than an artifact of applying the wrong criterion: it suggests that some portion of covariance structure among the observed indicators is not fully captured by

the specified model, even though the model's predictive metrics (R^2 , f^2 , Q^2) remain strong. Plausible sources of this gap include unmeasured contextual variables specific to the mandatory-adoption, safety-critical setting, such as supervisory pressure or prior incident history, that were outside the scope of the Extended TAM3 constructs used here. Future studies replicating this model in comparable industrial settings should consider incorporating additional contextual covariates and reporting HTMT-based discriminant validity alongside model fit indices to build a fuller picture of model adequacy. Path coefficient results are presented in Table 5.

Table 5. Inner Model Path Coefficients and Effect Sizes

Path	β	T-Statistic	p-Value	f^2	Decision
ATU $\rightarrow$ AU	0.849	28.921	0.000	0.882	Supported $\checkmark$
PEOU $\rightarrow$ PU	0.821	23.779	0.000	0.773	Supported $\checkmark$
TSE $\rightarrow$ PEOU	0.494	4.818	0.000	0.386	Supported $\checkmark$
PU $\rightarrow$ ATU	0.454	3.591	0.000	0.169	Supported $\checkmark$
PE $\rightarrow$ PEOU	0.270	2.853	0.004	0.141	Supported $\checkmark$
PEOU $\rightarrow$ ATU	0.317	2.780	0.005	0.106	Supported $\checkmark$
PEC $\rightarrow$ PEOU	-0.046	0.388	0.698	0.004	Not Supported
TA $\rightarrow$ PEOU	0.250	1.753	0.080	0.092	Not Supported

Actual Usage (AU) and Determinant

The Actual Usage (AU) variable has an R^2 value of 0.72 meaning that 72.1% of the variation in actual SCADA system usage behavior is strongly explained by the model. The results of the structural path analysis indicate that AU is directly and exclusively influenced by Attitude Toward Using (ATU) (path coefficient $\beta = 0,849$, t-statistic = 28,921, and p-value = 0,000) with a large effect size $f^2 = 0,882$. At the indicator level, consistently high mean AU values (4.216–4.383) were led by the AU1 indicator (safety indicator) with a score of 4.383. This confirms that work safety motivation in high-risk environments is the dominant driver of actual usage. These findings fully validate the TAM1 proposition regarding the role of attitude as a total mediator between the trust constructs (PU, PEOU) and actual behavior.

The success of this extrapolation demonstrates the applicability of the TAM1 model to a population of vocationally educated workers in the heavy industry sector, broadening the theory's generalizability beyond studies previously dominated by office information systems. From a managerial perspective, the success of digitalization is determined more by the organic formation of positive attitudes than by procedural or external incentives. This near complete mediation where PU and PEOU influence AU exclusively through ATU, with no direct paths retained represents a more parsimonious structure than typically reported in TAM3 extensions, which often retain a direct PU $\rightarrow$ AU path. This suggests that in safety-critical operational contexts, behavioral usage is governed less by a rational cost-benefit calculation (as PU $\rightarrow$ AU direct paths would imply) and more by an affectively mediated commitment to the system, reinforcing occupational safety motivation as a psychological rather than purely functional driver of adoption.

The roles of PU and PEOU to ATU

The path to ATU is significantly shaped by two main TAM variables, namely PU $\rightarrow$ ATU ($\beta = 0,454$, $t = 3,591$, $p = 0,000$) and PEOU - ATU ($t = 2,780$, $p = 0,005$). The larger path coefficient for PU confirms that perceptions of functional benefits (such as safety from hazardous zones and the elimination of human error) are stronger in dictating positive user attitudes than mere system ease of use. Although it has no direct path to AU, PEOU was found to have a very strong indirect effect through PU (β PEOU $\rightarrow$ PU = 0,821, $t = 23,779$, $p =$

0,000). This hierarchical pathway PEOU → PU → ATU → AU positions ease of use as the construct with the largest total indirect effect on actual usage. PEOU acts as the primary foundation that activates the entire SCADA technology adoption. A theoretically important finding emerges from the four TAM3 external determinants: only Technology Self-Efficacy ($\beta = 0.494$, $p = 0.000$) and Perceived Enjoyment ($\beta = 0.270$, $p = 0.004$) significantly predicted PEOU, while Perception of External Control and Technology Anxiety were both non-significant. This pattern is not a weakness of the model but a substantive finding about the boundary conditions of TAM3 in mandatory-adoption contexts. PEC captures perceived availability of organizational resources and support because SCADA usage in this study is a standardized, compulsory element of the FAT procedure rather than a discretionary choice, users' perception of external control over whether to adopt the system becomes largely irrelevant a mechanism consistent with prior findings that control-based determinants lose predictive power once adoption is compulsory (Brown et al., 2002). Similarly, the non-significance of Technology Anxiety, despite this population's relatively low technology exposure (84% non-university education), is explained by the low variance in TA scores themselves (mean 3.77–3.93) when a construct shows limited variability within a sample, its statistical capacity to explain variance in another construct is inherently constrained, irrespective of its conceptual relevance. Taken together, these results indicate that in safety-driven, mandatory-adoption industrial settings, internal psychological determinants (self-efficacy, enjoyment) retain their explanatory power, while external determinants (control, anxiety) do not a nuance that refines, rather than contradicts, the generalizability boundaries of the TAM3 framework (Venkatesh & Bala, 2008).

The Impact of Design Thinking on AU

Design Thinking was not modeled as a latent construct within the SEM-PLS structure and therefore its influence on AU cannot be statistically confirmed as a direct causal effect. However, its contribution can be descriptively inferred through the qualitative alignment between design decisions made during the Empathize-to-Prototype phases and the subsequently high PEOU scores (mean 4.183 – 4.252). The design interventions single-screen monitoring, high-contrast digital gauges, and automatic color-coded alerts were derived directly from pain points identified during the Empathize phase, and their correspondence with high PEOU ratings is consistent with, though not statistically proof of, a facilitating role for the design process. Similarly, the Testing phase, in which expert respondents directly operated the dashboard's remote-control functions prior to formal TAM measurement, is plausibly associated with the high ATU scores observed; direct interaction prior to attitude measurement is theoretically expected to produce more experientially-grounded, and typically more favorable, attitudes than evaluations based on imagined or described system use (Nigatu et al., 2024). We interpret this as a qualitative complementarity between the Design Thinking process and TAM outcomes, rather than a quantified causal pathway.

Practical Implications

For PT SBS and similarly-structured pump manufacturing facilities, three practical implications emerge. First, given that ATU is the sole significant predictor of AU, implementation strategy should prioritize attitude-building interventions, such as hands-on testing sessions prior to full deployment, over procedural mandates or external incentives alone. Second, because Technology Self-Efficacy is the strongest external predictor of PEOU, onboarding and training programs should emphasize building users' confidence in operating the system independently, rather than solely providing technical documentation or supervisory support, which corresponds to the non-significant PEC pathway. Third, the safety-driven usage pattern, in which the safety-indicator item AU1 scored highest at 4.383, suggests that framing SCADA adoption explicitly around occupational safety benefits, rather

than productivity or efficiency messaging alone, is likely to be the most effective adoption-driving narrative for similarly hazardous industrial environments.

Conclusion

For PT SBS and similarly-structured pump manufacturing facilities, three practical implications emerge. First, given that ATU is the sole significant predictor of AU, implementation strategy should prioritize attitude-building interventions such as hands on testing sessions prior to full deployment over procedural mandates or external incentives alone. Second, because Technology Self-Efficacy is the strongest external predictor of PEOU, onboarding and training programs should emphasize building users confidence in operating the system independently, rather than solely providing technical documentation or supervisory support (which corresponds to the non-significant PEC pathway). Third, the safety-driven usage pattern (AU1, the safety-indicator item, scored highest at 4.383) suggests that framing SCADA adoption explicitly around occupational safety benefits rather than productivity or efficiency messaging alone is likely to be the most effective adoption-driving narrative for similarly hazardous industrial environments.

This study demonstrates that using Design Thinking and TAM method provides a more comprehensive framework for SCADA system development and evaluation than applying either approach independently. The five-stage Design Thinking process produced a seven-feature SCADA dashboard that eliminates operator exposure to hazardous zones during FAT, directly addressing the critical safety, data integrity, and transparency deficits of the existing manual system. TAM evaluation confirmed high technology acceptance: the model explains 72.1% of Actual Usage variance, with Attitude Toward Using as the sole direct predictor ($\beta = 0.849$, $f^2 = 0.882$). Technology Self-Efficacy emerged as the critical external factor shaping ease-of-use perceptions, while occupational safety motivation was identified as the dominant driver of actual usage intent in this hazardous industrial context. Future research should conduct longitudinal measurement to verify behavioral usage after full deployment, apply multi-group analysis to examine acceptance differences across age and education sub-groups, and explore the formal operationalization of Design Thinking process quality as a latent construct within the TAM structural model.

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