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XAI-Powered Intelligent Compliance Management Systems for STCW and Environmental Regulatory Documentation at Maritime Training Institutions

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ABSTRACT

Maritime training institutions face overwhelming regulatory compliance burdens consuming 2,400+ annual staff hours manually compiling STCW certification evidence, verifying instructor qualifications against 2,847 specific requirements, cross-referencing simulator logs with competency standards, and preparing documentation for Port State Control inspections, yet manual processes suffer from 12-15% error rates creating certificate validity challenges, regulatory audit deficiencies, and graduate employability risks when documentation inadequacies discovered during vessel inspections. This research presents the design and validation of explainable artificial intelligence systems automating regulatory compliance verification while maintaining transparency and human oversight through interpretable decision logic, natural language explanations, and audit trail generation at Sekolah Tinggi Ilmu Pelayaran Jakarta. Employing design science research methodology with qualitative stakeholder evaluation, the study engaged compliance officers (n=8), quality assurance specialists (n=6), and regulatory auditors (n=7) through structured interviews examining automation accuracy, explanation adequacy, and institutional trust development. The knowledge graph-based XAI architecture integrated STCW Convention requirements, MARPOL environmental regulations, Indonesian maritime law, and institutional policies into unified semantic network enabling automated compliance verification, gap detection, and proactive remediation recommendations with SHAP-based feature attribution and attention mechanism visualization explaining AI reasoning. Thematic analysis revealed strong support for explainable compliance automation, identifying critical themes of administrative efficiency, audit readiness enhancement, and regulatory confidence improvement. Pilot implementation across 12-month period demonstrated 94% compliance verification accuracy, 89% reduction in manual documentation time (2,400 to 264 annual hours), 97% improvement in audit preparation completeness, and zero regulatory deficiencies during Ministry of Transportation accreditation inspection, contributing validated XAI architectures and empirical evidence supporting transparent intelligent automation in maritime regulatory compliance contexts addressing administrative burden reduction and institutional quality assurance imperatives.

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1. Introduction

Maritime training institutions operate within extraordinarily complex regulatory environments requiring compliance with International Maritime Organization STCW Convention specifying 2,847 distinct competency requirements across eleven functional areas, MARPOL environmental protection standards mandating sustainability and pollution prevention training, national maritime regulations varying by flag state including Indonesian maritime law containing 1,247 specific training institution requirements, port state control memoranda of understanding establishing regional inspection standards including Tokyo MOU covering Asia-Pacific with 847 quality criteria, and institutional accreditation frameworks from bodies including Indonesian National Accreditation Board requiring comprehensive quality management documentation, collectively creating regulatory compliance obligations consuming extraordinary administrative resources as institutions must continuously verify that training curricula, instructor qualifications, simulator capabilities, assessment processes, and student records satisfy multifaceted requirements spanning international conventions, national laws, regional agreements, and institutional standards, while maintaining comprehensive documentation proving compliance to regulatory authorities conducting inspections that directly impact institutional accreditation, graduate certificate validity, and reputation affecting enrollment and employer recognition [1].

Current compliance management approaches at maritime training institutions globally rely predominantly on manual processes where administrative staff, quality assurance officers, and department coordinators invest substantial time compiling evidence, cross-referencing requirements, identifying gaps, and preparing documentation including manual examination of thousands of student training records against STCW competency tables verifying each student completed required hours in navigation, engineering, safety, and specialized training areas, instructor qualification verification cross-checking faculty credentials against STCW trainer requirements ensuring appropriate certificates, endorsements, sea-time experience, and pedagogical qualifications, simulator compliance documentation proving equipment capabilities, maintenance records, and software updates satisfy convention standards for specific training scenarios, assessment process validation demonstrating examination content, practical test procedures, and grading rubrics align with competency standards, and institutional quality management evidence compiling policies, procedures, meeting minutes, and improvement initiatives satisfying accreditation requirements [2].

These manual compliance verification processes create multiple critical challenges including enormous administrative burden consuming 2,000-3,000 annual staff hours at typical maritime academies representing 1.0-1.5 full-time equivalent positions dedicated purely to regulatory compliance documentation rather than value-adding educational activities, human error vulnerabilities with manual cross-referencing across thousands of requirements and records producing 12-15% error rates creating compliance gaps that regulatory auditors identify during inspections, limited proactive gap detection as manual processes typically verify compliance reactively during audit preparation rather than continuously monitoring for emerging deficiencies enabling early remediation, delayed response to regulatory changes when international convention amendments or national law updates require curriculum modifications but institutions lack systematic mechanisms tracking regulatory evolution and triggering timely adaptations, and incomplete institutional knowledge where compliance understanding resides with few specialized staff creating succession risks when key personnel depart taking compliance expertise without systematic knowledge capture [3].

Sekolah Tinggi Ilmu Pelayaran Jakarta, Indonesia's premier maritime academy enrolling 3,500+ students annually across Navigation Officer, Marine Engineering Officer, and Maritime Business programs, exemplifies maritime education compliance challenges facing 1,200+ global maritime training institutions operating under similar regulatory frameworks. STIP Jakarta must maintain continuous STCW compliance for 127 distinct training courses, 180+ teaching faculty, 24 simulator systems, 6 training vessels, and 12 technical workshops serving 3,500 students generating 420,000 annual training hours requiring competency verification, while simultaneously satisfying Indonesian Ministry of Transportation accreditation standards, BPKP (Indonesia's Financial and Development Supervisory Agency) quality management requirements, and institutional policies governing educational delivery, student welfare, and safety management, creating compliance verification requirements consuming approximately 2,400 annual staff hours (equivalent to 1.15 full-time positions) dedicated to regulatory documentation through activities including quarterly compliance audits reviewing 10% sample of student records (approximately 350 students × 12 training areas × 4 quarters = 16,800 annual record verifications), annual instructor qualification reviews checking 180 faculty against 847 STCW trainer requirements (152,460 individual requirement checks), semi-annual simulator compliance documentation compiling 24 systems' maintenance logs, software updates, and capability matrices against convention standards, and continuous quality management documentation for accreditation maintaining 2,847 quality indicators across teaching, research, and community service domains [4].

Current manual processes at STIP Jakarta demonstrate documented inefficiencies and quality challenges including 14.3% error rate in student competency verification discovered during 2023 Ministry of Transportation accreditation inspection where manual record compilation missed 2,047 of 14,280 reviewed training hour entries creating documentation deficiencies requiring 6-week remediation effort consuming 340 additional staff hours, instructor qualification gaps affecting 12 of 180 faculty (6.7%) where manual verification failed to identify expired endorsements or missing pedagogical certificates until Port State Control inspection aboard training vessel questioned instructor credentials, simulator documentation incompleteness where 5 of 24 systems (20.8%) lacked complete maintenance records due to fragmented vendor databases and paper logbook archival creating audit preparation challenges, and reactive rather than proactive compliance management where gaps typically discovered during pre-inspection preparation 4-6 weeks before audits rather than continuous monitoring enabling early intervention, collectively creating audit preparation crisis cycles consuming 600-800 hours intensive effort immediately preceding regulatory inspections versus systematic ongoing compliance assurance distributing workload evenly throughout academic year [5].

Beyond administrative burden and quality concerns, compliance deficiencies create substantial institutional risks including accreditation jeopardy where systematic compliance gaps can result in conditional accreditation status requiring intensive remediation and follow-up inspections or in severe cases accreditation withdrawal affecting all graduates' certificate recognition, Port State Control detention exposure when training vessel inspections identify instructor qualification deficiencies or inadequate training documentation leading to vessel detention costing $25,000-$75,000 per incident plus reputational damage, graduate employability impacts when employers or manning agencies question certificate validity due to institutional compliance concerns, and legal liability where inadequate training documentation exposed during maritime accident investigations creates negligence claims against institutions whose graduates involved in casualties [6].

Artificial intelligence technologies offer promising approaches automating regulatory compliance verification through capabilities including natural language processing extracting requirements from regulatory documents, knowledge graphs representing complex regulatory frameworks as interconnected semantic networks, machine learning classifying training records and detecting compliance patterns, and automated reasoning inferring compliance status from evidence and rules, potentially transforming manual labor-intensive processes into efficient automated systems, yet traditional "black box" AI systems producing compliance determinations without transparent explanations prove unsuitable for regulatory contexts where institutions must justify decisions to auditors, understand AI reasoning to identify improvement opportunities, and maintain human accountability for compliance assurance rather than blindly accepting opaque algorithmic assessments potentially containing errors or biases, creating fundamental requirement that compliance AI systems must provide explainable, interpretable, auditable decision logic enabling human verification and regulatory acceptance [7].

Explainable AI (XAI) represents emerging AI paradigm emphasizing transparency and interpretability through techniques including feature attribution methods like SHAP (SHapley Additive exPlanations) quantifying how input features contribute to predictions, attention mechanisms highlighting which data elements AI focused on during decision-making, rule extraction deriving human-readable decision rules from complex models, counterfactual explanations showing how changing inputs would alter outcomes, and natural language generation producing human-understandable explanations of AI reasoning, collectively enabling "white box" AI systems where decision logic remains transparent and verifiable rather than opaque "black box" approaches producing predictions without justification, critical capability for regulatory compliance applications requiring auditability, accountability, and human oversight [8].

The fundamental research problem addresses the absence of explainable AI systems designed specifically for maritime regulatory compliance automation that can verify STCW competency requirements, instructor qualifications, simulator capabilities, and quality management standards with accuracy approaching or exceeding manual verification while providing transparent explanations enabling institutional staff to understand AI reasoning, verify decision correctness, identify compliance gaps requiring remediation, and satisfy regulatory auditors demanding evidence supporting compliance claims, all implemented within resource constraints limiting expensive custom AI development and requiring accessible interfaces for non-technical compliance officers lacking data science expertise, and validated through rigorous accuracy assessment plus stakeholder evaluation confirming trust development, explanation adequacy, and sustainable organizational adoption [9].

Specifically, this research investigates four interconnected questions establishing comprehensive investigation scope. First, what explainable AI architectures effectively automate maritime regulatory compliance verification integrating diverse data sources including student training records, instructor qualification databases, simulator logs, curriculum documentation, and assessment results with regulatory requirement frameworks spanning STCW Convention, MARPOL standards, Indonesian maritime law, and

institutional policies, while maintaining decision transparency through interpretable model designs, explanation generation capabilities, and audit trail documentation enabling human verification and regulatory acceptance?

Second, what explanation modalities including feature attribution quantifying requirement contribution to compliance determinations, attention visualization highlighting relevant evidence supporting decisions, natural language narratives describing AI reasoning in human-understandable terms, and counterfactual scenarios showing hypothetical compliance impacts of record changes most effectively support institutional staff understanding of automated compliance verification, trust development in AI system accuracy and reliability, gap identification enabling proactive remediation, and regulatory auditor confidence accepting AI-generated compliance documentation during inspections?

Third, what compliance verification accuracy levels do explainable AI systems achieve compared to manual human verification serving as gold standard benchmark, measured through precision quantifying confidence in positive compliance determinations, recall indicating completeness of compliance gap detection, F1-scores balancing precision and recall, and comparison against actual regulatory audit outcomes determining whether AI systems identify same deficiencies human auditors discover, plus cost-effectiveness analysis quantifying administrative time savings against AI development and operational costs establishing return on investment justifying technology deployment?

Fourth, how do explainable AI compliance systems impact institutional quality assurance measured through audit preparation efficiency, regulatory inspection performance, compliance gap remediation timeliness, and staff workload redistribution from routine documentation to value-adding improvement activities, plus stakeholder acceptance including compliance officer trust in automated verification, quality assurance specialist adoption in institutional processes, regulatory auditor confidence accepting AI-generated evidence, and organizational change management addressing workflow integration and cultural adaptation when implemented in Indonesian maritime education contexts characterized by limited AI expertise requiring accessible user interfaces, risk-averse regulatory cultures emphasizing conservative compliance approaches, and traditional manual verification preferences based on established practices and interpersonal relationships with regulatory authorities?

This research contributes significant theoretical and practical advances to explainable AI applications extending predominantly healthcare diagnosis and financial lending focus into regulatory compliance domains, and maritime education quality assurance scholarship addressing critical gaps in educational AI literature. Theoretically, it extends XAI frameworks predominantly developed for individual prediction tasks like medical diagnosis or loan approval into complex multi-requirement verification scenarios involving 2,847 interrelated STCW competency standards, demonstrating how explanation techniques require adaptation for regulatory contexts where decisions involve logical reasoning across multiple interconnected requirements rather than single prediction outputs, and where explanations must satisfy legal auditability standards beyond user understanding alone.

Methodologically, it validates knowledge graph approaches for regulatory framework representation demonstrating advantages over traditional database or document storage for capturing complex requirement relationships, inheritance hierarchies, and logical dependencies characteristic of maritime regulations, plus validates hybrid symbolic-neural AI architectures combining rule-based reasoning providing inherent interpretability with machine learning pattern recognition providing robustness to data variations, demonstrating optimal integration balancing explanation transparency and prediction accuracy.

Practically, the research delivers immediately deployable XAI compliance systems supporting Indonesia's maritime education quality assurance imperatives while providing empirical evidence of intelligent automation's impact on administrative efficiency, audit readiness, and regulatory performance. The validated knowledge graph schemas, XAI model architectures, explanation interface designs, and institutional adoption strategies inform technology deployment at Indonesia's 8 state maritime academies collectively investing 19,200+ annual staff hours in compliance documentation ($1.92 million annual labor cost at $100/hour average fully-loaded rate), potentially benefiting 1,200+ global maritime training institutions facing identical regulatory compliance burdens under STCW Convention universal applicability.

The investigation employs mixed-methods design science methodology combining iterative XAI system development through regulatory knowledge graph construction encoding STCW, MARPOL, Indonesian law, and institutional policies as interconnected semantic network, explainable AI model development implementing SHAP-based feature attribution and attention-based neural networks with natural language explanation generation, user interface design creating accessible compliance dashboards for non-technical staff, and pilot deployment processing actual STIP Jakarta compliance data across 12-month period, with comprehensive quantitative accuracy evaluation comparing AI compliance verification against human expert assessments and actual regulatory audit outcomes measuring precision, recall, F1-scores, and cost-

effectiveness through before-after staff time comparison, plus qualitative stakeholder evaluation through compliance officer interviews (n=8 responsible for STCW verification, quality management documentation, and audit preparation), quality assurance specialist consultations (n=6 managing institutional accreditation, curriculum quality, and continuous improvement), and regulatory auditor focus groups (n=7 from Ministry of Transportation, BPKP, and Port State Control conducting compliance inspections at maritime training institutions), analyzing perspectives through systematic thematic analysis identifying XAI system utility dimensions, explanation adequacy assessments, trust development factors, and adoption requirements, ultimately informing evidence-based recommendations for explainable AI deployment in maritime regulatory compliance supporting administrative efficiency enhancement, quality assurance improvement, and regulatory confidence strengthening critical to institutional sustainability and graduate certificate validity protection.

2. Research Method

This research employs design science research methodology combined with explainable AI system development protocols and rigorous accuracy validation procedures, creating systematic approach particularly suited for developing and evaluating transparent intelligent automation artifacts through iterative cycles of regulatory knowledge modeling, XAI algorithm implementation, explanation interface design, pilot deployment, accuracy assessment, and stakeholder validation, as established by Hevner et al.'s foundational framework adapted for explainable AI applications in regulatory compliance contexts [10]. Design science methodology proves especially appropriate for XAI research where innovation success depends not only on prediction accuracy measured through precision-recall metrics, but critically on explanation quality enabling human understanding and trust, regulatory acceptance satisfying audit requirements, and demonstrated administrative efficiency improvements justifying technology investments, requiring qualitative investigation alongside quantitative performance metrics [11].

The research integrates XAI system technical evaluation measuring classification accuracy and explanation quality, comprehensive operational impact assessment quantifying administrative time savings and audit performance improvements through before-after comparison, and qualitative stakeholder evaluation examining trust development and adoption requirements, recognizing that explainable AI platforms must satisfy diverse requirements spanning technical specialists evaluating algorithmic robustness, compliance officers assessing decision support utility, quality assurance specialists determining institutional integration feasibility, and regulatory auditors confirming legal auditability adequacy [12].

The research population comprises three distinct stakeholder groups essential for holistic XAI compliance system validation. The compliance officer group (n=8) includes STCW certification coordinator managing student competency verification and certificate issuance, instructor qualification specialist tracking faculty credentials and trainer endorsements, simulator compliance manager documenting equipment capabilities and maintenance, quality management coordinator compiling institutional accreditation evidence, two department compliance representatives overseeing Navigation and Engineering program regulatory adherence, external audit liaison coordinating Ministry of Transportation and Port State Control inspections, and compliance database administrator maintaining training records and documentation systems, selected to represent diverse compliance verification responsibilities, averaging 9.4 years maritime education compliance experience.

The quality assurance specialist group (n=6) consists of institutional quality assurance director managing overall accreditation strategy, curriculum quality coordinator evaluating teaching effectiveness and learning outcomes, assessment validation specialist ensuring examination rigor and fairness, continuous improvement analyst tracking quality indicators and improvement initiatives, BPKP liaison coordinating financial and quality audits with government supervisory agency, and internal audit manager conducting self-assessment compliance reviews, averaging 12.1 years quality management experience across maritime education and commercial sectors.

The regulatory auditor group (n=7) encompasses three Ministry of Transportation maritime education inspectors conducting STCW compliance audits, two BPKP quality system auditors evaluating institutional management practices, and two Port State Control officers inspecting training vessels and reviewing instructor qualifications, averaging 15.3 years regulatory inspection experience across maritime training institutions, commercial vessels, and government oversight, selected to provide authoritative assessment of XAI-generated compliance documentation's acceptability during actual regulatory inspections.

Research instruments integrate automated XAI system performance metrics, comprehensive compliance verification accuracy assessment, and structured qualitative protocols. The primary technical instrument comprises knowledge graph-based XAI architecture implementing Neo4j graph database encoding 2,847 STCW competency requirements, 1,247 Indonesian maritime law provisions, 847 Tokyo MOU quality criteria, 324 MARPOL training standards, and 2,847 institutional quality indicators as interconnected semantic

network with 14,294 nodes and 47,382 relationships representing requirement hierarchies, logical dependencies, and cross-references.

The XAI model architecture combines symbolic reasoning using Cypher graph query language for deterministic requirement checking with neural network classification using attention-based transformers (BERT fine-tuned on maritime regulatory text corpus) for fuzzy pattern matching in unstructured documentation, integrated through ensemble approach weighting symbolic and neural predictions based on confidence scores and explanation availability. SHAP (SHapley Additive exPlanations) feature attribution quantifies how student training records, instructor qualifications, or simulator capabilities contribute to compliance determinations. Attention mechanism visualization highlights specific requirement text and evidence documents supporting decisions. Natural language generation using GPT-2 fine-tuned on regulatory explanation corpus produces human-readable narratives describing compliance reasoning.

Independent variables systematically examined include compliance domains (STCW competency verification, instructor qualifications, simulator capabilities, quality management), requirement types (mandatory must-have, recommended should-have, optional may-have), evidence sources (structured databases, semi-structured logs, unstructured documents), and stakeholder roles (compliance officers, quality specialists, regulatory auditors). Dependent variables measured encompass XAI prediction accuracy (precision, recall, F1-scores comparing AI classifications to expert human assessments), explanation quality (comprehensibility ratings, trust development, decision justification adequacy), administrative efficiency (staff hours required for compliance verification before versus after XAI deployment), and audit performance (regulatory inspection scores, identified deficiencies, preparation completeness).

Qualitative instruments utilize semi-structured interview protocols for compliance officers (90-minute sessions) exploring XAI system decision support utility, explanation adequacy for understanding compliance determinations, trust development through repeated verification experiences, workflow integration feasibility, and cost-benefit perceptions. Quality assurance specialist consultation guides (75-minute sessions) examine institutional integration strategies, continuous improvement applications, accreditation evidence generation, and organizational change requirements. Regulatory auditor focus groups (120-minute sessions) assess AI-generated documentation acceptability, explanation transparency adequacy, audit trail sufficiency, and legal auditability standards compliance [13].

Data collection proceeded through five sequential phases aligned with design science cycles and XAI validation requirements. Phase one conducted comprehensive regulatory knowledge acquisition compiling complete STCW Convention text, MARPOL annexes, Indonesian maritime law compilation, Tokyo MOU criteria, and STIP Jakarta institutional policies totaling 14,847 distinct requirements through systematic document analysis, expert consultation with 12 compliance specialists, and regulatory database integration, followed by knowledge graph schema design and encoding using Neo4j creating interconnected semantic network representing requirement relationships and logical dependencies.

Phase two implemented XAI model development including BERT transformer fine-tuning on 2,300 maritime regulatory documents achieving domain-specific language understanding, attention mechanism implementation highlighting relevant requirement text during compliance verification, SHAP integration calculating feature attributions quantifying evidence contribution to decisions, natural language explanation generator development using GPT-2 producing human-readable compliance narratives, and symbolic reasoning rule implementation encoding deterministic requirement logic where appropriate, with progressive testing validating prediction accuracy and explanation quality through iterative refinement cycles.

Phase three executed accuracy validation creating gold standard dataset where three independent compliance experts manually verified 500 randomly sampled student records, instructor qualifications, and simulator documentation against complete regulatory requirements achieving inter-rater reliability Cohen's kappa 0.87 indicating substantial agreement, then comparing XAI system classifications to expert consensus measuring precision (correctly identified compliances ÷ all positive AI predictions), recall (correctly identified compliances ÷ all actual compliances), and F1-scores balancing precision-recall trade-offs, plus conducting temporal validation using historical data where XAI system predicted compliance status for 2022-2023 records compared against actual regulatory audit findings from Ministry of Transportation and Port State Control inspections establishing real-world accuracy.

Phase four implemented 12-month pilot deployment (January-December 2024) where XAI system provided compliance verification and gap detection for actual STIP Jakarta operations including monthly automated student competency verification for 350 graduating students, quarterly instructor qualification review for 180 faculty, semi-annual simulator compliance documentation for 24 systems, and continuous quality management monitoring for 2,847 institutional indicators, with comprehensive tracking of staff time required for compliance activities, identified gaps and remediation actions, and audit preparation efforts enabling before-after efficiency comparison.

Phase five conducted stakeholder evaluation through compliance officer interviews, quality specialist consultations, and regulatory auditor focus groups following sufficient operational experience (minimum 9 months XAI system usage) enabling informed judgments about utility, trust, limitations, and adoption requirements grounded in authentic compliance workflows rather than demonstration scenarios [14].

Data analysis employed triple-track methodology integrating XAI technical performance evaluation, operational impact quantification, and qualitative thematic analysis. Technical performance analysis calculated classification metrics including precision, recall, F1-scores, accuracy, and area under ROC curve for compliance verification tasks. Explanation quality assessment surveyed stakeholders rating comprehensibility, completeness, usefulness, and trust impact of SHAP attributions, attention visualizations, and natural language narratives using 10-point Likert scales. Computational efficiency measured query response times and processing throughput.

Operational impact analysis compared 12-month pilot period against historical baseline using independent samples t-tests for continuous variables (staff hours, audit scores) and chi-square tests for categorical outcomes (compliance gaps identified, audit deficiencies). Cost-benefit analysis quantified XAI development costs ($287,000 including knowledge graph construction $94,000, model development $127,000, interface design $42,000, deployment $24,000) and annual operating costs ($47,000 for cloud infrastructure, software licenses, technical support) against administrative time savings and audit performance improvements. Thematic analysis of qualitative data proceeded through systematic coding achieving Cohen's kappa 0.86, followed by axial coding, cross-group analysis, and narrative synthesis [15].

3. Results and Discussion

3.1 Results and Analysis

The explainable AI compliance system demonstrated substantial effectiveness across accuracy metrics, operational efficiency indicators, and audit performance improvements during 12-month pilot implementation at STIP Jakarta. Comprehensive evaluation encompassing knowledge graph encoding 14,294 regulatory requirement nodes, XAI processing 47,382 compliance verification queries, and operational data tracking 2,400 baseline versus 264 pilot staff hours revealed significant improvements in maritime regulatory compliance management while providing validated transparent intelligent automation architecture.

The hybrid symbolic-neural XAI architecture achieved strong prediction accuracy validating modeling approach. Overall compliance classification accuracy reached 94.2% (correctly classified 471 of 500 gold standard test cases), with precision of 0.93 (279 of 300 positive AI predictions were correct, 21 false positives), recall of 0.94 (279 of 297 actual compliances detected, 18 false negatives), and F1-score of 0.935 indicating excellent balanced performance. Accuracy varied by compliance domain with highest performance for instructor qualifications (96.3% accuracy) where structured credential databases enabled precise verification, strong performance for STCW competency verification (94.7%) despite complex multi-requirement checking, moderate performance for simulator compliance (91.2%) with more subjective capability assessments, and lower performance for quality management (88.4%) involving unstructured documentation and qualitative criteria.

Table 1: Explainable AI System Classification Performance

XAI Performance Metric	Measurement	Assessment
Overall Classification Accuracy	94.2% (471/500 correct)	Excellent performance
Precision (Positive Prediction Confidence)	0.93 (279/300 correct positives)	High confidence
Recall (Compliance Detection Completeness)	0.94 (279/297 compliances found)	Excellent coverage
F1-Score (Balanced Accuracy)	0.935	Strong overall performance
Instructor Qualification Accuracy	96.3%	Domain-specific excellence
STCW Competency Verification Accuracy	94.7%	Strong performance
Simulator Compliance Accuracy	91.2%	Good performance
Quality Management Accuracy	88.4%	Acceptable performance
Temporal Validation (2022-2023 Audit Prediction)	91.7% agreement with actual findings	Strong predictive validity

Temporal validation demonstrated strong predictive capability where XAI system analyzing 2022-2023 historical data identified 91.7% agreement with actual regulatory audit findings (87 of 95 compliance gaps discovered during Ministry of Transportation and Port State Control inspections were predicted by XAI retrospective analysis, plus 12 additional gaps XAI identified not caught by auditors, 8 XAI false positives flagging non-issues), validating real-world accuracy beyond controlled test set evaluation.

Explanation quality assessment revealed stakeholder satisfaction with XAI transparency mechanisms. SHAP feature attribution comprehensibility averaged 8.3/10.0 from compliance officers who valued quantitative contribution scores showing which specific requirements or evidence elements drove decisions.

Attention visualization usefulness rated 7.9/10.0 with stakeholders appreciating highlighted text indicating AI focus areas though sometimes finding visualizations overwhelming for documents with hundreds of requirements. Natural language explanation clarity achieved 8.7/10.0 with users strongly preferring narrative descriptions over purely technical outputs. Overall trust in XAI compliance determinations averaged 8.1/10.0 indicating strong but not unconditional confidence, with stakeholders emphasizing continued human verification importance for high-stakes decisions.

Table 2: Explanation Quality Assessment by Stakeholder Groups

Explanation Modality	Comprehensibility Rating	Usefulness Rating	Trust Impact	Stakeholder Preference
SHAP Feature Attribution	8.3/10.0	8.5/10.0	High	34% primary preference
Attention Visualization	7.9/10.0	7.6/10.0	Moderate	18% primary preference
Natural Language Narratives	8.7/10.0	8.9/10.0	Very High	48% primary preference
Combined Multi-Modal	N/A	9.1/10.0	Highest	Optimal approach
Overall XAI Trust Level	N/A	N/A	8.1/10.0	Strong confidence

Operational efficiency improvements proved dramatic. Annual staff time required for compliance verification decreased 89% from 2,400 hours baseline (representing 1.15 FTE) to 264 hours pilot period, generating 2,136 hours (1.03 FTE) administrative time savings valued at $213,600 annually at $100/hour fully-loaded labor cost. Time savings distributed across activities including student competency verification (92% reduction from 960 to 77 hours annually through automated STCW requirement checking), instructor qualification review (87% reduction from 720 to 94 hours via automated credential validation), simulator compliance documentation (84% reduction from 480 to 77 hours through automated evidence compilation), and quality management monitoring (91% reduction from 240 to 22 hours via continuous automated indicator tracking).

Beyond direct time savings, XAI enabled shift from reactive to proactive compliance management where continuous automated monitoring identified emerging gaps immediately enabling timely remediation versus traditional quarterly manual audits discovering issues months after occurrence creating larger remediation efforts. During pilot period, XAI detected 127 compliance gaps average 8.3 weeks before they would have been discovered through traditional processes (47 instructor certificate expirations flagged 12 weeks ahead enabling renewal without lapse, 38 student competency deficiencies identified 6 weeks before graduation enabling supplementary training, 24 simulator maintenance requirements detected 4 weeks ahead of scheduled audits preventing audit findings, and 18 quality management documentation gaps discovered 10 weeks before accreditation review enabling correction).

Table 3: Administrative Efficiency Improvements

Operational Efficiency Metric	Baseline (Manual)	Pilot (XAI-Automated)	Improvement
Total Annual Compliance Staff Hours	2,400 hours (1.15 FTE)	264 hours (0.13 FTE)	2,136 hours saved (89%)
Student Competency Verification	960 hours	77 hours	883 hours saved (92%)
Instructor Qualification Review	720 hours	94 hours	626 hours saved (87%)
Simulator Compliance Documentation	480 hours	77 hours	403 hours saved (84%)
Quality Management Monitoring	240 hours	16 hours	224 hours saved (93%)
Annual Administrative Cost Savings	N/A	$213,600 (at $100/hr)	Value of time saved
Proactive Gap Detection Lead Time	0 weeks (reactive)	8.3 weeks average	Early intervention enabled
Compliance Gaps Identified	47 (quarterly audits)	127 (continuous monitoring)	170% increase in detection

Audit performance demonstrated substantial quality improvements. Ministry of Transportation accreditation inspection conducted in October 2024 identified zero compliance deficiencies representing 100% inspection pass rate versus 14.3% deficiency rate during previous 2023 inspection before XAI deployment, with inspectors commending comprehensive documentation, proactive gap remediation, and audit preparation completeness. Port State Control inspections of training vessels conducted during pilot period found zero instructor qualification deficiencies versus 6.7% deficiency rate historically, attributing improvement to automated credential monitoring flagging expirations before vessel deployments. BPKP quality audit achieving "exemplary" 96.4% compliance score versus "satisfactory" 78.2% baseline score before XAI implementation.

Audit preparation efficiency improved dramatically with staff reporting 97% reduction in intensive pre-inspection preparation time from historical 600-800 hour crisis efforts 4-6 weeks before audits to 18-24 hours final verification review immediately before inspections, enabled by continuous XAI compliance monitoring maintaining audit-ready status rather than requiring emergency gap remediation during compressed pre-inspection periods.

Table 4: Regulatory Audit Performance Improvements

Audit Performance Indicator	Baseline (Pre-XAI)	Pilot Period (XAI)	Improvement
Ministry of Transportation Deficiency Rate	14.3% (2023 inspection)	0% (2024 inspection)	14.3 point improvement
Port State Control Deficiencies	6.7% historical rate	0% during pilot	6.7 point improvement
BPKP Quality Audit Score	78.2% (satisfactory)	96.4% (exemplary)	18.2 point improvement
Audit Preparation Hours	600-800 hours (crisis mode)	18-24 hours (verification)	97% reduction
Compliance Gaps Found by Auditors	47 findings (2023)	0 findings (2024)	Perfect performance
Audit Readiness Status	Periodic (quarterly)	Continuous (real-time)	Fundamental transformation

Cost-benefit analysis demonstrated compelling economic value. Total XAI development cost of $287,000 plus $47,000 annual operating costs compared favorably against $213,600 annual administrative time savings plus estimated $180,000 annual value of audit performance improvements (reduced deficiency remediation costs, avoided accreditation risks, enhanced institutional reputation) totaling $393,600 annual benefits, generating $346,600 net annual value ($393,600 benefits - $47,000 operating costs) and 10-month payback period ($287,000 implementation ÷ $346,600 net annual value × 12 months) providing strong return on investment justification.

Comprehensive qualitative evaluation revealed stakeholder endorsement with implementation considerations. Compliance officer perspectives (n=8) demonstrated 88% support (7 of 8 endorsing continued XAI usage, 1 preferring traditional methods). Six dominant themes emerged: **Administrative Burden Relief** emerged primary, with officers enthusiastically reporting 89% time savings enabling focus on strategic improvement activities rather than routine verification, noting particular value of automated student competency checking eliminating tedious manual cross-referencing thousands of training hours against STCW tables.

Proactive Gap Detection constituted second theme, with staff appreciating continuous monitoring identifying compliance issues immediately enabling timely remediation versus quarterly manual audits discovering problems months late creating larger remediation efforts, citing specific examples where XAI flagged instructor certificate expirations 12 weeks ahead preventing lapses that would have grounded training vessels.

Explanation Transparency represented third priority, with compliance officers valuing SHAP, attention, and natural language explanations enabling verification of XAI reasoning and confidence assessment, though noting occasional explanation complexity requiring technical background to fully interpret feature attributions and attention weights, recommending simplified explanation modes for diverse staff technical literacy levels.

Trust Development emerged fourth theme, with officers reporting gradual confidence increase through repeated verification experiences confirming XAI accuracy, though maintaining healthy skepticism emphasizing human oversight importance for high-stakes decisions, noting 94% accuracy means 6% error rate requiring vigilant review preventing blind acceptance of automated determinations.

Workflow Integration constituted fifth theme, with staff successfully incorporating XAI into daily routines through compliance dashboard usage, automated gap alerts monitored via email notifications, and monthly compliance reports generated automatically, though noting initial learning curve understanding system capabilities and optimal utilization strategies.

Audit Preparation Transformation formed final theme, with officers emphasizing fundamental shift from crisis-mode intensive preparation to confident continuous readiness enabled by real-time compliance monitoring, noting Ministry of Transportation inspectors' positive reception of comprehensive XAI-generated documentation providing detailed audit trails and evidence compilation.

Representative compliance officer assessment: *"XAI system transformed compliance from overwhelming administrative burden consuming 30% of my work time to manageable oversight requiring 3-4% effort, freeing me for strategic improvement initiatives. The 94% accuracy with SHAP and natural language explanations builds confidence while maintaining appropriate human verification for final decisions. Zero deficiencies on Ministry inspection versus 14% historically demonstrates tangible quality improvement beyond just efficiency gains."* [Compliance Officer 5]

Quality assurance specialist perspectives (n=6) revealed unanimous 100% endorsement with enthusiastic adoption interest. Five major themes emerged: Institutional Quality Enhancement emerged primary, with specialists citing 18.2-point BPKP audit score improvement (78.2% to 96.4%) as evidence of comprehensive quality elevation beyond compliance documentation, attributing enhancement to continuous monitoring enabling systematic gap remediation and quality management maturation.

Accreditation Confidence constituted second theme, with specialists expressing strong confidence in sustained accreditation renewal given zero-deficiency Ministry inspection and exemplary BPKP rating, eliminating previous anxiety about potential conditional status or intensive remediation requirements during multi-year accreditation cycles.

Continuous Improvement Integration represented third priority, with specialists incorporating XAI gap detection into institutional improvement processes where identified deficiencies trigger systematic root cause analysis, corrective actions, and preventive measures rather than purely reactive compliance fixes, demonstrating quality management system maturation.

Evidence-Based Decision Making emerged fourth theme, with specialists utilizing XAI-generated compliance analytics for strategic planning including curriculum modifications addressing systematic competency gaps, resource allocation prioritizing high-deficiency areas, and faculty development targeting qualification weaknesses revealed through credential monitoring.

Change Management Requirements formed final theme, with specialists noting organizational cultural transformation required for XAI adoption addressing initial staff resistance to AI "replacing" human judgment, emphasizing stakeholder engagement, transparent communication about AI augmenting rather than replacing human roles, and gradual rollout building confidence through pilot successes demonstrating value.

Regulatory auditor perspectives (n=7) provided authoritative validation with 86% acceptance (6 of 7 endorsing XAI-generated documentation adequacy, 1 expressing reservations). Four major themes emerged: Documentation Comprehensiveness emerged primary, with auditors praising XAI-generated compliance evidence completeness, detailed audit trails, and systematic organization enabling efficient inspection execution, noting stark contrast to fragmented manual documentation requiring extensive clarification and supplementary evidence requests.

Explanation Transparency Validation constituted second theme, with auditors confirming SHAP attributions and natural language narratives provided adequate decision justification satisfying legal auditability standards, though recommending explicit human verification certification accompanying AI-generated reports maintaining human accountability for compliance determinations.

Accuracy Confidence represented third priority, with auditors noting zero findings during 2024 Ministry inspection validating XAI system effectiveness, though emphasizing continued skeptical independent verification importance rather than accepting AI determinations without questioning, reflecting professional auditor culture emphasizing thoroughness and professional skepticism.

Regulatory Framework Evolution formed final theme, with auditors anticipating AI adoption acceleration across maritime training institutions requiring regulatory guidance development addressing AI compliance system acceptability standards, minimum accuracy thresholds, human oversight requirements, and audit trail specifications ensuring consistent implementation quality and regulatory confidence.

3.2 Discussion

The research findings comprehensively address original research questions while revealing implementation insights with broader implications for XAI adoption in regulatory compliance and maritime education quality assurance. The demonstrated 94.2% classification accuracy with 0.93 precision and 0.94 recall validates hybrid symbolic-neural architecture combining rule-based reasoning and machine learning pattern recognition, contradicting assumptions that either pure symbolic AI or pure neural networks alone suffice for complex regulatory verification, instead demonstrating complementary strengths integration where symbolic reasoning provides inherent interpretability and neural networks provide robustness to documentation variations [16].

The 89% administrative time reduction (2,400 to 264 annual hours) combined with zero audit deficiencies demonstrates XAI's dual value delivering both efficiency gains and quality improvements, enabling staff reallocation from routine verification to strategic enhancement activities while simultaneously improving regulatory performance through proactive gap detection and comprehensive documentation, addressing persistent tension between administrative burden relief and quality assurance maintenance by delivering both outcomes simultaneously rather than trading one against the other [17].

The explanation quality findings revealing 8.3/10.0 SHAP comprehensibility, 8.7/10.0 natural language clarity, and 8.1/10.0 overall trust validate multi-modal explanation approach combining quantitative feature attribution, visual attention highlighting, and narrative description providing complementary transparency mechanisms addressing diverse stakeholder preferences and technical literacy levels, with stakeholder emphasis on natural language explanations (48% primary preference) suggesting narrative descriptions prove most accessible for non-technical compliance officers despite SHAP and attention mechanisms' technical sophistication [18].

However, stakeholder-identified implementation considerations including 6% error rate requiring continued human verification, explanation complexity challenging less technical staff, initial resistance to AI adoption reflecting cultural preferences for established manual practices, and regulatory framework gaps lacking formal AI acceptability standards, highlight that technical capability alone proves insufficient for sustainable deployment without corresponding investments in user training, organizational change management, and regulatory advocacy establishing formal AI compliance system legitimacy [19].

The finding that regulatory auditors endorsed XAI-generated documentation (86% acceptance) while emphasizing human oversight importance and requesting explicit human verification certification demonstrates balanced perspective recognizing AI value while maintaining professional accountability standards, suggesting optimal approach positions XAI as decision support augmenting rather than replacing human judgment, with humans retaining final authority and responsibility for compliance determinations supported by AI-generated evidence and analysis [20].

4. Conclusion

This research successfully designed, implemented, and validated explainable AI regulatory compliance systems achieving 94.2% verification accuracy with 0.93 precision and 0.94 recall, 89% administrative time reduction from 2,400 to 264 annual staff hours valued at $213,600 savings, and zero regulatory audit deficiencies during Ministry of Transportation accreditation inspection representing perfect compliance performance versus 14.3% historical deficiency rate. Comprehensive stakeholder validation across compliance officers, quality assurance specialists, and regulatory auditors revealed 86-100% endorsement coupled with implementation requirements including continued human oversight, multi-modal explanation provision, organizational change management, and regulatory framework development. The knowledge graph-based XAI architecture encoding 14,294 regulatory requirements with hybrid symbolic-neural reasoning successfully processed 47,382 compliance queries during 12-month pilot demonstrating technical reliability (99.1% uptime), decision transparency (8.1/10.0 stakeholder trust), and cost-effectiveness (10-month payback period), contributing validated transparent intelligent automation architectures, explanation interface designs, and empirical evidence supporting XAI adoption in maritime regulatory compliance. The demonstrated administrative burden relief enabling staff reallocation to strategic improvement combined with audit performance enhancement achieving exemplary 96.4% BPKP quality rating positions explainable AI as transformative technology addressing Indonesia's maritime education quality assurance imperatives and institutional sustainability requirements, while providing replicable framework transferable to 1,200+ global maritime training institutions collectively investing 2.4+ million annual staff hours in manual regulatory compliance verification offering $240+ million potential efficiency savings through intelligent automation adoption supporting educational mission focus rather than administrative documentation burden.

REFERENCES

[1] International Maritime Organization, *STCW Convention Including 2010 Manila Amendments*. London, UK: IMO Publishing, 2017.
[2] A. Manuel and T. Baumler, "Digital transformation in maritime education," *WMU Journal of Maritime Affairs*, vol. 19, pp. 495-513, 2020.
[3] M. B. Simanjuntak, T. Handayani, and S. Soejatminah, "Quality assurance in maritime education," *Journal of Maritime Education*, vol. 12, no. 3, pp. 45-62, 2023.
[4] STIP Jakarta, *Accreditation Self-Evaluation Report 2024*. Jakarta: STIP Jakarta, 2024.
[5] Ministry of Transportation Republic of Indonesia, *Maritime Education Quality Standards 2020-2025*. Jakarta: Directorate General of Sea Transportation, 2020.
[6] International Association of Maritime Universities, *Best Practices in Maritime Education Quality Assurance*. Tokyo: IAMU, 2021.
[7] D. Gunning et al., "XAI—Explainable artificial intelligence," *Science Robotics*, vol. 4, no. 37, eaay7120, 2019.
[8] A. Adadi and M. Berrada, "Peeking inside the black-box: A survey on explainable artificial intelligence," *IEEE Access*, vol. 6, pp. 52138-52160, 2018.
[9] C. Molnar, *Interpretable Machine Learning: A Guide for Making Black Box Models Explainable*, 2nd ed. Online: Leanpub, 2022.
[10] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design science in information systems research," *MIS Quarterly*, vol. 28, no. 1, pp. 75-105, 2004.
[11] W. Samek, T. Wiegand, and K. Müller, "Explainable artificial intelligence: Understanding, visualizing and interpreting deep learning models," *ITU Journal*, vol. 1, pp. 1-10, 2017.
[12] D. Gašević, S. Dawson, and G. Siemens, "Let's not forget: Learning analytics are about learning," *TechTrends*, vol. 59, no. 1, pp. 64-71, 2015.
[13] J. W. Creswell and V. L. Plano Clark, *Designing and Conducting Mixed Methods Research*, 3rd ed. Thousand Oaks, CA: SAGE, 2018.
[14] A. Pardo and G. Siemens, "Ethical and privacy principles for learning analytics," *British Journal of Educational Technology*, vol. 45, no. 3, pp. 438-450, 2014.
[15] S. M. Lundberg and S. Lee, "A unified approach to interpreting model predictions," in *Proc. 31st Conf. NeurIPS*, Long Beach, CA, 2017, pp. 4765-4774.

[16] R. Guidotti et al., "A survey of methods for explaining black box models," *ACM Computing Surveys*, vol. 51, no. 5, article 93, 2019.
[17] M. Fullan, *The New Meaning of Educational Change*, 5th ed. New York: Teachers College Press, 2016.
[18] T. Miller, "Explanation in artificial intelligence: Insights from the social sciences," *Artificial Intelligence*, vol. 267, pp. 1-38, 2019.
[19] V. Venkatesh and F. D. Davis, "A theoretical extension of the technology acceptance model," *Management Science*, vol. 46, no. 2, pp. 186-204, 2000.
[20] M. T. Ribeiro, S. Singh, and C. Guestrin, "Why should I trust you? Explaining the predictions of any classifier," in *Proc. 22nd ACM SIGKDD*, San Francisco, CA, 2016, pp. 1135-1144.