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Automated Assurance of Compliance with Technical Standards (ITU-T, IEC, EN/ISO) And Regulatory Requirements Across the Entire Lifecycle of Fiber-Optic Lines Via Formalized Compliance Matrices and Verification of Material and Equipment Specifications

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Abstract

Against the backdrop of the expanding global market for fiber-optic systems, fueled by the rollout of 5G networks, the growth of the Internet of Things (IoT) ecosystem, and the construction of hyperscale data centers, traditional practices of compliance management in projects exhibit systemic inadequacy. The cost of design and installation errors, reaching 14% of the contract value, combined with cascading delays and budget overruns, creates demand for qualitatively different control mechanisms. This work substantiates a conceptual model for end-to-end, automated compliance assurance at all stages of the lifecycle of fiber-optic communication lines (FOCL). The core of the approach is a formalized machine-readable Fiber-Optic Line Lifecycle Compliance Matrix (FOL-CM), functioning as a single source of truth for the aggregate of regulatory and technical requirements. The architecture is described as integrating natural language processing (NLP) technologies for digitizing norms, artificial intelligence (AI) algorithms for verification procedures, and BIM modeling. The proposed model shifts verification from reactive, manual control to a proactive compliance-by-design paradigm, which makes it possible to significantly reduce costs, increase accuracy, and accelerate project execution.

Keywords: compliance automation, fiber-optic communication lines, project lifecycle, verification matrix, risk management, BIM, artificial intelligence, ITU-T, cost of nonconformance, systems engineering.

Introduction

The global telecommunications sector has entered a phase of radical reorganization, whose structural framework is the fiber-optic infrastructure. Consensus forecasts indicate an accelerated trajectory: the volume of the global fiber-optic market, by some estimates, will increase from 8,22 billion USD in 2024 to 17,84 billion by 2032, which is equivalent to a compound annual growth rate of 10,3% [1]. Alternative analytical data point to an even more expansive trajectory — from 13,04 billion USD in 2024 to 36,47 billion by 2034 at a CAGR of 11,72% [2]. The drivers are systemic technological shifts: large-scale deployment of fifth-generation networks (5G), whose number of subscribers by 2024 is estimated at 1,9 billion, as well as the pervasive diffusion of the Internet of Things (IoT) and cloud computing [1].

Growth is not only quantitative but also qualitative. Modern networks require a multiple increase in throughput, minimization of latency, and enhanced fault tolerance, which objectively complicates their architectural solutions. As a result, a dual strategic challenge is taking shape for market participants: the need to rapidly scale infrastructure to meet demand while simultaneously adhering strictly to a multi-tier regulatory and technical framework — from compliance with relevant recommendations (for example, ITU-T G.652 for single-mode fiber) to fulfilling national regulatory prescriptions that ensure reliability, interoperability, and security of networks [3].

In capital-intensive infrastructure initiatives, the cost of any error or deviation from requirements is critically high. Accumulated data on large-scale construction indicate that design defects alone generate aggregate direct and indirect losses exceeding 14% of the contract value [5]. Applied to fiber-optic communication line projects, typical miscalculations — for example, insufficient burial depth of the cable — result in rework, whose budgetary burden increases by 3–4 times relative to the initial installation costs [7].

These direct losses are exacerbated by structural management deficits. Empirical estimates show that 98% of construction projects experience budget overruns and/or schedule slippages, with the average volume of additional costs due to changes during implementation reaching 15% [8]. Traditional verification practices that rely on manual checks, expert opinions, and paper-based document flow demonstrate limited effectiveness under current conditions: they are labor-intensive, vulnerable to human-factor errors, produce inconsistency, and do not scale commensurately with rising complexity, forming bottlenecks and increasing aggregate risk [9, 28].

The scientific problem lies in the absence of a coherent integrated conceptual architecture purposefully designed for automated compliance verification at all stages of the life cycle of FOCL projects. Existing solutions and toolsets are fragmented, tied to individual phases (for example, design) or to specific tasks, and do not constitute a unified, data-driven, end-to-end management system.

The objective of the study is to develop and rigorously substantiate a conceptual model of automated compliance management, centered on the use of formalized machine-readable compliance matrices as a fundamental data type.

The author's hypothesis is that the pervasive integration of formalized compliance matrices across all phases of the project life cycle — from pre-project planning to operation — establishes a reliable, scalable, and transparent framework for an automated verification system. Such a system drastically reduces the probability of errors, lowers total life-cycle costs, and accelerates project delivery, shifting compliance management from ex post manual inspections to the proactive paradigm of compliance by design.

The scientific novelty lies in the development of an integrated life-cycle management model in which formalized compliance matrices serve as a machine-readable core that enables automated verification under conditions of multiplicity and heterogeneity of technical and regulatory standards.

The combination of rapid market growth and accompanying schedule pressure in project deployment exposes vulnerabilities of traditional methodologies: under these conditions, errors and nonconformities become virtually inevitable. Simultaneously, a global shortage of qualified engineering resources in high-technology domains is observed [12], which precludes trivially scaling expertise by expanding headcount. Under these circumstances, automation ceases to be merely a mechanism for efficiency gains and becomes a key risk management strategy and a necessary condition for the sustainable development of the sector. The proposed matrix model addresses this systemic problem directly, minimizing the dependence of verification processes on direct human involvement.

Materials and methods

The study relies on an integrated research strategy that combines complementary analytical methods to examine the problem comprehensively and to provide a rigorous justification of the proposed model. As part of a systematic literature review, a targeted analysis was conducted of peer-reviewed publications indexed in Scopus, IEEE Xplore, and Springer, as well as industry analytical reports from leading consulting organizations (Gartner, Deloitte, McKinsey) over a five-year period; the aim of the review is to consolidate current knowledge in the domains of project management for the construction of fiber-optic communication lines, compliance, and automation technologies. A comparative analysis was performed between traditional manual compliance practices and the proposed automated verification model; the comparison was carried out using key criteria—efficiency, accuracy, scalability, and risk profile. The basic methodological instrument is conceptual modeling, which makes it possible to integrate the disparate results of the review and the comparative analysis into a single, strictly structured, and logically consistent construct; the outcome is the development of the conceptual architecture of an automated compliance assurance system and its fundamental data model — Lifecycle

Compliance Matrix for Fiber-Optic Communication Lines (FOL-CM).

Results and discussion

The economic rationale for transitioning to automated verification systems is driven by the extremely high cost of errors and nonconformities. These costs comprise both direct and indirect losses that, taken together, have a cumulative and sharply negative effect on the project's financial performance. Direct costs include expenditures on materials and labor required to correct defects and perform rework [7, 21]. Indirect costs—often exceeding the direct ones—include schedule disruptions, penalties, legal expenses, and, critically, reputational losses for the contracting organization. Table 1 presents quantitative estimates of these cost components, aggregated based on an analysis of empirical data from a number of studies.

Table 1. Quantitative assessment of the cost of nonconformities and design errors in infrastructure projects (compiled by the author based on [5, 7, 8]).

Cost category	Value (% of contract cost or multiplier)
Direct costs of design errors	6.85%
Indirect costs of design errors	7.36%
Average project budget overrun	15%
Cost multiplier for rework (improper installation)	3x - 4x

The key thesis is that the cost of defect correction does not follow a linear relationship: as the project lifecycle progresses, it increases exponentially. An inaccuracy introduced at the design stage (for example, an erroneous choice of fiber type) can still be remedied with minimal losses. If such a miscalculation reaches the procurement stage, costs arise for purchasing unsuitable materials and their delivery. Detection during installation work turns into a double tariff: the replacement of components is complemented by dismantling and reinstallation. Finally, recording the error at the commissioning stage can trigger cascading failures, require comprehensive diagnostics, and call into question the economic feasibility of the entire project. This temporal escalation of costs creates a strong incentive to shift left, that is, to place checks as close as possible to the start of work. In full, such an approach is ensured only by automation tools [15, 16].

Traditional compliance-checking practices run into three systemically most vulnerable points, which are increasingly unacceptable in the current context.

Cognitive overload and the human factor: manual verification forces specialists to interpret arrays of regulations, technical specifications, and design documentation; the process is inertial and vulnerable to errors caused by fatigue, distraction, and the inevitable subjectivity of interpretations [10, 17].

Scalability and complexity: modern fiber-optic line projects include thousands of control points, distributed supply chains, and equipment from numerous manufacturers. Manual procedures are unable to ensure full coverage of requirements; verification degrades to selective control, leaving blind spots and generating latent risks [9, 23].

Opacity and absence of an audit trail: the results of manual checks often remain scattered across unrelated files, logs, and spreadsheets, which complicates the formation of a single, traceable, and immutable audit trail that is critically important for quality management, dispute resolution, and passing regulatory inspections.

To overcome the inherent limitations of manual approaches, the concept of the Fiber-Optic Line Lifecycle Compliance Matrix (FOL-CM) is introduced. The idea relies on mature systems engineering practices proven effective in the aerospace domain (in particular, on the Requirements Compliance Matrix at NASA) as well as in the implementation of other large-scale and high-criticality programs [18, 19].

FOL-CM is interpreted as a structured multidimensional data model that serves as a single and trustworthy source of truth for the set of regulatory and project requirements. A fundamental feature of the matrix is its dual representation: it remains human-interpretable, ensuring transparency of planning and managerial control, while simultaneously preserving machine formalizability, which allows it to be used as the central link of automated verification loops.

The logical organization of the matrix assumes that the rows unfold the stages of the project lifecycle, and the columns represent compliance domains. Each cell at their intersection records a specific compliance checkpoint. The proposed FOL-CM structuring scheme is presented in Table 2.

Table 2. Proposed structure of the Fiber-Optic Line Life Cycle Compliance Matrix (FOL-CM) (compiled by the author based on [4, 13, 19]).

Life cycle stage / Compliance area	**A. Material specifications (e.g., ITU-T G.65x fiber type)**	**B. Equipment specifications (e.g., IEC 60794)**	**C. Installation standards (e.g., burial depth)**	**D. Operational performance parameters (e.g., attenuation, dispersion)**	**E. Safety and environmental requirements**
1. Planning and feasibility study	Cell 1A	Cell 1B	Cell 1C	Cell 1D	Cell 1E
2. Network design	Cell 2A	Cell 2B	Cell 2C	Cell 2D	Cell 2E
3. Procurement	Cell 3A	Cell 3B	Cell 3C	Cell 3D	Cell 3E
4. Construction and installation works	Cell 4A	Cell 4B	Cell 4C	Cell 4D	Cell 4E
5. Fiber splicing and termination	Cell 5A	Cell 5B	Cell 5C	Cell 5D	Cell 5E
6. Testing and commissioning	Cell 6A	Cell 6B	Cell 6C	Cell 6D	Cell 6E
7. Operation and maintenance	Cell 7A	Cell 7B	Cell 7C	Cell 7D	Cell 7E

Each cell (checkpoint) includes a standardized set of fields, including:

Requirement ID — a unique identifier of a specific requirement.

Source Standard — a reference to the primary normative source (for example, ITU-T G.652.D).

Requirement Text — a formalized textual statement of the requirement.

Verification Method — the selected verification approach (for example, automated test, design documentation analysis, visual inspection).

Acceptance Criteria — measurable acceptance thresholds (for example, attenuation < 0,2 dB/km at a wavelength of 1550 nm).

Verification Status — the current verification state (for example, Compliant, Non-compliant, Not verified).

Evidence Link — a reference to the evidentiary artifact (for example, a file with OTDR measurement results, photographic confirmation).

Timestamp — the time mark of the last verification [24, 25].

On top of FOL-CM, an automated verification contour is formed; its conceptual architecture is presented in Figure 1.

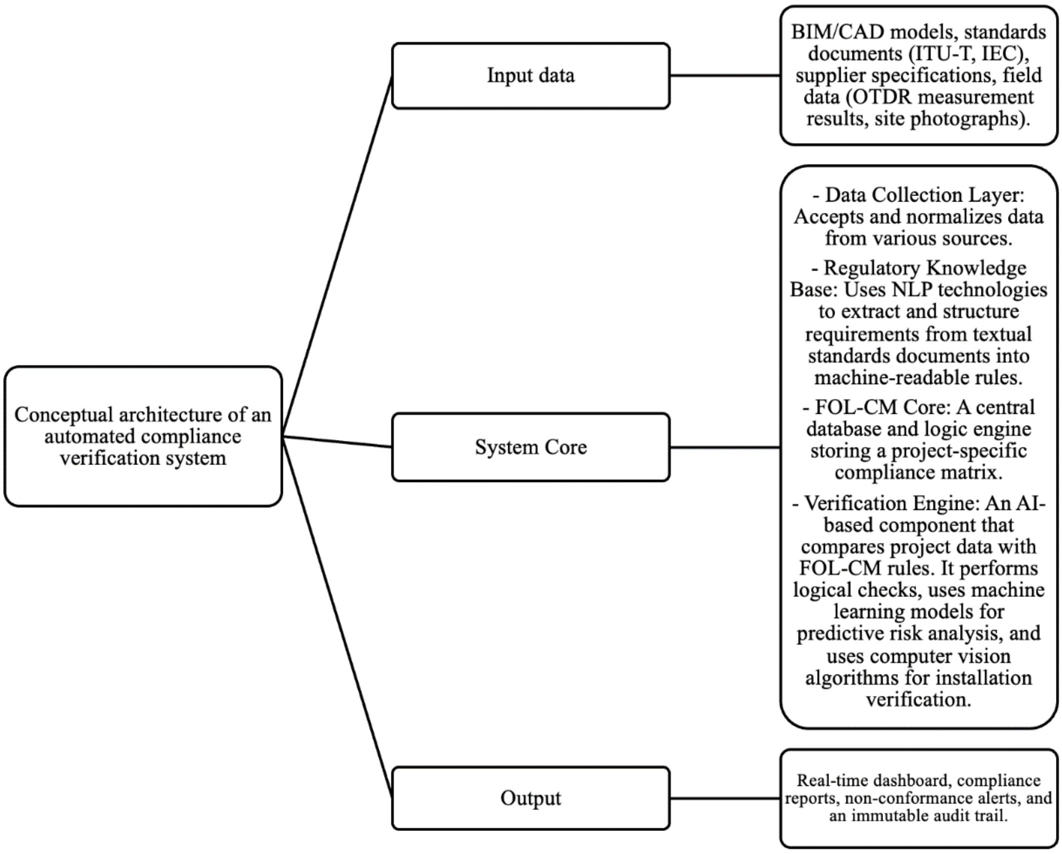

Fig.1. Conceptual architecture of an automated compliance verification system (compiled by the author based on [4, 6, 11, 14]).

The proposed architecture forms a continuous digital data loop in which compliance control is performed not at isolated points but as continuous monitoring across the entire project lifecycle.

The effectiveness of the model is clearly demonstrated in a set of case studies.

Case study 1: Design automation. The system performs machine analysis of the integral digital model of the network (for example, a BIM model) and compares it with the requirements recorded in FOL-CM. In automatic mode, it checks whether the materials specified in the project comply with IEC 60794, whether the minimum cable bend radii recommended by ITU-T are not violated, and so forth. Research on cognitive automation shows that this approach can reduce the duration of design work by 40–60% and increase the accuracy of compliance to 80% [4].

Case study 2: Verification at the construction stage. Unmanned platforms and mobile tools of field engineers transmit images and telemetry from the site to the system in real time. Using computer vision methods and data analytics, the system confirms the correctness of the cable type used, the compliance of splice loss parameters with standards (based on OTDR reflectometer readings), as well as the correctness of burial depth, immediately reflecting the status in FOL-CM.

Case study 3: Procurement automation. Prior to placing an order, the system analyzes the data sheets of the equipment being purchased (for example, transceivers and amplifiers) and compares the declared characteristics with FOL-CM requirements, identifying discrepancies before budget funds are expended.

Despite the apparent advantages, the implementation of such a system is associated with significant challenges:

- Initial investments and implementation complexity. Creating and integrating a comprehensive automated solution implies substantial upfront expenditures for the software platform, hardware infrastructure, and business process reengineering.

- Rule capture — digitization of standards. One of the most labor-intensive stages is the translation of legally and technically loaded requirements, often expressed in ambiguous natural language, into strict, formalized, machine-readable rules. This stage constitutes the critical bottleneck for all automated compliance-checking systems [26, 27].

- Workforce shortage. Successful implementation and operation require specialists with a rare combination of competencies at the intersection of telecommunications, data science, systems engineering, and software development; such profiles are extremely scarce in the labor market [13, 20].

The risks include:

- Excessive reliance on automation: A misconfigured or opaque system (black-box model) can create an illusion of reliability within which defects in the automation logic itself remain outside the field of view and elude timely detection.

- Cybersecurity: A centralized compliance management platform is a high-value target for adversaries; compromise of such infrastructure may lead not only to leakage of sensitive project data but — most critically — to deliberate authorization of noncompliant components or activities [22, 29].

The long-term development perspective of this concept is associated with the transition to the compliance by design paradigm. Within this framework, automated verification tools are embedded directly into the design loop (for example, into CAD/BIM tools), providing engineers with real-time feedback. This makes it possible to prevent the formation of decisions that violate requirements already at the stage of their construction, rather than recording nonconformities post factum. Such integration signifies a fundamental shift from reactive error detection to proactive prevention.

Conclusion

The conducted analysis demonstrates that the combination of factors — the exponential expansion of the market for fiber-optic communication lines, the growing architectural and organizational complexity of projects, and the high cost of errors — transforms the transition to automated compliance verification from an optional step into a strategic inevitability. The potential of traditional, predominantly manual control procedures has been exhausted: they are becoming a primary source of operational risks, schedule slippages, and unforeseen budget losses. In contrast, automation provides an integrated response that increases the efficiency, accuracy, and transparency of compliance assurance processes.

The results of the study confirm the initial hypothesis that a conceptual model based on formalized compliance matrices (FOL-CM) is a viable and reliable foundation for such automation. FOL-CM creates a unified information space that coherently integrates requirements, design decisions, evidentiary artifacts, and verification statuses at all stages of the life cycle. The presence of this integral layer is a necessary condition for the effective operation of AI algorithms that perform control and formal verification functions.

The proposed model has substantial practical value for key stakeholders in the telecommunications sector: network operators, EPC contractors, equipment manufacturers, and regulators. Its implementation reduces the risk profile, shortens implementation timelines, and establishes transparent, fully traceable audit trails.

Further research should focus on the following directions:

Pilot project development: creation and testing of system prototypes on real-world cases to validate the model and collect empirical data on its effectiveness.

Advancement of NLP models: development of natural language processing methods capable of automatically extracting and formalizing norms with high accuracy from heterogeneous regulatory and technical texts.

Standardization of data formats: development and promotion of open, standardized data exchange formats for FOL-CM, ensuring inter-system interoperability among market participants and the formation of a unified digital ecosystem.

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