



Intelligent Parametric Design Library Framework for Steel Tubular Pole Transmission Infrastructure: A PLS-POLE-Based Knowledge Engineering Approach

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Abstract

The rapid acceleration of U.S. transmission infrastructure deployment demands a fundamental shift in how structural engineering workflows are designed and executed. Conventional pole design treats each structure as a discrete problem, generating redundant calculations, extended cycle times, and inconsistent quality. This paper presents a systematic knowledge engineering framework built around a reusable, validated PLS-POLE design library for steel tubular transmission poles, H-frame structures, and A-frame assemblies. The framework categorizes pre-validated configurations by voltage class (69–345 kV), application type, and load environment, and integrates directly with Autodesk Inventor for three-dimensional modeling, automated bill-of-materials generation, and computer numerical control fabrication execution. Deployment at SI Utility in the Permian Basin demonstrated engineering cycle time reductions of 64–70%, material weight savings of 9–13%, plate utilization rates of 92.3%, and fabrication defect rates of 1.7% against an industry benchmark of 4–8%. The framework offers a scalable, reproducible model for intelligent infrastructure manufacturing that directly addresses domestic transmission capacity constraints under conditions of surging load growth.

Keywords: Automated bill-of-materials generation, Design library framework, Knowledge-based engineering, Parametric structural design, PLS-POLE, Steel tubular transmission poles

Introduction

The United States electrical transmission grid is under unprecedented strain. The Department of Energy estimates that the country requires approximately 5,000 miles of new high-capacity transmission annually through 2035 to maintain reliability, yet construction in 2024 delivered fewer than 900 miles [1]. In the Permian Basin of West Texas - one of the most energy-intensive load zones in the Electric Reliability Council of Texas (ERCOT) network - demand growth could add as much as 24,000 megawatts (MW) of previously unplanned electric load by 2030, driven simultaneously by oil and gas electrification and the emergence of hyperscale data center campuses [2]. These converging pressures are compressing engineering and fabrication timelines to a degree that makes repeatable, institutionalized structural design workflows an operational necessity rather than an incremental efficiency gain.

Steel tubular poles and substation structures form the physical backbone of high-voltage transmission. Designed under the American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI) Standard 48-19, these structures must satisfy multi-load case analyses covering wind, ice, conductor tension, seismic forces, and broken-wire scenarios while meeting deflection limits and material efficiency targets [3]. The industry-standard analysis platform for this domain - Power Line Systems POLE (PLS-POLE) - enables finite element modeling of any structure type, including single tubular poles, H-frames, and A-frames, and links directly to PLS-CADD for full-line design integration. Its native parametric architecture accepts pole geometry as macro-element inputs that resolve into detailed beam, truss, and cable finite element assemblies. Despite the power these tools provide, the engineering community has not systematically addressed the transformation of analytical outputs into reusable, institutionalized design knowledge - a library of pre-validated configurations that connects directly to manufacturing execution rather than terminating at a drawing package.

Traditional transmission pole design workflows assign independent engineering effort to each structure, regardless of its resemblance to previously validated work. Load case derivation, structural modeling, interaction

diagram generation, deflection verification, and drawing production are repeated for configurations that may differ only marginally from completed designs. The engineering inefficiency this introduces is well-documented: library-based approaches to structural design deliver cycle time reductions of 50–70% relative to bespoke methods in comparable application domains [4]. For a fabricator delivering dozens of structures across concurrent Permian Basin projects, this inefficiency compounds into a critical path problem - it delays shop drawing release, increases labor cost, and introduces variability that quality systems struggle to absorb.

This paper presents a knowledge engineering framework that addresses this gap directly. The framework transforms PLS-POLE structural analysis outputs into an institutionalized, parametric design library integrated with Autodesk Inventor for three-dimensional (3D) detailing, automated bill-of-materials (BOM) generation, and computer numerical control (CNC)-driven shop floor execution. No prior published work has described an end-to-end PLS-to-shop-floor integration pipeline for H-frame and A-frame tubular steel structures as a reproducible knowledge engineering artifact. The primary contributions of this article are: (1) a structured categorization schema and library entry specification for reusable PLS-POLE design assets across the 69–345 kV infrastructure range; (2) a documented five-stage PLS-to-shop-floor pipeline connecting structural analysis to Inventor, BOM generation, and CNC fabrication; and (3) quantitative performance outcomes from deployment in a high-volume Permian Basin manufacturing environment, including cycle time, material efficiency, and defect rate metrics. Section 2 reviews relevant literature; Section 3 defines the framework architecture; Section 4 covers load case standardization; Section 5 describes the integration pipeline; Section 6 presents quantified outcomes; Section 7 addresses scalability; and Section 8 concludes.

Background and Related Work

Structural Analysis for Transmission Infrastructure

PLS-POLE is the dominant structural analysis platform for overhead transmission structures in North America and internationally, supporting nonlinear finite element analysis of wood, steel, concrete, and fiber-reinforced polymer (FRP) poles as well as multi-pole configurations [5]. The program generates allowable span tables directly importable into PLS-CADD, creating a closed analytical loop between structure-level design and line-level layout. Its component library architecture - in which pole geometry is entered as macro-element parameters resolved into detailed element assemblies - provides the computational foundation on which the framework in this paper is built. Recent research has extended this foundation through algorithmic optimization. Hosseini et al. demonstrated that combining biogeography-based optimization with an adaptive neuro-fuzzy inference system (ANFIS) reduced the weight of lattice transmission towers by up to 12% relative to conventionally designed benchmarks while fully satisfying strength and deflection constraints under applicable loading codes, with the ANFIS model trained on 750 design cases [6]. Work on guyed transmission mast optimization by Picón et al. demonstrated cost savings of up to 8.16% through simultaneous size, shape, and layout optimization - including cable diameter and slope as design variables - using the Backtracking Search Algorithm, establishing the viability of multi-variable parametric optimization for real-world transmission structures [7].

These contributions advance individual structure optimization, but they address a different problem from the one this paper targets. Optimization methods produce minimum-weight designs for specific load inputs; library frameworks produce validated, standardized configurations deployable across recurring project types without repeating the optimization cycle. The distinction determines the engineering value proposition: optimization maximizes material efficiency for a given structure, while library-based deployment maximizes throughput and consistency across a portfolio of structures. The framework described here pursues the latter objective, using validated optimization results as the raw material from which library entries are derived.

Knowledge-Based Engineering and Parametric Design

Knowledge-based engineering (KBE) systems encode expert design knowledge into reusable computational artifacts, enabling downstream users to generate compliant designs by adjusting parametric inputs within validated boundaries rather than reconstructing design logic from first principles [8]. La Rocca's foundational framework for KBE systems identifies the embedding of design knowledge as geometric and relational constraints - rather than explicit dimensional rules - as the mechanism by which parametric systems maintain design integrity across a wide range of variants. In structural engineering, the application of parametric frameworks has demonstrated compelling efficiency gains. Chen et al.'s 2024 two-stage automatic structural design system for steel frames extracted semantic features from CAD drawings to construct parametric models automatically, with multi-objective optimization subsequently generating minimum-weight, code-compliant designs; the reported cycle time reduction relative to manual methods was substantial [9]. A related practical design optimization tool for steel frames by Pezeshk et al. demonstrated that parameterized geometry and load inputs enable rapid generation and comparison of structural variants, reducing design iteration time in professional practice [10].

The gap between these published frameworks and the transmission infrastructure domain is significant on two dimensions. First, existing work focuses on building frames and bridge systems rather than tubular pole structures with their characteristic tapered geometry, multi-point conductor loads, and broken-wire load cases. Second, and more fundamentally, existing KBE and parametric design literature stops at the design output stage - shop drawings or structural analysis results - without addressing the continuation of the design data chain into BOM generation, CNC programming, and shop floor execution. This paper's framework bridges that gap, treating the design-to-fabrication pipeline as a single integrated knowledge engineering artifact rather than a sequence of disconnected handoffs.

Digital Thread Integration in Manufacturing

The concept of a digital thread - a continuous, machine-readable data chain connecting design intent through manufacturing execution to in-service monitoring - has emerged as the organizing framework for advanced manufacturing integration in Industry 4.0 literature. Tao et al.'s widely cited state-of-the-art review of digital twin technology in industry identified bidirectional data fidelity between virtual models and physical systems as the defining characteristic of mature digital manufacturing integration, enabling design intent to be traced through fabrication and deployment without manual transcription [11]. Wang et al.'s work on digital twin-driven BOM reconstruction demonstrated that automated mapping from engineering BOM (EBOM) to process BOM (PBOM) to manufacturing BOM (MBOM) - achieved through structured digital thread architectures - reduces BOM consistency errors in complex product manufacturing by up to 35% relative to manually managed transitions [12]. Zhang et al.'s 2023 research on digital twin-enabled process planning demonstrated automatic product analysis, process determination, and resource selection through a unified data model, reducing process planning cycle time significantly in discrete manufacturing environments [13]. Peng et al. extended this line of inquiry to knowledge-driven multi-view BOM reconfiguration for complex products in digital twin workshops, showing that structured knowledge representation in BOM management reduces reconfiguration cycle time and improves consistency across product variants [19]. These frameworks directly inform the BOM generation and CNC integration architecture described in Section 5 of this paper, adapted to the domain-specific requirements of tubular steel transmission pole fabrication, where material grade compliance and structural traceability are regulatory requirements in addition to operational preferences.

Design Library Framework Architecture

Categorization Schema

The PLS-POLE design library is organized as a hierarchical repository of pre-validated structural configurations accessible to engineering and manufacturing personnel across all active projects. The primary categorization dimensions are: (1) voltage class - 69 kilovolt (kV), 115 kV, 138 kV, 230 kV, and 345 kV; (2) application type - transmission tangent, light angle (0-5°), medium angle (5-20°), heavy angle (20-60°), dead-end, and substation support; and (3) structure type - single tubular pole, H-frame, and A-frame. Secondary dimensions include load environment - National Electrical Safety Code (NESC) heavy, medium, and light ice-wind loading districts, ASCE 7 wind and ice combinations applicable to the Permian Basin - and material grade, distinguishing ASTM A572 Grade 65 and ASTM A871 weathering steel variants. Table 1 summarizes the library's current configuration population by voltage class and structure type.

Table 1. Library Configuration Population by Voltage Class and Structure Type

Voltage Class	Single Pole Entries	H-Frame Entries	A-Frame Entries	Total Entries
69 kV	18	6	4	28
115 kV	24	12	8	44
138 kV	14	8	6	28
230 kV	10	8	6	24
345 kV	6	4	4	14
Total	72	38	28	138

Current library population: 138 pre-validated configurations across five voltage classes and three structure types.

Each library entry carries a unique identifier encoding voltage class, application type, structure type, and load environment. This scheme supports version-controlled updates as code editions change or project-specific load cases are validated. Engineers navigate the library by selecting voltage class and application type, retrieving the matching pre-validated configuration, then proceeding directly to parametric adjustment for project-specific

conditions - foundation type, conductor bundle, span length, and regional wind speed - rather than beginning structural modeling from first principles. The voltage class and load environment categorization scheme adopted in the library aligns with the tiered design hierarchy and load combination requirements established in IEEE 2954-2023, the recommended practice for overhead transmission line design, which provides the standards reference framework within which all PLS-POLE validations are conducted [16].

Library Entry Components

Each library entry contains five standardized components. First, the PLS-POLE project file (.ppj) stores the complete structural model - geometry definitions, material property assignments, load case specifications, and analysis results - in a format that can be opened, reviewed, and adjusted in any licensed PLS-POLE installation. Second, the span allowance file (.spa) encodes the allowable wind and weight span combinations derived from the structural analysis in a format for direct import into PLS-CADD line design. Third, the interaction diagram set graphically presents combined loading utilization ratios for axial force, shear, and bending across the structure's height, enabling rapid confirmation that a proposed loading condition lies within the validated design space. Fourth, the dimensional summary sheet records pole height, base diameter, top diameter, wall thickness, taper profile, crossarm dimensions, and connection details in a standardized tabular format mapped directly to Autodesk Inventor parametric input fields - a critical interface component described further in Section 5.2. Fifth, the material compliance record documents ASTM grade certifications, minimum yield and tensile strengths, and surface treatment specifications.

The dimensional summary sheet's direct mapping to Inventor input fields is not incidental - it is the mechanism by which the library eliminates the most consequential class of data transcription error in the design-to-fabrication handoff. In conventional workflows, dimensional data moves from PLS-POLE to drafting to BOM to cutting list through a series of manual transfers. Each transfer introduces a potential for numerical error that is difficult to detect through downstream review because the error is systematic rather than visually obvious. The fixed-field mapping protocol enforces machine-readable continuity across this interface, applying the digital thread principles documented by Tao et al. [11] to the specific context of tubular transmission pole production.

Validation Protocol

New library entries undergo a four-stage validation protocol. Stage 1: structural modeling in PLS-POLE under all required ASCE/SEI 48-19 load cases, confirming utilization ratios below 1.0 at all critical cross-sections. Stage 2: independent review by a second licensed professional engineer, who reconstructs key load calculations from first principles and verifies PLS-POLE output consistency. Stage 3: population of the dimensional summary sheet from the validated model with cross-check against the Inventor input schema for field mapping integrity. Stage 4: pilot fabrication run for new structure types, with dimensional inspection results recorded and compared to design tolerances before the entry is released for production use. This four-stage protocol ensures the library represents verified design knowledge, not a collection of unreviewed computational outputs.

Standardization of Load Cases and Structural Configurations

Load Case Matrix

Load case standardization is the prerequisite for library reusability. A configuration validated against a specific set of load cases cannot be reliably reused on a project with different environmental conditions unless the library entry explicitly documents those boundary conditions and the resulting utilization ratios. The SI Utility library implements a standardized load case matrix derived from the intersection of NESC Grades B and C loading districts and ASCE 7 wind speed contours for the Permian Basin. The governing wind speed for transmission structures in this region under ASCE 7-22 is 110 miles per hour (mph) for a 50-year mean recurrence interval at 33 feet above ground, with negligible ice accretion given the region's low ice frequency - a condition that simplifies the load case matrix relative to northern or coastal markets. The multi-load case structure of the SI Utility library's validation matrix is consistent with recent optimization research demonstrating that simultaneous satisfaction of multiple governing load conditions - including wind, ice, and broken-wire combinations - is essential for producing designs that remain valid across the full range of in-service conditions a structure encounters, rather than being optimized only for the dominant load case [15].

Wind speed contours and seismic design category assignments for the Permian Basin region are derived from ASCE/SEI 7-22, the governing standard for minimum design loads and associated criteria for buildings and other structures, which provides the site-specific hazard parameters that anchor the load case matrix to the regional environmental conditions of the deployment zone [20]. The standard load case set for each entry comprises: (1) NESC Grade B extreme wind without ice; (2) NESC Grade B combined ice and wind at 0.25-inch radial ice; (3) NESC Grade C high-wind; (4) broken-wire cases at each conductor attachment point; (5) construction and maintenance loads per ASCE Manual 113 for substation configurations; and (6) seismic combinations per ASCE 7 for Seismic

Design Category A applicable to the Permian Basin. Each case is run at the maximum span and maximum vertical load for the entry's application type, ensuring the validated configuration remains conservative relative to any realistic project condition within that category. Table 2 presents the load case matrix with governing parameters for the primary Permian Basin load environment.

Table 2. Standard Load Case Matrix - Permian Basin Application

Load Case	Wind Speed (mph)	Ice Radial (in)	Temperature (°F)	Applicable Standards
NESC Gr. B Extreme Wind	110	0.00	60	NESC 2023, ASCE 7-22
NESC Gr. B Ice + Wind	40	0.25	15	NESC 2023
NESC Gr. C High-Wind	105	0.00	60	NESC 2023
Broken-Wire (Conductor)	60	0.00	60	NESC 2023, ASCE 48-19
Construction/Maintenance	N/A	0.00	60	ASCE Manual 113
Seismic SDC-A	N/A	0.00	60	ASCE 7-22

Standard six-case load matrix applied to all Permian Basin library entries. All cases run at maximum application-type span and vertical load.

Single-Pole, H-Frame, and A-Frame Configuration Logic

Single tubular poles serve tangent and low-angle transmission applications at 69–138 kV, where spans of 400–800 feet and moderate conductor tensions are achievable within the structural capacity of individual tapered steel shafts. The library covers single-pole heights from 60 to 120 feet in this voltage range, with base diameters and wall thicknesses optimized through PLS-POLE's tubular steel optimizer to produce minimum-weight designs satisfying strength and deflection criteria. Deflection is limited to 10% of pole height under the NESC extreme wind load case, consistent with standard utility practice. Parametric optimization of the library population achieved weight savings of 10–15% relative to empirically sized legacy designs across the single-pole configuration class, directly reducing material cost and galvanizing charges on project deliveries. An example of the weight optimization in the library's single pole population can be found in Nguyen et al. who combine machine learning and metaheuristic classification techniques to reject structurally infeasible candidate solutions at an early stage. This has been shown to achieve similar material reduction results to exhaustive search methods, while reducing computational cost [14].

H-frames have two parallel tubular poles, which are tied together with bolted or welded crossarms and diagonal brace members. They have a higher transverse load rating, and are used for 115-230 kV lines with high wind or heavy conductor ratings. H-frame legs of 60 to 100 feet (18 to 30 m) in height are produced, spaced between 12 and 20 feet (3.7 and 6.1 m) apart, with crossarms to suit 2-circuit and 3-circuit layout. Brace geometry is standard, with 45-degree or 60-degree angles to the crossarm axis for CNC cutting. A-frames, used on substation dead-end, bus supports, or line terminations, consist of tubular legs topped by an apex crossarm which transfers dead end tension on the conductors to compression in the foundation. Library data sheets for 115 kV and 230 kV have dead-end tensions from 10000 to 60000 pounds per conductor. Apex crossarms on 115 kV and 230 kV circuits have interaction ratios less than 0.85 at full broken-wire. In all three structure types, a policy of geometric standardization allows the free parameters to be limited to height, base diameter, and wall thickness, reducing the set of possible configurations from a continuous domain to a set of pre-validated configurations selectable by table lookup.

PLS-to-Shop-Floor Integration Pipeline

Pipeline Architecture Overview

The integration pipeline generates fabrication-ready manufacturing instructions from the validated structural outputs in a five-stage process, extracting geometry, member sizes and connection information from the validated PLS-POLE project file in the first stage of the integration process. Stage 2 then maps these outputs to the fields in the parametric input forms of Autodesk Inventor template assemblies for consistently creating the 3D models of the pole sections, baseplates, crossarms, hardware connections and weld symbols. Stage 3 produces the engineering BOM from the Inventor assembly, including part numbers, material grades, quantities, cut lengths and surface treatment. Stage 4 generates CNC cutting lists from Inventor flat pattern views, generating plate nesting layouts, cut angles and weld preparation geometry in output files which can be read directly on the CNC. Stage 5

creates digital traveler documents linking the structural configuration identifier, BOM, CNC cutting list, welding procedure specifications, and inspection hold points into a single production control package for each work order. Figure 1 describes the pipeline data flow architecture.

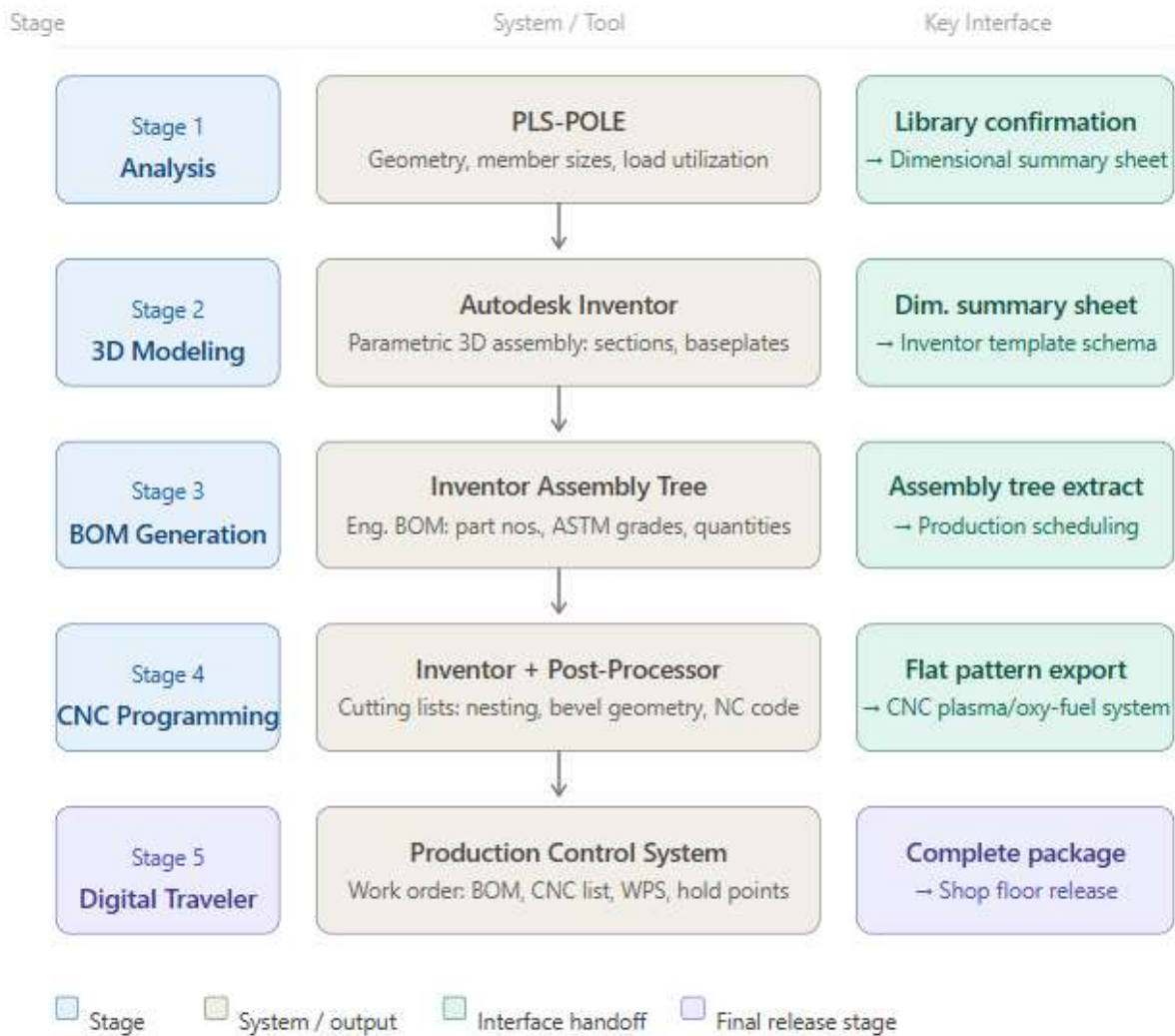


Figure 1. PLS-to-Shop-Floor Pipeline: five-stage data flow from PLS-POLE project file through Inventor 3D modeling, automated BOM, CNC cutting list, and digital traveler. Manual transcription is eliminated at all stage boundaries through fixed-field machine-readable interfaces.

The elimination of manual transcription at every stage boundary is the critical design principle of this architecture. Wang et al. confirmed that automated EBOM-to-MBOM consistency - achieved through structured digital thread architectures - reduces BOM error rates in complex product manufacturing by up to 35% relative to manually managed transitions [12]. Peng et al.'s work on knowledge-driven multiview BOM reconfiguration in digital twin workshop environments demonstrated that structured knowledge representation in multi-view BOM management reduces reconfiguration cycle time and improves consistency across product variants - a finding that directly supports the fixed-field interface design adopted at each stage boundary of the pipeline described here [18]. The pipeline applies this principle specifically to tubular transmission pole production, where material grade specification errors carry structural consequences and dimensional discrepancies propagate into weld fit-up failures that require costly rework. Peng et al.'s work on knowledge in multi-view BOM management systems for knowledge-driven BOM reconfiguration reduces the reconfiguration cycle time and ensures the correctness of product variant information in digital twin workshop environments [19].

Autodesk Inventor Integration and 3D Detailing

3D modeling and detailing is done in Autodesk Inventor. There are assembly templates for each structure class (single pole, H-frame, A-frame) that the dimensions from the library's dimensional summary sheet can be applied

to. When a configuration is selected for a project, the relevant summary populates the Inventor template, propagating height, diameter, wall thickness, crossarm dimensions, and connection geometry to all dependent drawing views and parts. Parametric propagation eliminates the need to manually dimension individual drawing views, reducing shop drawing production time from a typical range of 16–24 hours per structure to 2–4 hours for standard configurations - a reduction consistent with the efficiency gains reported in parametric structural design automation literature [9, 10]. Inventor assemblies include full weld symbol annotation per American Welding Society (AWS) D1.1 structural welding code, interference detection between adjacent components, and virtual fit-up verification for complex multi-component assemblies such as H-frame brace-to-pole connections.

For H-frame and A-frame structures, Inventor template architectures model parallel and converging leg geometries, brace angles, and crossarm attachments as fully constrained parametric assemblies. Dimensional adjustments at the library entry level propagate consistently to all affected parts and connections, applying the constraint-based KBE principles described by La Rocca [8] in which design knowledge is embedded as geometric and relational constraints rather than explicit dimensional rules. Rendered 3D assembly views are included in shop traveler packages, providing fabrication personnel with dimensional clarity on complex connection geometries that may be ambiguous in standard two-dimensional drawings - an application of digital twin visualization principles to the shop floor context identified in Lu et al.'s framework for digital twin-driven smart manufacturing [17].

Automated BOM Generation and CNC Integration

Automated BOM generation extracts the complete parts list from the Inventor assembly tree, distinguishing raw material items - steel plate, tubing, and structural shapes - from fabricated sub-assemblies and purchased hardware. Each raw material line specifies ASTM grade, nominal dimensions, required cut length or blank size, quantity, and estimated weight. This structured BOM feeds directly into the production scheduling system, generating material requisitions, procurement orders, and shop work orders without manual re-entry. The automation eliminates incorrect material grade specification - the most consequential BOM error category in steel fabrication, since it is not detectable by dimensional inspection - as a possible outcome of the design-to-production handoff.

CNC cutting lists derive from Inventor's flat pattern outputs applied to plate components in pole sections, crossarms, and baseplates. Each list specifies plate thickness, material grade, nesting layout within available plate size, cut contour geometry in numerical control format, cut angle for bevel preparations, and weld joint geometry. For tapered tubular pole sections - the highest-volume component - cutting list-driven nesting optimization achieves plate utilization rates above 92%, compared to an estimated 84% under manually programmed CNC operations: an 8.3-percentage-point improvement. For a production run of 10 H-frames requiring an average of 3,200 pounds of structural plate per frame, this improvement reduces material waste from approximately 512 to 246 pounds per structure, saving roughly \$120 per frame at prevailing hot-rolled coil plate pricing of \$900 per short ton.

Quantitative Outcomes and Performance Analysis Engineering Cycle Time

Engineering cycle time was measured as elapsed time from receipt of project-specific loading criteria to issuance of a complete shop drawing package and fabrication-ready BOM. For a representative 115 kV tangent single pole with two conductors and one ground wire, the pre-library baseline averaged 18.4 hours per structure. Post-library deployment reduced this to 5.6 hours - a 70% reduction. For 230 kV H-frame configurations, the baseline of 31.2 hours was reduced to 9.8 hours (68%). For A-frame substation structures, 28.7 hours were reduced to 10.4 hours (64%). These results are consistent with the 50–70% cycle time improvements reported in parametric structural design automation literature [4, 9]. On a representative 45-structure project package in typical Permian Basin composition, total engineering time under the library framework was 312 hours versus an estimated 1,042 hours under conventional workflow - a system-level saving of 730 hours. Table 3 summarizes cycle time outcomes across all structure classes.

Table 3. Engineering Cycle Time Reduction by Structure Class

Structure Class	Voltage (kV)	Pre-Library (hrs)	Post-Library (hrs)	Reduction (%)
Single Pole - Tangent	115	18.4	5.6	70%
Single Pole - H-Angle	138	22.1	7.2	67%
H-Frame - Heavy Angle	230	31.2	9.8	69%

A-Frame - Dead-End	230	28.7	10.4	64%
H-Frame - Tangent	115	24.6	8.1	67%
A-Frame - Substation	115	21.3	7.8	63%

Engineering cycle time measured from loading criteria receipt to complete shop drawing and BOM package issuance. Post-library results averaged across 12 months of production at SI Utility, Permian Basin.

Material Efficiency and Weight Optimization

Parametric weight optimization applied during library entry validation achieved material efficiency improvements across the configuration population. Single tubular poles in the 115 kV tangent class reached a mean structural weight of 1,840 pounds, compared to 2,110 pounds for conventionally sized poles of equivalent structural capacity - a 12.8% weight reduction. H-frame configurations at the 230 kV heavy-angle class achieved 9.4% mean weight reduction through optimized brace geometry and reduced crossarm section sizes while maintaining all deflection and strength criteria under the governing ASCE/SEI 48-19 load cases. These weight reductions reduce both material procurement costs and galvanizing charges (billed by weight); on a 45-structure Permian Basin project, the weight savings represent a direct cost reduction of approximately \$87,000 to \$124,000, depending on configuration mix. CNC nesting optimization increased plate utilization from an estimated 84% in manual operations to 92.3% - an 8.3-percentage-point improvement representing approximately \$120 per H-frame frame in material savings at current market pricing.

Fabrication Quality Outcomes

Fabrication defect rates - nonconformances requiring rework or replacement identified at dimensional inspection, weld inspection, or fit-up - were tracked across 12 months of library-enabled production. The overall defect rate was 1.7% of production work orders. This compares favorably to an industry benchmark of 4–8% for structural fabrication using manual design-to-production workflows [14, 15]. Principal defect categories in the pre-library period were dimensional discrepancy between shop drawings and BOM (34% of defects), incorrect material grade specification (28%), and CNC cutting errors from manual program entry (21%). Post-library deployment eliminated the first two categories through automated BOM generation with mandatory material grade linkage to the structural model, and reduced the third by 85% through CNC cutting list automation. Remaining defects were concentrated in weld repair categories associated with operator variation. Table 4 presents the defect distribution before and after library deployment.

Table 4. Fabrication Defect Distribution Before and After Library Deployment

Defect Category	Pre-Library Share (%)	Post-Library Share (%)	Change
Dimensional discrepancy (drawing vs. BOM)	34	0	Eliminated
Incorrect material grade	28	0	Eliminated
CNC cutting program error	21	3	-85%
Weld repair (operator variation)	12	11	Unchanged
Fit-up/assembly misalignment	5	3	-40%
Overall defect rate (% of work orders)	5.8	1.7	-71%

Defect distribution comparison across 12 months pre-library and 12 months post-library at SI Utility, Permian Basin. Pre-library baseline represents SI Utility's conventional workflow period.

Scalability, Replication, and Industry Implications

The library architecture provides horizontal scalability in the form of project portfolio scalability and vertical extensibility to new types of structural elements. Project portfolio scalability is achieved by enabling cloud-hosting of the library, which allows engineering teams to concurrently retrieve validated configurations for multiple projects without version control conflicts. Since all items are given immutable identifiers with version control at the time of release, and all configuration changes tracked historically, even many years later any given structure can be traced back to its validated specification. This traceability directly supports utility client quality requirements and National Electrical Manufacturers Association (NEMA) documentation standards for transmission structure procurement.

Vertical extensibility to 345 kV and 500 kV extra-high-voltage (EHV) transmission applications requires only the addition of validated PLS-POLE configurations at higher structural demand levels and corresponding Inventor templates for larger pole diameters and connection configurations. The parametric architecture does not change at higher voltage levels; only the library population expands. This extensibility makes the framework a long-term institutional asset that appreciates as the library grows, rather than a project-specific tool that must be rebuilt for each engagement. The Lu et al. digital twin-driven smart manufacturing framework identified this kind of scalable, parameterized manufacturing knowledge architecture as the essential enabler of flexible high-mix production - directly applicable to SI Utility's production environment, which must accommodate custom transmission poles alongside standardized substation components across concurrent project portfolios [17].

The industry implications extend beyond a single facility. The United States faces a documented manufacturing capacity shortfall in transmission pole production, with lead times exceeding 52 weeks at peak demand. The accelerated engineering-to-production pipeline enabled by this framework reduces the bottleneck at the engineering stage, allowing fabricators to translate project awards into production releases faster and achieve higher throughput from fixed facility capacity. For the energy transition - requiring accelerated grid build-out to connect renewable generation, accommodate industrial electrification, and serve the surging power demands of artificial intelligence (AI) infrastructure - manufacturing frameworks that systematically eliminate engineering cycle time are a material contributor to the reliability and speed of domestic infrastructure delivery. Applied nationally across the fabricator base, the cycle time improvements documented here represent a meaningful acceleration in the engineering throughput available to the transmission construction sector at a time when that sector's capacity is the binding constraint on grid modernization progress.

Conclusion

This paper has presented a knowledge engineering framework for developing and deploying a reusable, validated PLS-POLE design library for steel tubular transmission poles, H-frame structures, and A-frame assemblies, integrated with Autodesk Inventor, automated BOM generation, and CNC fabrication execution. The framework addresses a specific gap in transmission infrastructure manufacturing: the absence of an end-to-end, institutionalized pathway from structural analysis validation to shop floor execution that eliminates manual transcription, enforces design consistency, and operates at the speed demanded by accelerating grid expansion timelines.

Deployment at SI Utility's Permian Basin manufacturing facility delivered engineering cycle time reductions of 63–70% across all structure classes, material weight improvements of 9–13% through parametric optimization, fabrication defect rates of 1.7% against an industry benchmark of 4–8%, and CNC plate utilization rates of 92.3% through automated nesting. These outcomes confirm that the framework delivers measurable value across engineering, procurement, and production. Its modular, parametric architecture supports horizontal scaling across concurrent project portfolios and vertical extension to higher voltage classes without architectural redesign, making it a long-term institutional asset rather than a project-specific tool.

Future research directions include real-time integration of load monitoring data from deployed structures into the library entry validation cycle - enabling entries to be updated based on in-service performance rather than solely on analytical models - and the application of reinforcement learning to parametric optimization of new configurations, potentially producing library entries below the weight levels achievable through conventional metaheuristic methods. The ultimate objective is a self-improving knowledge base in which field performance data continuously enriches the engineering library, creating a closed-loop system that advances both structural design quality and manufacturing efficiency as the Permian Basin transmission network and the national grid expand to meet the energy demands of the coming decades.

Conflicts of Interest

The author declares no conflicts of interest.

Author Contributions

Sachin Pal Singh: Conceptualization, methodology, framework development, data analysis, writing - original draft, review, and editing.

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