Operationalizing Quantum Project Management:

Defining Improved Metrics for Management of Large Complex Projects[1]

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Introduction

Quantum Project Management (QPM)[2] [3] is a new management paradigm that replaces Taylorism's Scientific Management paradigm upon which classical project management is founded. It is focused on Large Complex Projects (LCP) and their analogous behavior to quantum and relativistic systems in the world of physics. It has been detailed through

Projects are complex adaptive systems

[1] How to cite this paper: Prieto, R. (2026). Operationalizing Quantum Project Management: Defining Improved Metrics for Management of Large Complex Projects, *PM World Journal,* Vol. XV, Issue I, January.
[2] Prieto, R. (2024). Quantum Project Management, PM World Journal, Vol. XII, Issue I, January 2024. https://pmworldlibrary.net/wp-content/uploads/2024/01/pmwj137-Jan2024-Prieto-Quantum-Project-Management-.pdf
[3] Quantum Project Management A monograph on a new theory for management of large complex projects (2024); ISBN 978-1-304-08165-0

a series of articles in the *PM World Journal*[4] [5] [6] [7] [8] [9] and earlier foundational work described in this journal[10] [11] [12] [13] [14] [15] and elsewhere[16] [17] [18] [19], with various aspects of significance to the theory further expanded on. This paper explores new metrics which actualize the application of this shift in mindset and frameworks.

It is important to highlight that the quantum properties of physics are increasingly being translated into meaningful real world applications such as quantum computing (complex optimization problems), quantum sensors (critical to GPS and medical imaging) and quantum entanglement (ultra-secure communications). Similar potential benefits may be derived in the project management realm through QPM.

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[4] Prieto, R. (2024). Measurement of Complexity in Large Complex Projects, PM World Journal, Vol. XII, Issue IV, April. https://pmworldlibrary.net/wp-content/uploads/2024/04/pmwj140-Apr2024-Prieto-Measurement-of-Complexity-in-Large-Complex-Projects.pdf
[5] Prieto, R. (2024). Quantum Project Management and the Concept of Spacetime, PM World Journal, Vol. XII, Issue V, May. https://pmworldlibrary.net/wp-content/uploads/2024/05/pmwj141-May2024-Prieto-Quantum-Project-Management-and-Concept-of-Space-time.pdf
[6] Prieto, R. (2024). Navigating Complexity, PM World Journal, Vol. XIII, Issue VI, June https://pmworldlibrary.net/wp-content/uploads/2024/06/pmwj142-Jun2024-Prieto-Navigating-Complexity.pdf
[7] Prieto, R. (2024). Quantum Project Management, Large Complex Projects, and Entanglement, PM World Journal, Vol. XII, Issue VII, July 2024.
[8] Prieto, R., Hajiya, A. (2024). Managing Complexity in Large Complex Projects, PM World Journal, Vol. XIII, Issue XI, December.
[9] Prieto, R. (2025). Artificial Intelligence, Complexity, and Quantum Project Management: A Transformative Approach, PM World Journal, Vol. XIV, Issue VII, July.
[10] Prieto, R. (2020). A Deeper Look at the Physics of Large Complex Projects: A Neoclassical Project Management Theory is Required; PM World Journal, Vol. IX, Issue VIII, August.
[11] Prieto, R. (2015). Physics of Projects; PM World Journal Vol. IV, Issue V – May; https://www.researchgate.net/publication/275888028_Physics_of_Projects
[12] Prieto, R. (2020). Systems Nature of Large Complex Programs; PM World Journal, Vol IX, Issue VIII, August.
[13] Prieto, R. (2017). Complexity in Large Engineering & Construction Programs; PM World Journal, Vol VI, Issue XI, November
[14] Prieto, R. (2015), Project Management Theory and the Management of Large Complex Projects; PM World Journal, Vol IV, Issue VI, June
[15] Prieto, R. (2014), Challenges of Dealing with Uncertainty; PM World Journal, Vol IV, Issue I, January
[16] Prieto, R. (2015). Theory of Management of Large Complex Projects; Construction Management Association of America; ISBN: ISBN 580-0-111776-07-9; October.
[17] Large Complex Projects as Open Systems; National Academy of Construction Executive Insight https://www.naocon.org/wp-content/uploads/Large-Complex-Programs-as-Open-Systems.pdf
[18] Flows in Large Complex Projects; National Academy of Construction Executive Insight; https://www.naocon.org/wp-content/uploads/Flows-in-Large-Complex-Projects.pdf
[19] R. Prieto, Theory of Management of Large Complex Projects; Construction Management Association of America (2015); ISBN 580-0-111776-07-9

Key Insights Related to LCP

QPM has provided a framework for describing key insights related to LCP. These are described in Prieto (2024) and recapped here:

- LCP represent open systems[20] that influence and are influenced by their contextual setting and its behaviors over time
- LCP, by their very scale and complexity, are imbued with uncertainty and have a propensity to fundamental indeterminism characterized by emergent behaviors and outcomes
- Traditional decomposition of projects (breaking project into smaller pieces/tasks) does not fully describe an LCP. LCP are complex entangled systems where the whole is greater than the sum of its parts.
- LCP are strongly influenced by the totality of all surrounding ecosystems, stakeholders, forces and flows and in turn influence and interact and shape them.
- Neither the LCP nor its surrounding universe are static. Disruptive events, especially significant ones, ripple through the broader system-of-systems changing each. The potential for significant impacts grows with time as the LCP context is stretched.
- Flows arise from disruptions and disturbances in the surrounding ecosystem impacting the LCP and changing its context. Some flows may take longer to emerge or be more persistent as the LCP and its surrounding universe change.
- Strategic Business Outcomes (SBO) clarity and alignment requires continuous alignment to address the natural precession associated with LCP. It is essential to ensure that the addition of "wants" do not contribute to the LCP collapsing under its own weight.
- Frames of reference in an LCP are rarely aligned and require continuous attention to understanding their interplay.

Recognition of these insights is a critical first step in actualizing this changed project management framework but implementation requires execution, and execution requires management metrics appropriate to the challenge at hand. This paper explores new management metrics to aid in implementation of a QPM approach for LCP. It builds on prior work related to complexity, uncertainty and other significant areas critical to the management of LCP, further developing some and adding some new ones.

[20] Large Complex Programs as Open Systems; National Academy of Construction Executive Insight Large Complex Programs as Open Systems; https://www.researchgate.net/publication/348690977_Large_Complex_Programs_as_Open_Systems_Key_Points#fullTextFileContent

Management Metrics for LCP Under a QPM Approach

The author's focus is centered on large engineering and construction projects but the metrics outlined in this paper are applicable in other domains. Other modified metrics are still required and are being evaluated. In the balance of this paper we look at metrics related to the following aspects of QPM applied to LCPs:

- Complexity[21]
- Uncertainty[22]
- Project Ecosystem
  - Stakeholder Assessment[23] (key aspect of the surrounding ecosystem)
  - Project Foundational Assumption Migration[24]
- Safety

1. Complexity Metric

1.1 Current Focus and Relevance

The **Complexity metric** in Quantum Project Management (QPM) is central to understanding and managing the multifaceted, interdependent, and emergent characteristics of Large Complex Projects (LCPs). Traditional complexity measures[25] [26] in project management have often focused on static structural and organizational features—such as the number of stakeholders, tasks, interfaces, and requirements. However, with the rise of QPM, complexity is being reconceptualized as a dynamic

[21] Managing Complexity in Large Complex Projects; Prieto, R., Hajiya, A.; PM World Journal; Vol. XIII, Issue XI – December 2024; https://pmworldlibrary.net/wp-content/uploads/2024/12/pmwj147-Dec2024-Prieto-Hajiya-Managing-Complexity-in-Large-Complex-Projects.pdf, https://www.researchgate.net/publication/386870526_Managing_Complexity_in_Large_Complex_Projects#fullTextFileContent

[22] Prieto, R. (2025). Measuring Uncertainty in Large Complex Projects, PM World Journal, Vol. XIV, Issue XI, November; https://pmworldlibrary.net/wp-content/uploads/2025/11/pmwj158-Nov2025-Prieto-Managing-Uncertainty-in-Large-Complex-Projects-3.pdf; https://www.researchgate.net/publication/397300009_Managing_Uncertainty_in_Large_Complex_Projects_1#fullTextFileContent

[23] Net Promoter Score - Measure Customer Loyalty and Satisfaction; National Academy of Construction; https://www.researchgate.net/publication/395260783_Net_Promoter_Score

[24] Prieto, R. (2025). Metrics for Assumption Management in Large Complex Projects, *PM World Journal,* Vol. XIV, Issue XII, December

[25] Vidal, L. A., Marle, F., and Bocquet, J. C. 2011. Measuring project complexity using the Analytic Hierarchy Process. International Journal of Project Management, 29(6): 718-727

[26] Project complexity assessment and management tool; International Conference on Sustainable Design, Engineering and Construction, Procedia Engineering 145 (2016) 491 – 496; Bac Dao, Sharareh Kermanshachi, Jennifer Shane, Stuart Anderson

property akin to quantum entanglement and system entropy, moving beyond static interrelationships to capture probabilistic, adaptive, and emergent behavior of project elements.

This shift acknowledges that LCPs are no longer well-ordered, deterministic systems but are instead subject to discontinuities, feedback loops, and non-linear interactions. In QPM, complexity reflects the **degree of interconnectedness**, the **rate of information exchange**, and the **potential for emergent behaviors**—all of which significantly affect project adaptability, risk, and successful outcomes. Recognizing and quantifying these aspects have clear practical benefits for project managers, especially as LCPs become increasingly integrated, digitalized, and vulnerable to rapid change.

For QPM, capturing complexity enables better resource allocation, anticipatory risk management, and design of responsive control mechanisms. This is especially pertinent as quantum-inspired computational and analytical tools allow more granular identification and real-time monitoring of complexity drivers, thus supporting dynamic decision-making and the early identification of cascading failures or synergies.

1.2 Current Formula and Explanation

Historically, complexity in project management has been quantified using metrics such as:

$$C_{total} = aN + bI + cS$$

Where:

- C_{total} represents the overall complexity score for the project.
- **N** is the number of elements (tasks, components, or work packages).
- **I** is the number of interactions between these elements (e.g., interfaces or dependencies).
- **S** is a measure of system structural diversity (e.g., number of different component types or organizational layers).
- **a, b, c** are weighting coefficients reflecting the relative importance of each dimension, determined by experts or historical data analysis.

These variables are typically measured via:

- Project schedules and breakdown structures for **N** ;
- Dependency matrices or interface lists for **I** ;

- Organizational charts, system diagrams, or stakeholder registers for **S**.

This approach, while a step forward from earlier methodologies that simply counted activities or deliverables, remains essentially additive and static—it does not fully capture the recursive, dynamic, or emergent aspects that typify quantum-influenced complexity in LCPs.

1.3 Proposed Improvements and Value-Add

Improvement Rationale:

To align the complexity metric with QPM principles, it is necessary to transition from additive, structural quantification towards a formulation that incorporates the *dynamic information flow*, *adaptive feedback*, and *entanglement* among project components. QPM suggests that complexity should reflect not just the *number* but the *quality* and *strength* of interdependencies, their potential for propagation of change, and the ease (or resistance) with which the system adapts to disruption.

Added Value:

- **Capturing Emergence:** Includes metrics for emergent behaviors, such as *network entropy*[27] or measures from computational complexity theory (e.g., computational resources required to simulate or optimize the project state).
- **Dynamic Feedback:** Considers time-dependent feedback (delays, accelerations, amplification effects), not just static connectivity.
- **Quantum Analogies:** Leverages concepts from quantum physics, such as *entanglement entropy*[28], to evaluate the degree to which changes in one subsystem are probabilistically linked to changes in another.
- **AI Integration:** Utilizes predictive analytics and machine learning to continuously recalibrate complexity scores in response to real-time signals.

This upgraded metric thus enables adaptive project steering, more precise risk anticipation, and identification of potential points of brittleness or resilience in the project network.

[27] Network entropy is a measure of disorder and complexity in a network, quantifying the randomness and information encoded within its structure. Shannon Entropy is one type of network entropy and is commonly used to measure the uncertainty associated with the degree distribution of a network.
[28] Entanglement entropy is a measure of the degree of quantum entanglement between two subsystems in a composite quantum system.

1.4 Revised Formula and Explanation

The upgraded metric draws on network science and quantum information theory, specifically *network entropy* and *weighted entanglement entropy*. A representative revised formula might be:

$$C_{QPM} = H - \sum_{i=1}^{n}\sum_{j=1}^{n} \gamma_{ij} \cdot \log(\rho_{ij} + \varepsilon)$$

Where:

- **C_{QPM}:** QPM-derived complexity metric (dimensionless, higher values = greater complexity).
- **H:** Structural (Shannon[29]) entropy of the project network, calculated as:

$$H = -\sum_{i=1}^{n} \rho_i \log(\rho_\iota)$$

where **p_i** is the normalized weight of activity/node **i** in the project (e.g., based on resource allocation, criticality, or frequency of information exchange).

- **$\gamma_{\{ij\}}$:** The interaction entanglement coefficient between nodes **i** and **j** computed from correlation[30] or co-evolution data (e.g., historical change records, simulation runs).
- **$p_{\{ij\}}$:** Probability of change propagation from **i** to **j** within a specified timeframe, estimated from Bayesian or ML-driven models using historical and current project data.
- **ε:** A small positive constant (e.g., 10^{-9}) to prevent logarithmic singularities.

Data Sources and Measurement Approaches:

- Project Information Systems (PIS) and integrated digital twins for **p_i** (resource/time tracking, task logs).

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[29] Shannon Entropy is a measure of the information content of data, where information content refers more to what the data could contain, as opposed to what it does contain. In this context, information content is really about quantifying predictability, or conversely, randomness. Shannon Entropy decreases when order is imposed on a system and increases when the system is more random. Entropy is maximized (and predictability minimized) when all outcomes are equally likely.

[30] An Overview of Correlation; National Academy of Construction Executive Insights https://www.naocon.org/wp-content/uploads/An-Overview-of-Correlation.pdf

- Automated dependency tracking in BIM, PLM, or PMIS tools for $\gamma_{\{ij\}}$ (interface change impacts, cross-functional meeting analytics).
- ML-based change propagation models, utilizing historical fault logs, change orders, and "what-if" scenario simulations to estimate $p_{\{ij\}}$.

This approach:

- **Represents both diversity and deep-network interdependence** (higher entanglement and correlated changes produce higher complexity scores).
- **Allows day-to-day recalibration:** AI/ML systems continually update estimates as project state changes.
- **Provides actionable insights:** Sensitivity analysis can identify "hot zones" of complexity that may require simplification or decoupling[31] interventions.

2. Uncertainty Metric

2.1 Current Focus and Relevance

Uncertainty[32] is a defining characteristic of LCPs, especially in QPM where the predictability of outcomes is fundamentally limited by non-linear dynamics, emergent interactions, and exogenous variables. Existing methods of quantifying uncertainty in projects generally focus on risk registers, risk matrices, or probabilistic cost/schedule estimates—essentially capturing "known unknowns."

In a QPM paradigm, uncertainty is not just a static property to be minimized, but an ongoing, multi-dimensional phenomenon closely allied with the quantum concept of indeterminacy. QPM frameworks treat uncertainty as a measure of the system's range of possible futures, its flexibility, and its sensitivity to interventions, in a manner loosely analogous to Heisenberg's uncertainty principle in physics. This means that large,

[31] Coupling in Large Complex Projects; National Academy of Construction Executive Insight https://www.naocon.org/wp-content/uploads/Coupling-in-Large-Complex-Projects.pdf
[32] Uncertainty in Large Complex Projects; National Academy of Construction Executive Insight; https://www.naocon.org/wp-content/uploads/Uncertainty-in-Large-Complex-Projects.pdf; https://www.researchgate.net/publication/366165771_Uncertainty_in_Large_Complex_Projects_Key_Points#fullTextFileContent

complex projects need to embrace uncertainty for adaptive advantage[33] rather than simply seek to eradicate it—a foundational shift in mindset.

By making uncertainty an explicit, dynamic, and rigorously quantified variable, QPM enables decision-makers to balance exploration with exploitation, strategically allocate contingencies, and prevent overconfidence in deterministic plans—a critical capability in high-stakes, high-ambiguity environments.

2.2 Current Formula and Explanation

A common current approach to quantifying uncertainty is through the computation of standard deviation or coefficient of variation for key project performance indicators (KPIs). For example, the uncertainty in project duration might be expressed as:

$$U = \frac{\sigma_T}{\mu_T}$$

Where:

- **U:** Relative uncertainty in project duration (dimensionless).
- **σ_T:** Standard deviation of project duration, estimated via Monte Carlo simulation, PERT analysis, or expert judgement.
- **μ_T:**Mean (expected) project duration.

Alternatively, uncertainty may be aggregated across multiple KPIs:

$$U_{total} = \sqrt{\sum_{i=1}^{n} \omega_i \left(\frac{\sigma_i}{\mu_i}\right)^2}$$

Where:

- **w_i :** Weight for each KPI **i** (e.g., cost, schedule, quality).

[33] The effects of uncertainty over time grow exponentially so if you plot the impact of uncertainty on a log scale you will get a straight line. If you think of a parameter's value as V(t) where t is time, then you can write it as V(t) = V(0)*EXP (kt), where V(0) is your value at time of estimate or contract and k is a positive constant related to the particular parameter. In the case of an unmodified contract, k=0, and the contract value if you will is unchanged over time. Now think of a parameter such as labor cost where a higher labor escalation rate is realized throughout the project period. Here k would be equal to the delta between the labor rate growth assumed in the contract and the actual realized rate. The slope of that log plot would be k.

Measurement relies on historical data, risk databases, project performance tracking, and scenario analysis outputs.

However, these formulations treat uncertainty as merely a function of dispersion or variance, without accounting for the multidimensional, systemic, and sometimes epistemic qualities of uncertainty encountered in LCPs.

2.3 Proposed Improvements and Value-Add

Improvement Rationale: QPM advocates an *information-theoretic* and *process-holistic* conceptualization of uncertainty, inspired by quantum mechanics and modern uncertainty quantification science. This new view accounts for:

- **Aleatory and epistemic sources[34]:** Both inherent (randomness) and knowledge-based (ignorance, model limitations).
- **Entropic measures:** Entropy is used as the core quantifier, capturing the richness and unpredictability of the project's possible future states.
- **Interventional feedback:** Uncertainty is dynamically updated based on new measurements, stakeholder actions, and environmental feedback—analogous to state collapse in quantum measurement.
- **Scenario diversity:** Explores "uncertainty bandwidth" across divergent scenarios, mapping plausible outcomes rather than just point estimates.

Value-Add:

- Enables adaptive, scenario-responsive planning and risk appetite calibration.
- Quantifies the informational value of additional data collection or stakeholder engagement, guiding optimal investment in learning.
- Avoids the "illusion of precision" that plagues traditional deterministic forecasts.

2.4 Revised Formula and Explanation

The quantum-inspired, entropic uncertainty metric can be formulated as:

$$U_{QPM} = \mathrm{H(S)} + \delta\hat{S}$$

[34] The distinction between aleatory and epistemic uncertainty is crucial. Aleatory uncertainty arises from the inherent randomness of a phenomenon, which cannot be reduced by accumulating more data. Epistemic uncertainty, on the other hand, is related to the knowledge or data available about a phenomenon and can be reduced by increasing the amount of information.

Where:

- U_{QPM}**:** Quantum Project Management Uncertainty Metric.
- **H(S):** Shannon entropy of the project "state" distribution S
- **S** is the discrete scenario distribution {s_k} with probabilities P(s_k) obtained from expert elicitation, ML-predicted distributions, or Monte Carlo simulations.
- $\delta\hat{S}$ is mean scenario spread or scenario bandwidth, i.e., the expected distance between the best and worst plausible outcomes: E[max(s_k) − min(s_k)].
- Data Sources:
  - Integrated project databases, digital twins, real-time dashboards, and scenario generation engines.
  - AI-driven scenario modeling modules.

Measurement involves:

- Regularly updating scenario sets {s_k}, with update frequency driven by trigger events, new data acquisition, or structured stakeholder "decision pulses."
- Calibrating probabilities using Bayesian inference and/or learning from observed deviations.

The final uncertainty score reflects both the richness and unpredictability of the future via entropy, H(S), and the expected range of deviation from plan, $\delta\hat{S}$. This dual quantification raises situational awareness and supports risk-intelligent governance at upper management layers.

3. Project Ecosystem - Stakeholder Assessment (Net Promoter Index[35])

3.1 Current Focus and Relevance

Stakeholder engagement[36] represents a pivotal determinant of LCP success, as these projects often span multiple organizations, socio-political boundaries, and regulatory

[35] The term Net Promoter Index (NPI) has been used here and is synonymous with Net Promoter Score (NPS) used in other works by the author.
[36] Stakeholder Management in Large Engineering & Construction Programs; PM World Journal Vol. X, Issue VII – July 2021; pmwj107-Jul2021-Prieto-stakeholder-management-in-large-engineering-construction-programs.pdf (pmworldlibrary.net);

regimes. The **Net Promoter Index (NPI)** has emerged as a simple yet powerful indicator of overall stakeholder satisfaction, loyalty, and likelihood to champion or obstruct project progress. It is one measure of the condition of the surrounding project ecosystem.

In its traditional application within project management, NPI provides an aggregate measure of stakeholder willingness to recommend or endorse the project, derived from structured survey responses. Its utility in LCPs lies in its ability to synthesize complex, qualitative stakeholder attitudes into a single, comparable score, allowing for benchmarking, trend analysis, and targeted engagement interventions.

For QPM, stakeholder assessment via NPI is essential—not only for measuring satisfaction but in recognizing scale-dependent resonance phenomena, emergent resistance, or support patterns across vast stakeholder ecosystems, which can cascade into substantial project risk or advantage.

3.2 Current Formula and Explanation

The standard NPI formulation is:

NPI = %P - %D

Where:

- **NPI:** Net Promoter Index (ranges from -100 to +100).
- **%P:** Percentage of "Promoters"—stakeholders giving the highest ratings (typically 9 or 10 on a 10-point scale) to the question, "How likely are you to recommend this project to someone like you?"
- **%D:** Percentage of "Detractors"—stakeholders giving lowest ratings (0-6 on a 10-point scale).
- Passives (ratings 7-8) are ignored in the index.

Data are derived from targeted stakeholder surveys, which may include project partners, key end-users, regulators, and directly impacted communities. These structured assessments are usually administered quarterly or at key project milestones.

This method is straightforward and allows time trend tracking, but it is relatively insensitive to nuance, influence weighting, or the propagation of stakeholder sentiment through the LCP's social-political network.

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https://www.researchgate.net/publication/273119019_Stakeholder_Management_in_Large_Engineering_Construction_Programs

3.3 Proposed Improvements and Value-Add

Improvement Rationale: For LCPs under QPM, NPI should capture not just the static snapshot of stakeholder attitudes, but their relational strength, network influence, and time-dependent evolution. The quantum approach also suggests ***superposition***—wherein some stakeholders can simultaneously harbor positive and negative dispositions toward different dimensions of the project, and ***entanglement***—where groups' attitudes influence one another.

Key upgrades include:

- **Weighted NPI:** Adjusts for the influence, criticality, and network centrality of each stakeholder or group, recognizing that not all stakeholders are equally impactful.
- **Temporal Dynamics:** Models changes in NPI across project phases and after key events (policy changes, crises, major deliverables).
- **Sentiment Superposition:** Allows for multidimensional attitude tracking (e.g., support for project objectives vs. process dissatisfaction), applying a vector approach to stakeholder sentiment.

Value-Add:

- More accurately reflects the *strategic risk or support* associated with stakeholder sentiment.
- Guides targeted engagement where negative sentiment would have the highest leverage or spillover effects.
- Enhances predictive analytics by embedding NPI's evolution into broader project risk and opportunity modeling.

3.4 Revised Formula and Explanation

A quantum-inspired, network-weighted NPI is expressed as:

$$NPI_{QPM} = \sum_{i=1}^{n} \omega_i \, (P_i - D_i)$$

Where:

- **NPI $_{QPM}$:** Weighted Net Promoter Index.
- **n:** Number of individual stakeholders or stakeholder groups.

- **w_i:** Influence weight of stakeholder **i**, derived from network analysis (centrality, betweenness, regulatory power, or historical impact).
- **P_i:** Proportion of "Promoter" responses from stakeholder **i** (fraction of positive responses in group **i**).
- **D_i:** Proportion of "Detractor" responses from stakeholder **i**.

Alternatively, if stakeholders are scored across multiple dimensions **d**:

$$NPI_{QPM}^{(d)} = \sum_{i=1}^{n} \omega_i^{(d)} \left(P_i^{(d)} - D_i^{(d)}\right)$$

Where all variables carry an additional dimension index **d**.

Data Sources and Measurement Approaches:

- Structured multi-dimensional survey responses, integrated with digital engagement logs.
- Stakeholder influence maps computed via social network analysis (SNA)[37], digital twin platforms, or AI-based reputation analysis tools[38].
- Longitudinal data capture—tracking evolution of sentiment over time and correlating to major project events.

This formulation captures both the *relative weight* of each stakeholder's attitude and the *vectorial nature* of possible attitudes, more accurately reflecting real-world influence and the cascading effects of changing opinions in an LCP context. It enhances both operational and governance-level decision making by informing which relationships most urgently require recalibration or intervention.

[37] Social network analysis (SNA) is the process of investigating social structures through the use of networks and graph theory. In SNA, nodes represent individual actors (people, organizations, or entities), while edges (or ties) represent the relationships or interactions between them.
[38] These tools include sentiment analysis and predictive modeling.

4 Project Foundational Assumption Migration Metrics

4.1 Current Focus and Relevance

Large complex projects (LCPs) depend on hundreds to thousands of explicit and tacit assumptions that form the working baseline for estimates, schedules, procurement and safety decisions. They help shape and define the broader project ecosystem. Current practice centers on assembling Assumption Registers: spreadsheets or simple databases that record an assumption's ID, baseline value, owner and—occasionally—evidence and last update. In practice these registers are often incomplete, inconsistent, updated irregularly, and lack standardized distance metrics, consequence encoding, time-aware confidence, or any formal link to governance actions. As a result:

- Many micro-migrations (small, routine changes to assumptions) go unrecorded and later synchronize into systemic failures.
- Executive oversight lacks a normalized, auditable signal to compare projects or trigger timely rebaseline decisions.
- Correlated migrations and entanglement are invisible because registers treat assumptions as isolated rows rather than nodes in an influence network.

Recognizing these gaps is the first step: making assumption migration a governed, instrumented input (not a loose artifact) is necessary to convert scattered records into predictive governance signals.

4.2 Current Formula and Explanation

Where Assumption Registers do exist they are typically used in a limited, manual fashion:

- Capture baseline and current values, owner and ad hoc notes.
- Periodic human review (monthly or milestone-driven) that may mark an assumption as "updated" or "validated."
- Escalation relies on qualitative judgement or simple thresholds applied in isolation (for example "if funding is delayed, notify sponsor").

This corresponds to a traditional/legacy "formula" for assumption management best described as a limited implementation of an Assumption Register.

Limitations of that approach:

- No normalized migration metric, so cross-assumption comparability is weak.
- No formal consequence weighting or normalization that scales per-assumption importance.
- No time-aware confidence decay or event amplification; registers treat a change as a discrete fact without modeling aging or fragility.

- No entanglement representation, so propagation and systemic fragility are invisible.

Because of those limits, existing practice is reactive and brittle. Decisions are made after outcomes show up in EVM or contingency draws, not earlier when the foundation is eroding.

4.3 Proposed Improvements and Value-Add

Upgrade the assumption discipline by operationalizing two complementary indices that together convert registers into predictive governance instruments:

- **Assumption Governance Index (AGI)**
  - AGI aggregates per-assumption migration Mi, consequence weights Wi, and time-aware confidence Ci into a normalized governance KPI that summarizes current foundation integrity.
  - Value added: produces a single, auditable metric executives can read (AGI bands map to governance actions: monitor, review, program rebaseline, executive steering). AGI elevates aging, materiality and shock sensitivity (via Ci and event multipliers), and surfaces where a small set of assumptions are driving portfolio fragility.
- **Assumption Diffusion Index (ADI)**
  - ADI models the network propagation of an assumption change using an entanglement matrix E, a temporal kernel K(Δt), and a transfer function g(·). It measures footprint (consequence-weighted exposure), velocity (time to p% of footprint) and reach (fraction of portfolio consequence affected).
  - Value added: flags latent systemic exposure before AGI moves; prioritizes triage by velocity (act now vs. monitor); identifies diffusion hubs and high-leverage edges for targeted remediation.

Joint value of AGI + ADI

AGI and ADI provide extraordinary insights and potentials when used together. While AGI may be used in isolation, ADI is not designed to do so with high confidence. Used jointly they provide:

- **Two-axis decision surface:** AGI = magnitude (how bad now); ADI = propagation potential (how bad it can become and how fast). This supports precise triage: immediate containment (high ADI velocity), targeted controls (high AGI concentrated in few assumptions), or measurement investments (high ADI variance driven by low-confidence edges).

- **Governance-ready outputs:** both indices are versioned, traceable to register evidence, and accompanied by uncertainty bands (bootstrap/posterior) so escalation rules can require SME confirmation proportional to confidence.
- **Behavioral improvement:** embedding these indices into charters, dashboards and decision rules shifts culture from ad hoc updates toward peer-reviewed evidence, reducing gaming and improving timeliness of rebaselining.

Operational examples of benefit can be seen in these examples:

- A small commodity-price migration with high ADI footprint and short velocity triggers immediate procurement cadence changes[39] and targeted hedging before AGI crosses rebaseline thresholds.
- A cluster of modest migrations across high-Wi assumptions raises AGI even while ADI is low; governance allocates contingency and starts focused verification rather than broad containment.

4.4 Revised Formula and Explanation

Presenting compact, governance-ready formulations[40] (notation aligns with established register fields):

- **Per-assumption components** (for assumption i)
  - Migration metric: $M_i(t) \in [0,1]$ — normalized distance from baseline (numeric delta / $\Delta crit$ or ordinal mapped distance).
  - Consequence weight: $W_i \geq 0$, normalized so $\Sigma_i W_i = 1$.
  - Time-aware confidence: $C_i(t) \in (0,1] = a_{0,i} \cdot \exp(-\lambda_i \cdot (t - t_{0,i})) \cdot \varphi_i(t)$, with $\varphi_i(t) \geq 1$ an event-driven amplifier; cap at 1[41].
- **Assumption Governance Index (AGI)**

[39] A minor shift in commodity prices affects a large portion of the assumptions and activities meaning it has broad exposure or impact requiring purchasing schedules or buying patterns to be adjusted right away.

[40] Governance and calibration notes (essential for defensible use)

- Entanglement estimation: hybridize data-driven (co-migration frequencies, rank correlations, Granger-style tests) with structured expert elicitation; apply shrinkage A = f(n_obs) to blend data and prior, record provenance and confidence tier per edge.
- Matrix hygiene: clip e_{ij} to [−1,1], sparsify weak links with a governance-chosen threshold T, version and log every change.
- Uncertainty: calibrate kernels, g(.), θ via Bayesian/MCMC where data exist; report median plus 50%/90% bands and bootstrap sampling variability.
- Escalation rule templates: map AGI bands and ADI velocity thresholds to actionable playbooks (triage checklist, monitoring cadence, SME signoff rules, mandatory evidence attachments).

[41] Time-aware confidence starts at an initial value and naturally decays over time at a rate λ. However, when reinforcing events occur, an amplifier $\varphi(t)$ boosts confidence back up. The system ensures confidence never exceeds 1, keeping it bounded like a probability.

- $AGI(t) = 100 \cdot \Sigma_i W_i \cdot C_i(t) \cdot M_i(t)$
- Interpretation: AGI ∈ [0,100]; higher values indicate substantive migration among consequential/low-confidence assumptions. AGI bands (example) map to governance actions: Green 0–20, Yellow 20–50, Amber 50–75, Red 75–100.

- **Assumption Diffusion Index (ADI)** — discrete-time propagation over horizon H
  - Core network objects:
    - $E = [e_{ij}]$, $e_{ij} \in [-1,1]$: signed entanglement coefficients (directional influence from $i \rightarrow j$).
    - $K(\Delta t)$: temporal kernel (exponential, power-law, boxcar, or multimodal) that attenuates influence over lag.
    - $g(\cdot)$: transfer function (linear, saturating, deadzone) mapping node state to transmitted signal.
    - Thresholds θ_j: per-node affected cutoffs.
  - Iterative update ($t = 0...H$)[42]:
    - Initialize seeds $p_i(0) = s_i$ (seed magnitudes), $p_j(0) = 0$ for others.
    - Propagate: $p_j(t+1) = p_j(t) + \Sigma_i K(\Delta t) \cdot e_{ij} \cdot g(p_i(t))$.
    - Affected indicator: $a_j(t) = 1\{p_j(t) \geq \theta_j\}$.
  - Single-source footprint over horizon H:
    - $Footprint_i(H) = \Sigma_{t=0...H} \Sigma_j w_j \cdot Pr[a_j(t) = 1 \mid seed\ i]$
      (for deterministic runs Pr is 0/1; for stochastic runs it is estimated frequency).
  - Portfolio ADI[43]:
    - $ADI(H) = (1 / W_{tot}) \cdot \Sigma_i w_i \cdot Footprint_i(H)$, with $W_{tot} = \Sigma_i w_i$; rescale to 0–100 for dashboards.
- **Velocity and Reach**[44]

[42] *The iterative update process defines how influence or magnitude propagates across nodes over discrete time steps $t = 0 \ldots H$. At initialization, designated seed nodes i are assigned starting magnitudes $p_i(0) = s_i$, while all other nodes j begin at zero. At each subsequent step, propagation occurs according to the kernel $K(\Delta t)$, the edge weight e_{ij}, and the transformation function $g(p_i(t))$, updating node j's state as $p_j(t+1) = p_j(t) + \sum_i K(\Delta t) \cdot e_{ij} \cdot g(p_i(t))$. An affected indicator $a_j(t)$ is then assigned, equal to 1 if the propagated magnitude at node j exceeds its threshold θ_j, and 0 otherwise. This construct ensures traceable identification of nodes that cross activation thresholds during the iterative horizon.*

[43] *Portfolio ADI represents a weighted average of individual asset footprints over the horizon H. Each asset i contributes according to its weight w_i, normalized by the total portfolio weight $W_{tot} = \sum_i w_i$. The resulting measure, $\mathrm{ADI}(H) = \frac{1}{W_{tot}} \sum_i w_i \cdot \mathrm{Footprint}_i(H)$, provides a consolidated view of exposure across the portfolio. For dashboard reporting, values are rescaled to a 0–100 range to ensure comparability and intuitive visualization.*

[44] *Velocity and Reach describe the dynamics of propagation from a seed node. Velocity $V_i(p)$ is the shortest time interval Δt in which cumulative exposure from seed i reaches at least a fraction p of its total footprint over horizon H. Reach $R_i(H)$ expresses the breadth of influence: it is the normalized, weighted probability that any portfolio node j becomes activated at some point in time when seed i initiates propagation. The weighting by w_j/W_{tot} ensures that Reach reflects both the likelihood of activation and the relative importance of each node within the portfolio.*

- Velocity V_i(p): minimal Δt such that cumulative exposure ≥ p · Footprint_i(H).
- Reach R_i(H) = (1 / W_tot) · Σ_j w_j · Pr[max_t a_j(t) = 1 | seed i].

5. Safety (SDRI) Metric

5.1 Current Focus and Relevance

Safety is a non-negotiable priority in LCPs, especially in engineering megaprojects, major infrastructure, and high-hazard environments. The Safety Degradation Risk Index[45] (SDRI) has become a leading composite metric intended to holistically capture *the project's safety climate, lagging and leading safety performance indicators, and systemic resistance to safety failures*.

Current SDRI formulations aggregate reported incidents, near-misses, regulatory breaches, and procedural compliance rates into a single risk index. For QPM, however, the role of safety must be viewed through the lens of *systemic resilience*, *adaptive capacity*, and *risk propagation*—mirroring quantum concepts of system state and perturbation propagation. QPM introduces the idea that safety is not just the absence of harm, but an emergent property of both the project's structure and real-time operational behavior.

Safety in QPM is managed as a property of *both the project's current state and its potential to shift under stress or perturbation*, changing the focus from after-the-fact reporting to predictive, adaptive management of risk landscapes.

5.2 Current Formula and Explanation

A representative current SDRI is:

$$SDRI = \alpha IR + \beta NM + \gamma NC + \delta PC$$

[45] A robust SDRI framework emphasizes a 2:1 weighting of leading over lagging indicators for effective early-warning and risk management. The SDRI quantifies risk using a blend of empirical field data and scenario-based modeling where high-risk exposures (e.g., major equipment operation, height work, confined spaces) are weighted according to recent incident frequencies and site conditions.
(PDF) Safety Degradation Risk Index (SDRI) for NAICS 23 Construction Managers: A Comprehensive Analysis for the U.S. Construction Sector and Its Subsectors . Available from: https://www.researchgate.net/publication/395239022_Safety_Degradation_Risk_Index_SDRI_for_NAICS_23_Construction_Managers_A_Comprehensive_Analysis_for_the_US_Construction_Sector_and_Its_Subsectors#fullTextFileContent

Where:

- **SDRI:** Safety Degradation Risk Index (higher values = greater risk, lower safety).
- **IR:** Incident Rate (e.g., recordable injuries per 200,000 work hours).
- **NM:** Near-Miss Rate (number of near-miss events per reporting period).
- **NC:** Non-Compliance Count (number of observed/proven safety rule violations).
- **PC:** Procedural Compliance Score (percentage adherence to safety-critical processes, inverted so that lower compliance increases risk score).
- **α, β, γ, δ:** Weightings reflecting relative risk impact.

Data Sources:

- Incident and near-miss reporting logs.
- Safety audits and compliance checklists.
- Regulatory inspection and enforcement records.
- Workforce safety climate surveys.

While useful, the current SDRI approach is often a lagging indicator, with limited sensitivity to hidden system weaknesses or adaptive safety culture features. It also typically lacks the ability to predict emergent risk escalation resulting from compounding disturbances.

5.3 Proposed Improvements and Value-Add

Improvement Rationale: QPM upgrades the safety metric by introducing:

- **Network/Systemic Safety Propagation:** Measures the *probability and impact of risk propagation* through interdependent project elements, akin to quantum state transitions.
- **Leading Insights:** Integrates real-time leading indicators (e.g., proactive hazard reporting, safety climate sentiment, AI-derived behavioral analytics).
- **Resilience and Adaptation:** Models not only static risk levels but the *system's capacity to absorb shocks*, revert to safe states, and recover from perturbations, using concepts from quantum state recovery and information resilience.

Value-Add:

- Enables the early detection of weak links or emergent "hot spots" that could trigger safety incidents.
- Supports dynamic safety interventions, allocating resources not just according to past incidents but predicted vulnerability.
- Embeds learning and adaptation into the safety system, rewarding proactive behaviors and real-time hazard elimination.

5.4. Revised Formula and Explanation

The upgraded QPM SDRI might take the following form:

$$SDRI_{QPM} = \sum_{i=1}^{n} \lambda_i \left[R_i \left(1 + \kappa_{i)}\right] - \mu A_{lead}$$

Where:

- **$SDRI_{QPM}$:** Quantum Project Management Safety Degradation Risk Index (low values = safer system).
- **n:** Number of interconnected major subsystems or workfronts.
- **λ_i:** Systemic risk propagation weight for subsystem **i,** incorporating both direct and cascading risk impacts, estimated from historical data, system modeling, and AI-predicted propagation coefficients.
- **R_i:** Base risk for subsystem **i**, comprising incident, near-miss, and compliance data.
- **κ_i:** Vulnerability amplification coefficient for subsystem **I**, reflecting the potential for risk amplification via interconnectedness (e.g., derived from network analysis, Bayesian propagation models, or digital twin stress-testing).
- **μ:** Scales effect adjustment coefficient capturing the impact of leading proactive safety actions.
- **A_lead:** Aggregate leading safety action score reflecting leading safety actions taken (e.g., proactive hazard eliminations, "stop-work" interventions, safety climate improvement initiatives), normalized to system scale.

Data Sources and Measurement Approaches:

- Integration of digital twins, live operational risk dashboards, and AI-based event prediction tools.

- Collects and weights real-time data from system-wide monitoring (IoT sensors, worker wearables, audit bots).
- Behavioral analytics from digital engagement platforms (e.g., natural language analysis of safety meeting notes, workforce sentiment).

This advanced SDRI dynamically adjusts the composite risk score by factoring in both the likelihood and impact of risk propagation within the interconnected project environment, as well as the cumulative effect of proactive safety interventions. It thus functions as both a *diagnostic* and *prescriptive* safety tool, in keeping with the adaptive, quantum-inspired ethos of LCP management.

Summary of QPM Metric Modifications

The following table summarizes the key improvements to metrics for use in QPM applied to LCPs. *Additional metrics providing added insights into behaviors and forces acting in and on the project's ecosystem are under development.*

Comparative Summary Table			
QPM Metric	**Traditional Formula (Key Variables)**	**Upgraded Formula (Key Variables)**	**Key Added Value**
Complexity	$C_{total} = aN + bI + cS$	$C_{QPM} = H - \sum_{i=1}^{n}\sum_{j=1}^{n} \gamma_{ij} \cdot \log(\rho_{ij} + \varepsilon)$	Captures dynamic entanglement, emergence, adaptive feedback
Uncertainty	$U = \frac{\sigma_T}{\mu_T}$	$U_{QPM} = \mathrm{H(S)} + \delta\hat{S}$	Information-theoretic, scenario-driven, captures both epistemic and aleatory uncertainty
Stakeholder (NPI)	NPI = %P - %D	$NPI_{QPM} = \sum_{i=1}^{n} \omega_i (P_i - D_i)$	Weights influence, tracks temporal and multidimensional sentiment

Comparative Summary Table			
QPM Metric	**Traditional Formula (Key Variables)**	**Upgraded Formula (Key Variables)**	**Key Added Value**
Assumption Migration – Assumption Governance Index (AGI)	Limited Implementation of Assumption Register	AGI(t)=100·Σi Wi·Ci(t)·Mi(t)	Normalized governance KPI; materiality + time-aware confidence; entanglement-aware escalation bands
Assumption Migration – Assumption Diffusion Index (ADI)	Limited Implementation of Assumption Register	ADI(H) = (1/Wtot)·Σi wi·Footprint_i(H) with p(t+1)=p(t)+Σ K(Δt)eij g(p_i(t))	Early-warning of propagation; velocity, reach, footprint; edge-level remediation and cadence guidance
Safety (SDRI)	$SDRI = \alpha IR + \beta NM + \gamma NC + \delta PC$	$SDRI_{QPM} = \sum_{i=1}^{n} \lambda_i \left[R_i \left(1 + \kappa_{i)}\right] - \mu A_{lead}$	Predicts propagation, includes system resilience and leading indicators

The table emphasizes how **QPM reframes each metric to capture emergent complexity, quantum-like uncertainty, networked stakeholder influence, assumption migration in the broader project ecosystem, and system-level safety behaviors.** Rather than simply aggregating observable factors, upgraded QPM metrics *model* the propagation, interaction, and dynamic feedback processes central to LCP performance.

For example, in the **Complexity** metric, the shift from counting structural elements to evaluating entanglement and entropy fundamentally improves the manager's ability to *see where interventions will have the greatest impact*, and to anticipate where problems might spread or self-organize. Similarly, the **Uncertainty** metric's move from simple variance to scenario entropy allows leaders to measure both what is unknown and the value of gaining new information—steering investments in learning and adaptability.

In **Stakeholder Assessment**, the upgraded NPI provides executive teams with an explicit, actionable map of where political or social risk resides and at what leverage points targeted engagement will yield the greatest return. By complementing overall sentiment with influence weighting and multidimensionality, QPM minimizes the risk of "silent resistance" from low-profile but high-impact stakeholders.

In **Assumption Migration**, the Assumption Governance Index (AGI) and the Assumption Diffusion Index (ADI) , move well beyond today's often lacking Assumption Registers, providing LCP project managers and executive teams with a predictive, auditable framework for detecting foundational erosion, quantifying systemic propagation risk, and triggering timely, evidence-backed governance actions that traditional assumption registers cannot support.

Most critically, the **Safety** metric's new formulation gives project leadership a real-time, forward-looking view of risk not just as an artifact of past incidents, but as a dynamic, interconnected property of the project's present and future state. This enables both preemption and rapid recovery in the face of emerging threats, capturing the essence of high-reliability organizations.

Integrating Upgraded Metrics: Toward a Quantum Project Management Dashboard

The real promise of these upgraded metrics lies in their **integration within a QPM dashboard**, where complexity, uncertainty, stakeholder dynamics, and safety status can be continuously monitored, modeled, and anticipated.

Such a dashboard would leverage:

- Real-time data feeds and AI analytics from integrated project information platforms and digital twins.
- Scenario generators and simulation engines to stress-test project states and explore intervention outcomes.
- Automated feedback loops adjusting risk appetites, contingency allocations, and engagement strategies as new data arrives.

Practical implications include:

- **Earlier warnings:** Predictive analytics identify tipping points or triggers for rapid escalation.

- **Faster recovery:** When disruptions occur, scenario diversity analysis and network safety propagation guides optimal containment responses.
- **Improved engagement:** Stakeholder NPI signals enable more precise, context-aware communication and collaborative problem-solving—preventing minor misalignments from snowballing into major disruptions.
- **Continuous learning:** Tracking shifts in complexity and uncertainty over time generates organizational "memory," refining models and strategies for future LCPs.

Conclusion

The evolution of metrics for Complexity, Uncertainty, Stakeholder Assessment (NPI), Assumption Migration (AGI/ADI) and Safety (SDRI) in Quantum Project Management represents a profound leap in the capacity of organizations to manage Large Complex Projects effectively. Each metric transforms from a static, descriptive artifact into a dynamic, predictive, and prescriptive tool, deeply integrated with AI and digital technologies, and informed by analogies drawn from quantum physics and contemporary complexity science.

These upgraded metrics:

- Reflect the fundamentally **dynamic, interconnected, and emergent nature of modern LCPs**;
- **Equip leaders with real-time, actionable insights** for anticipatory intervention and adaptive decision-making;
- **Enhance project resilience and stakeholder alignment** even in the face of volatility and ambiguity.

As QPM matures, its metrics will continue to evolve—increasingly incorporating learnings from operational experience, AI/ML advances, and cross-industry best practices, ensuring LCP management remains at the leading edge of organizational performance, safety, and value realization.

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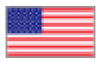

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