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Risk Assessment and Advanced Risk Reduction in 380 KV Overhead Transmission Line Construction

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Abstract: *Overhead transmission line (OHTL) construction combines civil works, structural erection, heavy lifting, work at height, electrical interfaces, transportation and conductor-stringing activities within long and changing work fronts. At 380 kV, loss of control during tower erection, climbing, stringing or work near electrical systems can have severe consequences. This study develops an Integrated OHTL Risk Reduction Method (IORRM) that links activity-level Hazard Identification and Risk Assessment (HIRA) with Failure Mode and Effects Analysis (FMEA), Bow-Tie barrier analysis, Job Safety Analysis (JSA), Permit-to-Work (PTW), lifting-plan verification, weather hold points, digital safety controls and leading indicators. The approach is designed to address a practical weakness identified in the Part-II study: the difference between having a written control and verifying that the control is actually effective at the work front. The supplied dataset contains twelve representative OHTL activities with baseline risk scores from 12 to 20 and residual scores from 6 to 10. Across the twelve activities, the mean risk score falls from 16.25 to 8.17, a modelled reduction of 49.7%, and the number of critical tasks (risk score ≥17) falls from five to zero. The FMEA examples show RPN reductions, including a reduction from 270 to 81 for fall-from-height failure. Leading indicators also improve, with lift-plan verification increasing from 55% to 93% and PTW compliance from 62% to 94%. These results are explicitly modelled rather than audited company performance because verified site registers, incident records and work-hour data were not supplied. The paper therefore presents a reproducible safety framework and an analytical template that can be validated using actual project observations.*

Keywords: 380 kV OHTL; construction safety; HIRA; FMEA; RPN; Bow-Tie; critical-task verification; PTW; tower erection; stringing; risk reduction.

I. INTRODUCTION

Electricity transmission networks depend on reliable high-voltage corridors to transfer bulk power between generating stations, substations and load centres. Overhead transmission lines remain an important solution for long-distance transmission because they are comparatively accessible for construction and maintenance and generally require less civil intervention than underground alternatives. The safety challenge becomes more pronounced as voltage level, structural dimensions, conductor systems, lifting requirements and work-front complexity increase. The Part-II study characterizes 380 kV OHTL construction as a multi-hazard work system in which excavation, temporary works, lifting, work at height, electrical exposure, transportation, manual handling and weather can occur within the same project lifecycle.

The engineering domain associated with the supplied OHTL Design source covers conductor swing, ground clearance, right-of-way, tower erection lifting plans, PLS-CADD workflows, tower foundations and sag-tension considerations. These engineering interfaces are directly relevant to safety because temporary construction configurations can differ

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from the final operating configuration. For example, wind-induced conductor movement can affect clearances, while tower erection involves temporary stability and changing crane load paths. The Part-II document therefore treats engineering information as contextual input and retains approved project drawings and client specifications as the controlling sources for actual construction decisions.

The central research problem is not simply that OHTL work contains hazards. The more useful safety question is whether critical controls remain reliable when conditions change. Conventional systems may contain generic risk assessments, PPE requirements, toolbox talks and supervisor checks, but OHTL risk can change rapidly with wind, crane radius, temporary tower geometry, simultaneous operations, conductor tension, traffic or proximity to energized infrastructure. The study therefore proposes moving from a static risk register toward a task-sensitive and continuously verified control system.

1.1 Aim, objectives and contribution

The aim is to identify, assess and reduce occupational hazards associated with 380 kV OHTL construction by applying an integrated risk-management method. The objectives are to identify hazards across major activities, assess baseline risk using HIRA, prioritize failure modes using FMEA/RPN, develop Bow-Tie models for major scenarios, apply the hierarchy of controls with emphasis on engineering controls, introduce dynamic pre-task review and critical-control verification, compare baseline and post-control indicators, and develop practical recommendations for OHTL safety management.

The research contribution is therefore methodological rather than the invention of a new risk equation. The Part-II literature gap is defined as the need to integrate established methods—HIRA, FMEA, Bow-Tie, dynamic task review and leading indicators—into a single OHTL-specific operational model. The proposed IORRM addresses this gap by linking hazard identification to barrier ownership and field verification.

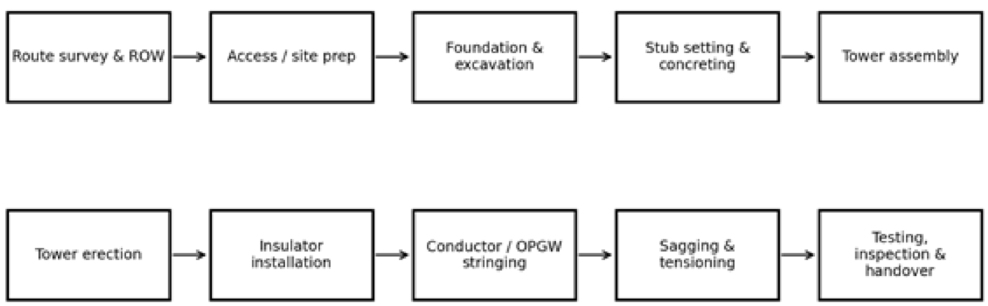

Figure 1. OHTL construction work breakdown and safety interfaces.

II. LITERATURE REVIEW

The literature reviewed in the Part-II study sits at the intersection of electrical safety, construction safety, structural reliability, lifting operations, work at height, risk assessment and occupational health. ISO 45001 provides a management-system perspective involving hazard identification, risk assessment, operational control, competence, emergency preparedness, monitoring and continual improvement. The ILO construction code emphasizes prevention across the construction lifecycle and cooperation among clients, designers, employers and workers. OSHA overhead-line guidance emphasizes structural integrity, climbing safety, electrical exposure and line-work precautions.

OHTL engineering literature adds an important safety dimension because sag and tension, clearance, wind effects, tower loading, foundation stability and stringing arrangements influence the conditions under which construction is performed. The supplied technical-domain material covers conductor swing, ROW, lifting methodology, foundations and PLS-CADD workflows. These sources explain engineering interfaces, while the Part-II study correctly notes that project-specific design documents, client requirements and statutory provisions must control actual construction.

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Construction hazard research identifies falls from height, dropped objects, lifting failures, vehicle interactions, excavation collapse, electrical contact and housekeeping as recurring injury mechanisms. OHTL projects amplify these hazards through remote work fronts, variable terrain, long access routes and environmental changes. In electrical work, severe injury can result from shock or arc-related mechanisms and may be followed by secondary falls.

For work at height, the literature logic is consistent with the hierarchy of controls: the objective is to reduce exposure using engineered access, fall-protection systems, secure tools and materials, rescue planning and competent supervision rather than relying on PPE alone. In tower erection, the temporary-structure problem is particularly important because partially erected members may have different stability characteristics from the completed tower. Safe lifting therefore requires load calculations, crane selection, rigging design, working radius, ground conditions, wind limits, exclusion zones and communication.

Stringing and sagging introduce stored mechanical energy and uncontrolled movement. Rope failure, incorrect tension, crossing interfaces and communication failure can create high-consequence events. The Part-II methodology consequently treats the stringing corridor, approved stringing plan, communication protocol, equipment inspection, crossing protection, exclusion zone and emergency-stop criteria as integrated controls rather than separate paperwork items. Weather is treated similarly: wind, lightning, rain, visibility and heat are translated into task-specific hold points rather than being left as generic warnings.

Literature area	Established strength	Research gap addressed
ISO 45001	OH&S management framework	Translate management requirements into OHTL task controls
ILO construction guidance	Lifecycle prevention and worker participation	Apply prevention principles to linear OHTL work fronts
IEC 60826	Engineering loading and reliability context	Connect weather/engineering interfaces with safety controls
OSHA overhead-line guidance	Electrical and structural safeguards	Integrate with tower construction risks
HIRA/JSA	Activity and task hazard identification	Add failure-oriented and barrier-oriented analysis
FMEA	Prioritization using S, O and D	Use RPN to focus on critical OHTL failure modes
Bow-Tie	Threat–top-event–consequence visualization	Convert barriers into owned, verifiable controls

Table 1. Literature synthesis and research gap.

2.1 Research gap and conceptual proposition

The literature does not indicate that one technique can replace the others. HIRA is useful for activity-level exposure, FMEA provides a failure-mode perspective, and Bow-Tie clarifies the logic of prevention and mitigation. The practical gap is the interface between analysis and execution: a risk register may say that an exclusion zone, lift plan or fall-protection system is required, but the work should not proceed unless the barrier is present, suitable, understood and verified. IORRM is designed around this interface.

III. AREA OF STUDY AND OHTL CONSTRUCTION SYSTEM

The study area is the construction environment of a 380 kV overhead transmission line, characterized by long linear work fronts, tower locations distributed along a right-of-way, temporary access routes, heavy material movement and sequential work packages. The exact route, coordinates, contractor, tower count and project dates are deliberately not inferred because the supplied Part-II document states that these project-specific details must be populated from verified records.

A typical 380 kV OHTL system includes lattice steel towers, foundations, cross-arms, insulator strings, phase conductors, earth wires/OPGW, clamps and fittings. Safety problems often arise at interfaces between components: lifting steel members, attaching insulators, handling conductor reels, tensioning stringing lines and maintaining required clearances. The construction sequence used in the study contains ten work packages, beginning with route survey and ROW activities and progressing through testing and handover.

WP	Work package	Representative hazards
1	Route survey / ROW	Terrain, traffic, heat, slips, remote work
2	Access / site preparation	Vehicles, dust, equipment interaction
3	Foundation excavation	Collapse, falls, plant, services
4	Foundation / stub work	Rebar, concrete, lifting, formwork
5	Tower assembly	Manual handling, dropped objects
6	Tower erection	Lifting, collapse, wind, exclusion zone
7	Climbing / insulator work	Falls, dropped tools, weather
8	Stringing / OPGW	Stored energy, rope failure, traffic
9	Sagging / tensioning	Mechanical energy, communication failure
10	Testing / handover	Electrical exposure, incomplete controls

Table 2. OHTL construction work packages.

Equipment used in such work includes cranes, hydra/crane trucks, excavators, compactors, concrete equipment, generators, welding sets, pullers, tensioners, winches, conductor reels, stringing blocks, torque tools, chain blocks, ladders, fall-arrest systems and communication equipment. The safety significance of this equipment is not only its presence; inspection, certification, operator competence, maintenance, rated capacity and compatibility with the approved method statement determine whether the equipment is a reliable barrier.

The workforce typically includes project and construction managers, safety personnel, civil and erection supervisors, riggers, crane operators, electricians, line workers, drivers, helpers, surveyors and rescue/first-aid personnel. Competency must be role-specific because lifting supervision, rigging, tower climbing, rescue and electrical safety require different knowledge and authorization. Remote terrain, heat, wind, dust and communication limitations further influence fatigue and emergency response.

IV. PROBLEM IDENTIFICATION

The problem-identification stage converts the broad statement that OHTL construction is hazardous into measurable loss-of-control mechanisms. Each activity is decomposed into task steps, energy sources, exposed persons, initiating events and consequences. The resulting hazard profile is dominated by work at height, lifting and dropped objects, and electrical exposure, stringing stored energy, excavation, vehicle movement and weather.

ID	Activity	Hazard	Potential consequence	Initial R
H01	Excavation	Sidewall collapse	Burial / fatal injury	12
H02	Foundation	Unprotected rebar	Puncture / fall	12
H03	Tower assembly	Dropped member	Struck-by injury	16
H04	Tower erection	Uncontrolled load	Fatal struck-by	20
H05	Tower climbing	Fall from height	Fatality	20
H06	Insulator work	Dropped tools	Struck-by	16
H07	Stringing	Rope/conductor failure	Severe injury	20
H08	Sagging	Unexpected tension release	Severe injury	15
H09	Crane operation	Overturn / collision	Fatality	20
H10	Vehicle movement	Pedestrian collision	Fatality	12
H11	Electrical proximity	Contact / flashover	Fatality	20

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H12	Weather	High wind/lightning	Multiple injuries	16

Table 3. Baseline hazard register – modelled framework from Part-II.

The baseline register shows why severity alone cannot be used to prioritize controls. Tower erection, climbing, stringing, heavy lifting and electrical proximity all carry a risk score of 20, but the initiating mechanisms differ. A useful safety intervention therefore needs to address the specific energy pathway: lifting instability, fall exposure, stored mechanical energy or electrical proximity. The 5P root-cause structure—People, Plant, Process, Place and Management—helps avoid blaming individuals and directs corrective action toward system conditions.

5P domain	Typical contributing conditions
People	Competence, fatigue, communication and supervision
Plant	Crane capacity, rigging, tools, vehicles and inspection
Process	JSA, PTW, lift plan, stringing procedure and rescue plan
Place	Terrain, weather, ROW, traffic and electrical proximity
Management	Planning, resources, contractor control, audit and learning

Table 4. Root-cause categories used for problem formulation.

4.1 Critical accident scenarios

Three major accident scenarios are selected for Bow-Tie analysis: fall from tower, uncontrolled lifting/dropped object and electrical contact/flashover. These scenarios are useful because they connect the initiating threat with a top event and then with consequences, while allowing preventive and mitigative barriers to be assigned owners and verification frequencies.

V. PROBLEM FORMULATION AND INTEGRATED RISK-REDUCTION METHOD

The research problem is formulated as a risk-control optimization problem: reduce occupational risk while maintaining construction productivity and compliance with approved engineering methods. The baseline risk score is calculated as $R = L \times S$, where likelihood reflects exposure frequency, probability and control reliability, while severity represents the credible worst-case consequence. FMEA complements rather than replaces HIRA by using $RPN = S \times O \times D$ to prioritize failure modes.

Variable	Meaning
L	Likelihood rating, 1–5
S	Severity rating, 1–5
R	Risk score = L × S
O	FMEA occurrence rating, 1–10
D	FMEA detection rating, 1–10
RPN	Severity × Occurrence × Detection
CR	Control-reliability concept
KPI	Leading or lagging safety indicator

Table 5. Risk-analysis variables.

5.1 Integrated OHTL Risk Reduction Method (IORRM)

IORRM contains five connected layers. First, the activity is decomposed and screened through HIRA so that hazards are linked to task steps and energy sources. Second, FMEA is applied to selected failure modes to identify where occurrence and detection need improvement. Third, Bow-Tie analysis identifies preventive and mitigative barriers for major scenarios. Fourth, the hierarchy of controls is used to select controls, with preference for engineering and planning measures over reliance on individual behaviour. Fifth, dynamic field verification uses PTW, weather hold points, lift-plan checks, competency verification and leading indicators.

The important conceptual addition is control reliability. A control is treated as reliable only when it is present, suitable, understood and verified. A fall-arrest harness, for example, does not constitute a complete barrier if an approved

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anchor, rescue arrangement or worker competence is missing. This converts safety from a checklist of documents into a question of whether the control can actually prevent or mitigate the credible event at the time of work

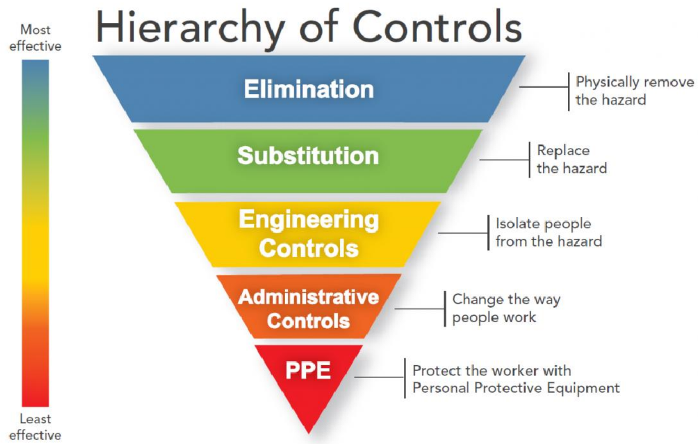

Figure 2. Hierarchy of controls supporting the proposed IORRM.

VI. METHODOLOGY

The methodology combines qualitative hazard identification with semi-quantitative risk scoring, FMEA prioritization, Bow-Tie barrier analysis and comparative performance evaluation. The research sequence begins by understanding the construction process, identifying hazards, establishing baseline risk, prioritizing critical risks, developing advanced controls, verifying controls and comparing baseline with post-control indicators.

The intended primary data include site observations, photographs, task observations, interviews, toolbox-talk records, PTW records, inspection checklists, equipment certificates, near-miss records and work-hour data. Secondary information includes method statements, risk assessments, design drawings, standards and technical literature. Because the present Part-II file did not contain verified primary records, the numerical results used in this paper are explicitly modelled.

Risk score	Category	Decision rule
1–4	Low	Routine controls and monitoring
5–9	Moderate	Improve controls and supervisor verification
10–16	High	Formal action plan and management attention
17–25	Critical	Do not start/continue until controls are verified

Table 6. Risk classification criteria.

HIRA is conducted in ten logical steps: identify the activity; break it into task steps; identify hazards and energy sources; identify exposed persons; determine consequences; rate likelihood and severity; calculate risk; apply the hierarchy of controls; reassess residual risk; and assign ownership and verification frequency. This sequence creates a direct chain from hazard recognition to accountable control implementation.

6.1 Critical-task verification and PTW

For critical tasks, JSA must identify hold points rather than merely describe the job. Before work proceeds, the supervisor confirms that workers understand the method, equipment is fit for purpose, weather is acceptable, exclusion zones are established and emergency arrangements are ready. If an essential barrier is missing, the critical-task card can prevent work from starting. PTW is then used for formal authorization of critical operations such as work near energized systems, major lifting and stringing crossings, with scope, hazards, controls, responsible persons, validity and stop-work conditions recorded.

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6.2 Lifting, weather and digital controls

A lift plan is treated as an engineering control document. It verifies load weight, centre of gravity, crane capacity at working radius, ground conditions, outrigger configuration, rigging capacity, lifting points, wind limits, exclusion zones, communication and emergency-stop criteria. Weather hold points are task-specific and use approved client or manufacturer limits rather than generic numbers. If limits are exceeded, the task is suspended and requires re-authorization after conditions return to acceptable limits.

Digital controls are proposed as a traceability layer rather than a substitute for supervision. QR-coded equipment and fall-protection inspection records, digital PTW status, competency verification and mobile corrective-action close-out can reduce the likelihood of outdated paperwork. The operational value comes from making the current status visible and auditable at the work front.

6.3 Bow-Tie and emergency preparedness

Bow-Tie analysis is converted into a management tool by assigning barrier owners and verification frequencies. For tower rescue, the plan must consider suspension in a harness, restricted access and the need for rapid communication and medical escalation. Rescue kits, trained rescuers, access routes, first aid, emergency transport and communication must be verified before climbing begins.

The main analysis measures are mean risk score, percentage risk reduction, compliance percentage and—when sufficient paired field data are available—statistical significance testing. Mean risk score is $\Sigma R/n$; risk reduction is $(R_{before} - R_{after})/R_{before} \times 100$; and compliance is compliant observations divided by total observations multiplied by 100.

VII. RESULTS AND DISCUSSION

The results in this section are the numerical model supplied in Part-II, not audited company results. The baseline HIRA contains twelve activities. Seven activities fall in the high category and five are critical, with tower erection, climbing, stringing, heavy lifting and electrical proximity receiving a risk score of 20.

Activity	L	S	Baseline R	Residual R	Reduction %
Excavation	3	4	12	6	50.0
Rebar/formwork	3	4	12	6	50.0
Tower assembly	4	4	16	8	50.0
Tower erection	4	5	20	10	50.0
Climbing	4	5	20	9	55.0
Insulator installation	4	4	16	8	50.0
Stringing	4	5	20	10	50.0
Sagging	3	5	15	8	46.7
Heavy lifting	4	5	20	9	55.0
Road movement	3	4	12	6	50.0
Electrical proximity	4	5	20	8	60.0
Weather exposure	4	4	16	8	50.0

Table 7. Baseline and residual risk scores – modelled Part-II dataset.

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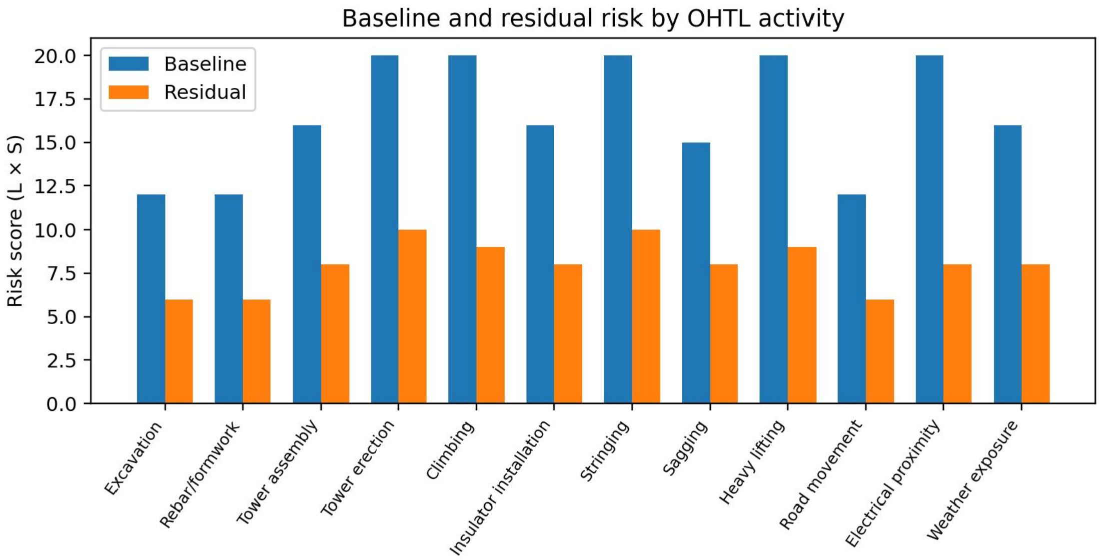

Figure 3. Baseline versus post-control risk scores using the Part-II modelled dataset.

The post-control dataset shows a consistent reduction across all twelve activities. Electrical proximity shows the largest reduction at 60%, while climbing and heavy lifting each show 55%. Tower erection and stringing fall from 20 to 10, which is a 50% reduction. Sagging shows the smallest reduction, from 15 to 8, or 46.7%. The pattern supports the study's argument that the strongest improvement is associated with controls that modify the exposure pathway—such as controlled lifting, fall protection, exclusion zones and electrical authorization—rather than simply increasing PPE use.

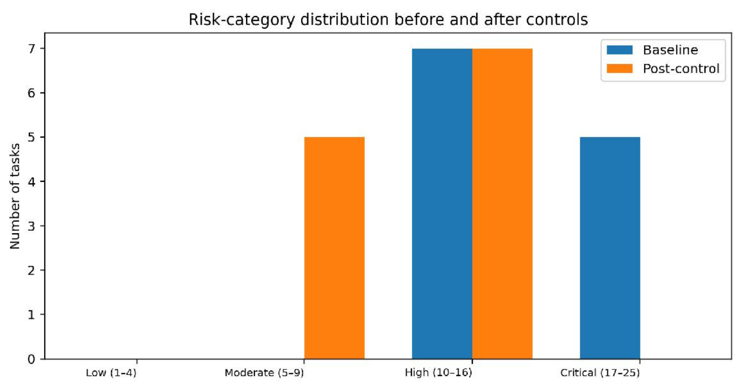

Figure 4. Distribution of tasks across risk categories before and after the proposed controls.

At the aggregate level, the mean risk score decreases from 16.25 to 8.17, a 49.7% reduction. The critical-task count decreases from five to zero, while five tasks move into the moderate/low range. The number of high-category tasks remains seven because the post-control scores of 10 are still classified as high under the adopted matrix. This is an important interpretation: risk reduction does not mean that every task becomes low risk; rather, the controls can move a task below the critical threshold while retaining management attention for residual high risks.

7.1 FMEA analysis

FMEA provides a second lens because it asks how a failure can occur and how effectively the system can prevent or detect it. In the supplied model, fall from height has the highest baseline RPN of 270, followed by electrical contact at 250 and dropped object at 240. After the proposed controls, the fall-from-height RPN becomes 81. This reduction does

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not imply that the severity of a fall has changed; instead, occurrence and detection are improved through engineered fall protection, planning and verification.

Failure mode	S	O	D	RPN before	RPN after	Reduction %
Dropped object	8	6	5	240	72	70.0
Fall from height	9	6	5	270	81	70.0
Crane overturn	9	4	6	216	72	66.7
Electrical contact	10	5	5	250	75	70.0
Excavation collapse	9	4	5	180	60	66.7
Vehicle collision	8	4	6	192	64	66.7
Heat stress	6	5	5	150	54	64.0
Stringing failure	10	5	4.2	210	70	66.7

Table 8. FMEA comparison and RPN reduction – modelled Part-II data.

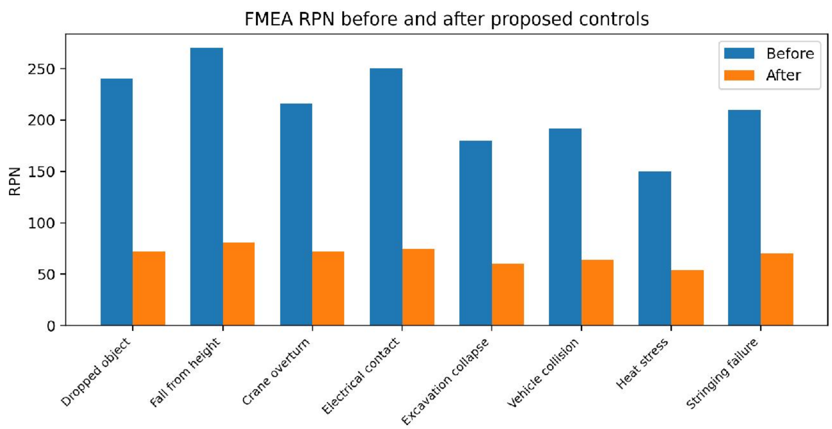

Figure 5. FMEA Risk Priority Number reduction.

The FMEA results show why occurrence and detection are useful control variables. A dropped object can be addressed through tool tethering, exclusion zones and controlled lifting; a crane overturn can be addressed through lift-plan verification, ground assessment and rated-capacity checks; electrical contact requires formal authorization and electrical controls; and stringing failure requires inspection, communication and emergency-stop criteria. The analysis therefore connects each numerical RPN reduction to a plausible control mechanism rather than treating the percentage as a standalone performance claim.

7.2 Leading indicators

Indicator	Baseline %	After method %	Improvement (pp)
PTW compliance	62	94	32
JSA compliance	68	96	28
PPE compliance	74	97	23
Toolbox talk	70	95	25
Lift-plan verification	55	93	38
Weather check	58	92	34
Inspection close-out	60	90	30

Table 9. Leading-indicator comparison – modelled Part-II data.

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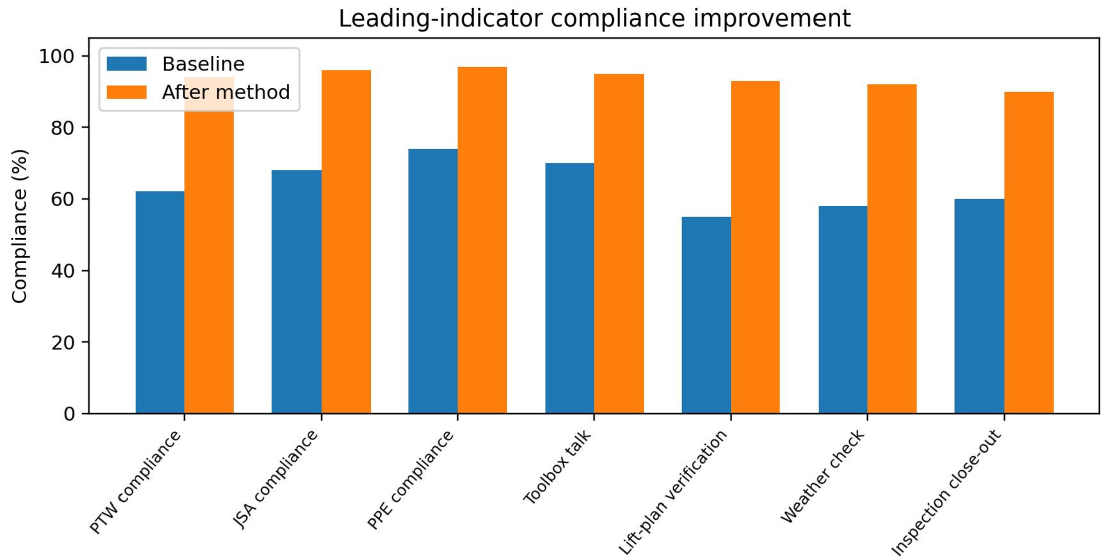

Figure 6. Improvement in leading safety indicators.

The largest improvement is lift-plan verification, increasing from 55% to 93%, followed by weather checks from 58% to 92% and PTW compliance from 62% to 94%. These indicators are important because they precede the event rather than merely recording the event after harm has occurred. If a critical lift begins without a verified lift plan, the organization has lost an opportunity to prevent the event. Conversely, a verified plan, suitable crane capacity, stable ground, controlled exclusion zone and defined stop criteria create multiple barriers before energy is introduced.

PPE compliance also increases from 74% to 97%, but the interpretation should not be that PPE is the main reason for risk reduction. The Part-II discussion explicitly argues that engineering and planning controls are essential and that PPE is not the principal driver. The more meaningful change is the combined improvement in authorization, lifting verification, weather checks and inspection closure.

7.3 Calculation and interpretation

For tower erection, the model uses a baseline likelihood of 4 and severity of 5,

Giving $R = 4 \times 5 = 20$.

After controls, likelihood is reduced to 2 while severity remains 5, giving residual $R = 10$.

The percentage reduction is therefore $(20 - 10)/20 \times 100 = 50\%$.

The unchanged severity is appropriate because the credible worst-case consequence remains fatal; the improvement comes from reducing the probability of reaching that consequence.

For fall from height, the baseline FMEA uses

$S = 9$, $O = 6$ and $D = 5$, giving $RPN = 270$.

After advanced controls, $O = 3$ and $D = 3$, giving $RPN = 81$.

The resulting 70% reduction is a combined improvement in occurrence and detection, while severity remains constant.

7.4 Why control verification matters

A document is not a barrier until it changes the exposure pathway. An exclusion zone is effective when unauthorized people are actually prevented from entering the lifting radius. A weather check is effective when the crew stops work when the approved limit is exceeded. A rescue plan is effective when equipment, trained rescuers, access and communication are ready before the worker climbs. This distinction is central to IORRM because it shifts safety management from document completion to field reliability

The modelled findings should nevertheless be interpreted with caution. The Part-II file states that actual site work-hour and incident records were not supplied and that the safety-performance trend is a preferred reporting format rather than an empirical project record. Therefore, no claim is made here that injury frequency or incident rates were actually reduced at the project site. The defensible finding is that the proposed analytical framework produces a substantial modelled reduction in calculated risk and improves the control-compliance indicators used in the supplied dataset.

VIII. PROPOSED FIELD IMPLEMENTATION FRAMEWORK

The framework can be implemented as a repeating Plan–Verify–Execute–Review cycle. Before work, the responsible supervisor reviews the approved method statement, JSA, PTW, competency status, equipment inspection, weather, exclusion zones and emergency arrangements. During work, the supervisor monitors barrier status, communication, weather and changes in the work front. After completion, the team inspects the worksite, closes permits, records observations and captures lessons learned.

Stage	Verification question	Evidence
Plan	Is the task method and hazard assessment current?	Approved method/JSA
Authorize	Are critical controls verified before start?	PTW/critical-task card
Prepare	Is equipment fit and personnel competent?	Inspection/certificates/competency
Execute	Are barriers maintained under changing conditions?	Supervisor observations
Stop/Restart	Are weather or control limits exceeded?	Hold-point record
Close	Are corrective actions and permits closed?	Digital/physical close-out
Learn	Were near misses and barrier failures reviewed?	Learning record

Table 10. Practical IORRM implementation cycle.

The proposed digital layer can support this cycle by linking QR codes to equipment inspection status, maintaining current PTW information, checking competency validity and recording corrective-action close-out. The technology should remain subordinate to field supervision: if a digital system says that an inspection is current but the equipment is visibly damaged, the field condition controls the decision. This principle preserves the safety engineer's professional responsibility while improving traceability.

IX. CONCLUSION

The study demonstrates that 380 kV OHTL construction should be treated as a dynamic, multi-hazard system rather than a collection of independent construction tasks. The dominant exposure pathways identified in the Part-II study are falls from height, dropped objects, uncontrolled lifting, and electrical contact/flashover, stringing failures, excavation collapse, vehicle interaction and adverse weather.

The proposed IORRM integrates HIRA, FMEA, and Bow-Tie, hierarchy of controls, JSA, PTW, lift-plan verification, weather hold points, digital traceability and leading indicators. Its principal value is the connection between risk analysis and barrier verification. The modelled results show a mean risk-score reduction from 16.25 to 8.17, a 49.7% reduction, and a reduction of critical tasks from five to zero. FMEA examples also show substantial RPN reductions, including 270 to 81 for fall from height. These results support the research hypothesis at the level of the supplied modelled dataset, while not constituting audited field evidence.

For publication-quality validation, the next step is to replace the modelled values with actual paired observations from the project: task-level HIRA scores, work-hours, PTW records, JSA compliance, lift-plan verification, weather observations, near misses, incidents, corrective-action closure and verified photographs. The Part-II document itself recommends this distinction between observed facts, literature-derived principles, engineering assumptions and modelled examples as a requirement for academic credibility.

X. RECOMMENDATIONS

Engineering controls should be the first focus. Critical tower lifts should use engineered lifting plans that account for actual load, working radius, ground conditions, outrigger configuration, rigging certification, wind and exclusion zones. Tower climbing should use approved fall-arrest anchor systems and engineered access arrangements. Excavations should use protection appropriate to soil and depth, while road, utility and existing-line crossings should use approved protection. Mechanical aids should be introduced where repetitive manual handling creates avoidable exposure.

Administrative controls should support, not replace, engineering controls. Critical activities should use task-specific PTW; daily pre-task reviews should account for changing conditions; specialized roles should be linked to competency matrices and authorization cards; weather hold points should have documented restart criteria; toolbox talks should focus on the day's critical hazards; and workers should have stop-work authority without production penalty. 毅filecite學turn2file0學L569-L581傢

For lifting, crane selection must be based on actual load and working radius rather than nominal capacity alone. Ground bearing, outriggers, rigging, wind and exclusion zones must be verified before the lift. For work at height, fall protection, tool control and rescue readiness must be completed before climbing. For electrical work, the responsible electrical authority's isolation, grounding, minimum-approach-distance and permit requirements must be followed. Stringing should have one competent controller coordinating equipment, communications, crossings, exclusion zones, emergency stop and weather criteria.

Indicator	Target concept
Critical-control verification	100% before critical-task start
PTW compliance	≥95%
Lift-plan verification	100% for defined critical lifts
Weather checks	100% for weather-sensitive tasks
Inspection closure	≥90% within agreed period
Rescue readiness	100% before tower climbing
Training/competency validity	100% for authorized roles

Table 11. Recommended safety-performance dashboard.

XI. FUTURE SCOPE

The framework can be extended through IoT-based monitoring, AI-assisted risk prediction, computer vision, digital twins and probabilistic barrier reliability. Wind-speed sensors, equipment telemetry, location tracking and environmental monitoring could feed a safety dashboard linked to approved task limits. Machine-learning models could combine near-miss history, weather, work type, crew composition and equipment condition to identify high-risk periods, provided the models are explainable and validated.

Computer vision could assist in detecting missing PPE, unsafe access, exclusion-zone intrusion and unsafe lifting configurations, but human supervision would remain necessary. A digital twin or BIM/PLS-CADD interface could connect tower locations, access roads, lifting zones, crossings and clearance constraints with safety information. Future quantitative research could assign probabilities of failure to critical barriers and move from semi-quantitative risk scoring toward probabilistic risk modelling. Multi-project validation across 132 kV, 220 kV, and 380 kV and higher-voltage projects would provide a stronger test of generalizability

XII. LIMITATIONS AND DATA INTEGRITY

The most important limitation is data provenance. The Part-II document explicitly states that verified site registers, incident logs, work-hour records, instrument readings and company HIRA sheets were not supplied. Consequently, all numerical comparative results are modelled and are not audited company results. This manuscript preserves that distinction rather than presenting illustrative numbers as measured field performance. Before journal submission, the

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researcher should replace modelled values with verified field observations, site photographs, company records, training and attendance records, inspection reports and measured data.

A second limitation is that project-specific route coordinates, client identity, contract number, tower count, construction dates and approved engineering drawings were not supplied. The study therefore remains a generalized 380 kV case-study framework. The supplied OHTL Design source is used as technical-domain context rather than as evidence for confidential project facts.

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