Quantum Annealing Implementation for Optimization Problems

U Kanade[1]

[1] Dept of Mathematics/ GCOE Karad/India

How to Cite this Article:

Kanade, U. (2026). Quantum Annealing Implementation for Optimization Problems. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(8), 1-9. https://doi.org/10.55041/ijcope.v2i8.042

https://doi.org/10.55041/ijcope.v2i8.042

Abstract—
Presented in this paper is the theory and practical implementation of quantum annealing for project scheduling and resource-allocation tasks that can be mapped to Ising or Quadratic Unconstrained Binary Optimization (QUBO) models. Quantum annealing is a meta-heuristic that exploits quantum tunnelling to search the energy landscape of combinatorial optimization problems. The Quantum Annealing Process Flowchart is detailed stage by stage. Hybrid quantum-classical workflows that embed annealing inside a Monte Carlo or digital-twin loop are described, together with supporting figures of the energy landscape and the hybrid architecture. Cross-domain analogies with ULD configuration and related combinatorial problems illustrate transferability. The paper concludes with implementation considerations and the current maturity of the technology for construction and logistics applications.

Keywords: quantum annealing implementation; Ising model; QUBO; combinatorial optimization; project scheduling; hybrid quantum-classical; energy landscape; digital twin; Monte Carlo; supply-chain resilience; ULD configuration

I. INTRODUCTION

Construction and infrastructure projects are among the most complex organized human activities, involving hundreds or thousands of interdependent activities, limited renewable and non-renewable resources, contractual milestones, and pervasive uncertainty arising from weather variability, labour productivity, design changes, equipment reliability, and supply-chain disruptions. Efficient project delivery therefore requires scheduling methodologies capable of simultaneously handling precedence constraints, resource limitations, and uncertainty within extremely large solution spaces. For more than six decades, CPM and PERT have served as the foundation of construction planning [11] because they effectively represent activity precedence relationships and identify the sequence of tasks governing overall project duration. However, modern construction scheduling increasingly exhibits the characteristics of a large scale combinatorial optimization problem [10] in which the number of feasible schedules grows exponentially with project size, rendering exhaustive search computationally impractical.

The growing complexity of contemporary projects has motivated the development of probabilistic and simulation-based scheduling techniques that extend deterministic network methods. Monte Carlo simulation has become the standard approach for quantifying schedule uncertainty by repeatedly sampling activity duration distributions to generate confidence intervals, probabilistic completion dates, and schedule risk profiles. At the same time, advances in BIM [12], sensor technologies, and digital twin [13], [14] platforms enable continuous integration [15], [16] of real time project information with scheduling models, allowing plans to be updated dynamically as site conditions evolve. These developments have also highlighted the importance of supply-chain resilience [6], [7], since material shortages, logistics delays [8], and supplier disruptions [9] can significantly alter project schedules and resource availability.

Despite these advances, identifying globally optimal schedules under multiple interacting constraints remains computationally challenging because the underlying optimization landscape [17] contains numerous local optima separated by complex constraint interactions. Recent progress in quantum computing has therefore attracted attention as a potential means of addressing such optimization problems. Quantum annealing implementation provides a physics inspired framework for solving discrete optimization problems [18] by encoding scheduling objectives and constraints into Ising or QUBO formulations. Rather than relying solely on deterministic search heuristics, quantum annealing explores the problem's energy landscape through quantum fluctuations and tunnelling, offering a mechanism for escaping local minima that often impede classical optimization algorithms.

II. LITERATURE REVIEW

Construction project scheduling has evolved from early Gantt charts to sophisticated optimization and simulation techniques capable of addressing the increasing complexity of modern infrastructure projects. The introduction of the CPM and the PERT in the late 1950s established network based scheduling as the foundation of project planning. While CPM provides deterministic schedules based on precedence relationships, PERT introduced probabilistic activity durations through three-point estimates. However, both methods have limitations when applied to large projects characterized by uncertainty, resource constraints, and dynamic operating conditions.

Resource Constrained Project Scheduling Problems (RCPSP) are recognized as NP hard combinatorial optimization problems [19], [20] because the number of feasible schedules grows exponentially with project size. Exact optimization methods become computationally prohibitive for large instances, leading to widespread adoption of metaheuristic algorithms such as Genetic Algorithms, Simulated Annealing, Tabu Search, Particle Swarm Optimization, and Ant Colony Optimization. Although these approaches produce high-quality solutions, they may become trapped in local optima within complex optimization landscapes.

To address uncertainty, probabilistic scheduling techniques have become increasingly important. Monte Carlo simulation extends deterministic schedules by repeatedly sampling activity duration distributions to estimate completion-date probabilities, schedule contingencies, and confidence levels (P50, P80, and P90). Modern implementations incorporate correlated risks, weather effects, productivity variation, equipment failures, and procurement delays, making Monte Carlo simulation a standard tool for quantitative schedule risk analysis.

Recent advances in BIM, IoT technologies, and digital twins [21], [22], [23] have enabled continuous schedule updating using real-time project information. Digital twins integrate design models [24], [25], construction progress, sensor data, and resource information to support adaptive planning, while improving supply-chain resilience by incorporating procurement and logistics data [26] into scheduling decisions.

III. CLASSICAL CPM/PERT AND MODERN COMBINATORIAL FORMULATIONS.

Yet classical CPM is deterministic: each activity is assigned a single duration. PERT introduces three-point probabilistic estimates but still relies on simplifying assumptions (independent activity durations, a single dominant critical path) that systematically understate schedule risk—the well-known merge-bias problem. Monte Carlo simulation overcomes many of these limitations by sampling full distributions of activity durations and evaluating the network thousands of times, thereby producing empirical distributions of project completion time, criticality indices and sensitivity rankings.

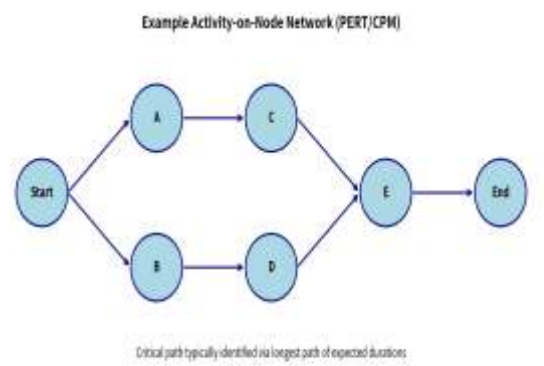

Figure 1. Example activity-on-node network illustrating precedence relationships that underlie both

classical CPM/PERT and modern combinatorial formulations.

Even with powerful Monte Carlo engines, however, a second class of difficulty remains. Many of the decisions that must be made inside each simulated scenario resource levelling, multi skill crew assignment, equipment allocation, sequencing under spatial or safety constraints, multi-project portfolio selection are combinatorial optimization problems. Their decision spaces grow exponentially with the number of activities and resources. Exact classical solvers (branch-and-cut, constraint programming) become impractical beyond modest instance sizes; meta-heuristics (genetic algorithms, tabu search, simulated annealing) provide feasible but not necessarily high-quality solutions and still require careful tuning.

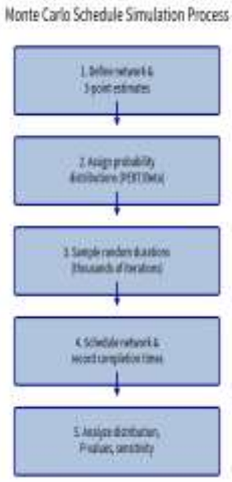

Figure 2. Monte Carlo Process Flowchart – the classical probabilistic engine that quantifies schedule risk and can call quantum-annealing sub-solvers.

Quantum annealing addresses precisely this combinatorial core. By mapping the decision problem onto an Ising or QUBO Hamiltonian and evolving a physical quantum system toward low energy states, the method exploits quantum tunnelling to explore rugged energy landscapes more effectively than purely thermal classical annealing. The approach is especially attractive for the noisy intermediate-scale quantum (NISQ) era because it does not require deep, fully coherent gate-model circuits.

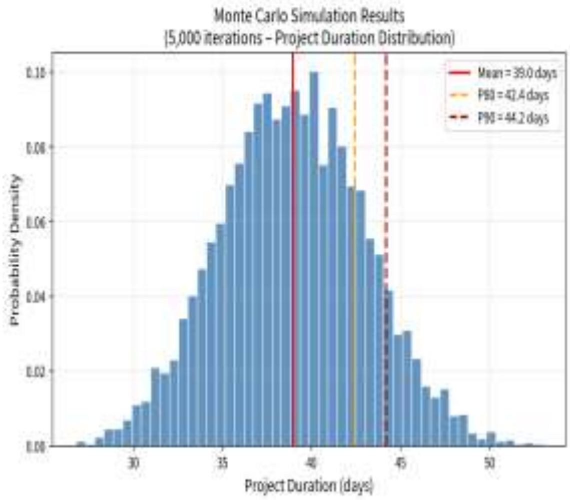

Figure 3. Typical Monte Carlo histogram of project duration used as the outer risk-evaluation layer.

IV. MONTE CARLO S-CURVE

The **S-curve** provides a cumulative probability distribution of project completion dates, allowing decision-makers to assess the likelihood of meeting different schedule targets. Rather than producing a single deterministic completion date, thousands of simulation iterations are performed by randomly sampling activity durations from their assigned probability distributions while preserving network logic and, where appropriate, activity correlations. The resulting completion times are sorted to generate an S-shaped cumulative distribution curve, from which confidence levels such as **P50**, **P80**, and **P90** are derived.

These percentile values represent increasing levels of schedule confidence. The **P50** completion date corresponds to a 50% probability that the project will finish on or before that date and is often interpreted as the "most likely" outcome. The **P80** date provides an 80% confidence level and is widely adopted for contingency planning because it offers a more conservative schedule with a lower risk of overrun. The **P90** date represents a highly risk-averse target, indicating only a 10% chance that the project will exceed the predicted completion time. Together, these confidence levels provide a practical framework for quantifying schedule uncertainty and communicating risk to project stakeholders.

In a hybrid quantum classical scheduling framework, the Monte Carlo S-curve serves as the benchmark against which quantum annealed schedules are evaluated. Quantum annealing is used to search for optimized activity sequences or resource allocations that minimize project duration while satisfying precedence and resource constraints. Once an optimized schedule is obtained, it is subjected to the same Monte Carlo simulation process to evaluate its robustness under uncertainty. Comparing the deterministic completion time alone is insufficient because two schedules with identical planned durations may exhibit very different risk profiles.

The comparison is therefore performed by overlaying the S-curves of the baseline and annealed schedules and examining shifts in key confidence levels.

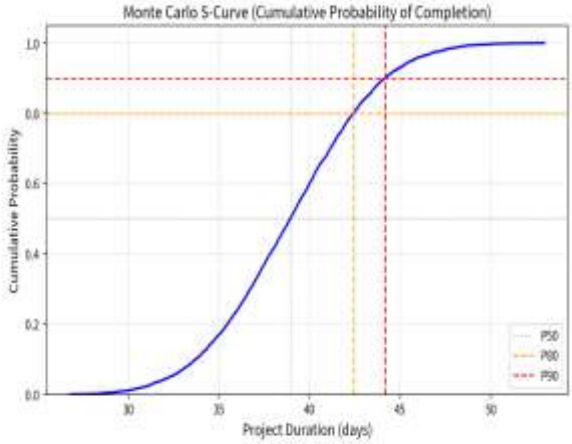

Figure 4. Monte Carlo S-curve providing P50/P80/P90 confidence levels against which annealed schedules can be compared.

The comparison is therefore performed by overlaying the S-curves of the baseline and annealed schedules and examining shifts in key confidence levels. An effective annealed schedule is expected to shift the cumulative distribution to the left, indicating earlier completion across a range of probabilities, while also reducing the spread of the distribution, reflecting lower schedule variability. Improvements can be quantified by comparing reductions in the P50, P80, and P90 completion dates, decreases in standard deviation, and increases in the probability of meeting contractual milestones. For example, if the baseline schedule has a P80 completion time of 420 days and the annealed schedule reduces this to 402 days, the hybrid optimization demonstrates an 18-day improvement at the 80% confidence level rather than merely reducing the deterministic critical-path duration.

Consequently, the Monte Carlo S-curve becomes more than a visualization tool; it provides a rigorous probabilistic validation of optimization results. It enables researchers and practitioners to determine whether quantum annealing produces schedules that are not only shorter in theory but also more resilient to uncertainty in practice. By integrating probabilistic risk assessment with quantum optimization, the hybrid framework supports decision-making based on confidence levels rather than single-point estimates, thereby offering a more realistic and risk-informed approach to construction project scheduling.

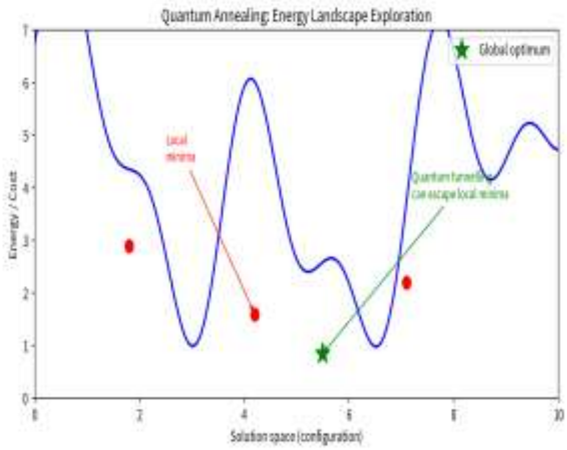

Figure 5. Energy landscape of a combinatorial scheduling problem. Quantum tunnelling offers a mechanism to escape local minima that trap classical search.

Practical quantum annealing implementation, however, is non-trivial. The logical problem must be minor-embedded onto the limited-connectivity hardware graph; annealing schedules and chain strengths must be calibrated; and the raw samples must be post-processed classically before they can be returned to a Monte Carlo or digital-twin loop. Hybrid quantum-classical architectures therefore emerge as the natural integration pattern: the outer classical layer retains responsibility for uncertainty quantification, data assimilation and stakeholder communication, while the inner quantum-annealing layer attacks the hardest combinatorial sub-problems that arise on individual scenarios or rolling horizons.

Figure 6. Hybrid Quantum-Classical Optimization Flowchart showing the hand-off between classical Monte Carlo / digital-twin layers and the quantum annealer.

Conceptual hybrid architecture in which quantum annealing refines candidate schedule configurations that are subsequently re-evaluated using probabilistic risk analysis. In this framework, stochastic techniques such as Monte Carlo simulation first quantify schedule uncertainty by generating distributions of activity durations and identifying high-risk critical paths. The resulting risk information is translated into an optimization problem that can be solved using quantum annealing, which efficiently searches a large combinatorial solution space to identify improved activity sequences, resource allocations, or execution strategies that minimize project duration, cost, or risk. The optimized schedule is then returned to the probabilistic simulation environment, where it is re-evaluated under thousands of uncertainty scenarios to determine its residual schedule risk, confidence levels, and sensitivity to key risk drivers. This iterative feedback loop combines the strengths of classical stochastic simulation for uncertainty quantification with quantum optimization for rapid exploration of complex scheduling alternatives. Although current applications remain largely conceptual because of hardware limitations and problem-size constraints, such hybrid quantum–classical architectures represent a promising direction for next-generation construction project scheduling and decision support under uncertainty.

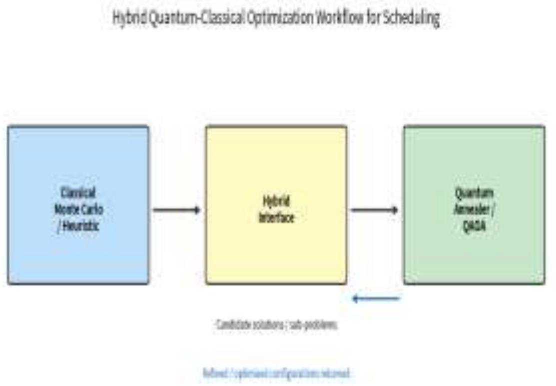

Figure 7. Conceptual hybrid architecture in which quantum annealing refines configurations that are then re-evaluated for residual schedule risk.

The same modelling style and the same hybrid workflow transfer beyond construction. Unit Load Device (ULD) configuration in air-cargo logistics, vehicle routing under capacity constraints, and certain energy-system dispatch problems share the quadratic-binary structure that quantum annealing is designed to exploit. Digital-twin implementations further amplify the value of the approach by keeping the classical data and risk layers continuously current, so that the quantum annealer is always presented with the most relevant sub-problem.

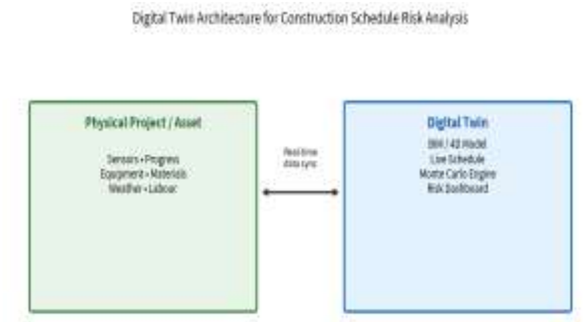

Figure 8. Digital-twin context in which a live probabilistic model can invoke quantum-annealing services for combinatorial sub-problems.

This paper therefore pursues four objectives. First, it reviews the theoretical foundations of quantum annealing Ising and QUBO formulations, the role of quantum tunnelling, and the necessity of minor embedding. Second, it presents a detailed Quantum Annealing Process Flowchart that practitioners can follow from problem formulation through classical post-processing. Third, it situates annealing inside hybrid quantum-classical and digital-twin architectures that also perform Monte Carlo risk analysis. Fourth, it discusses current hardware limitations, implementation best practices, and the transferability of the method to neighboring combinatorial domains. The overarching claim is that quantum annealing implementation is already a viable specialized tool for selected construction and logistics sub-problems and will become progressively more powerful as hardware connectivity and hybrid software mature.

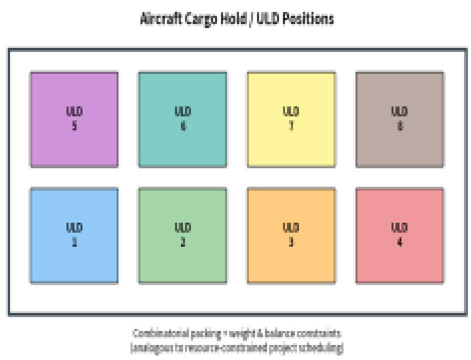

Figure 9. ULD configuration – a cross-domain combinatorial packing problem amenable to the same Ising/QUBO and quantum-annealing treatment.

V. CONCLUSION

Construction scheduling and resource allocation involve complex combinatorial optimization problems that become increasingly difficult as project size, uncertainty, and resource interactions grow. Quantum annealing represents a promising optimization paradigm for addressing these challenges by mapping scheduling problems onto Ising or QUBO Hamiltonians and exploiting quantum tunnelling to search efficiently for low energy solutions. Although current quantum annealers remain constrained by hardware limitations, including qubit connectivity, noise, and problem size, they have demonstrated potential for solving practical optimization problems when combined with classical algorithms. Hybrid quantum classical frameworks that integrate quantum annealing with Monte Carlo simulation, digital twins, and artificial intelligence are particularly promising, enabling simultaneous optimization and probabilistic risk assessment. Continued advances in quantum hardware, embedding techniques, and hybrid optimization methods are expected to enhance the applicability of quantum annealing, making it an increasingly important component of next generation construction scheduling and schedule risk management systems.

REFERENCES

[1] AG Matani , "Improving Energy Efficiency By Controlling Mechanical Losses Of Electric Motors In Smes And Ssis ," International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) ISSN 2249-6890 Vol. 3, Issue 4, Oct 2013, 63-68

[2] A Gudadhe & et al," On LS Spaces of Gelfand Shilov Technique," Bulletin of Pure & Applied Sciences, Vol 25, Issue 1, Pp 351-354, 2006.

[3] A Gudadhe & et al," Distributional LK transform, distributional impulsive signals and system response," Proceedings of the 7th WSEAS International Conference on Applied Mathematics, Pp 1-6, 2005

[4] A Gudadhe & et al," On Structure Formula for Generalised Laplace Meijer Transform," Acta Ciencia Indica Mathematics, Vol 32, Issue 1, Publisher Pragati Prakashan Meerut, 2006

[5] A Gudadhe & et al," On analytic behaviour of LK transform of generalised function," Acta Ciencia Indica Mathematics, Vol 31, Issue 3, Publisher Pragati Prakashan Meerut, 2006

[6] Akarshan Gulhane, "Internet of Things, Artificial Intelligence, and Quantum Computing: A Convergent Framework for Smart Logistics Ecosystems" International Journal of Engineering Science and Advanced Technology (IJESAT) Vol 24 Issue 12, 2024 pp 297 of 317

[7] Akarshan Gulhane, "Industry 5.0 and Intelligent Logistics: Transforming Supply Chain Operations through Human-Centric Automation" International Journal of Engineering Science and Advanced Technology (IJESAT) Vol 24 Issue 12, 2024 pp 287 of 296

[8] Akarshan Gulhane, " advancements in automotive batteries:," a review international engineering journal for research & development, Volume 8 Issue 6 pp. 18-57, 2023. https://iejrd.com/index.php/%20/article/view/3141

[9] Akarshan Gulhane, " The Future of Vehicles: Solar-Powered Battery Electric Hybrid Vehicle Architecture," 2020

https://contest.techbriefs.com/2020/entries/automotive-transportation/10457

[10] Akarshan Gulhane, " digital twin technology for building resilient and adaptive global supply chains: a review," International Research Journal of Modernization in Engineering Technology and Science Volume:06/Issue:12, 2024. DOI: https://www.doi.org/10.56726/IRJMETS64992

[11] Akarshan Gulhane, " Artificial Intelligence Applications In Sustainable Logistics And Green Supply Chain Management: A Bibliometric Review," International Research Journal Of Modernization In Engineering Technology And Science," Volume:06/Issue:12, 2024. Doi: Https://www.Doi.Org/10.56726/Irjmets65006

[12] Akarshan Gulhane, " Artificial Intelligence And Blockchain Integration For Enhancing Supply Chain Transparency, Traceability, And Resilience," International Research Journal of Modernization in Engineering Technology and Science Volume:06/Issue:12, 2024. DOI: https://www.doi.org/10.56726/IRJMETS65016

[13] Akarshan Gulhane, " Power Line Carrier Communication Based Anti-Theft System," International Journal of Research in IT and Management (IJRIM) Euro Asia Research and Development Association, Volume 4, Issue 12,

Pages 1-11, 2014 : https://indianjournals.com/article/ijrim-4-12-001

[14] Akarshan Gulhane, " Battery sizing for plug-in hybrid electric vehicles — Formula hybrid," IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI) pp 368-372 (or 549 in some indexes) 2017 https://ieeexplore.ieee.org/document/8392317/ doi: 10.1109/ICPCSI.2017.8392317

[15] Akarshan Gulhane, " A review of resilience in global supply chains," International Engineering Journal for Research & Development (IEJRD) Volume 8, Issue 4, 2024,: http://www.iejrd.com/index.php/iejrd/article/view/3140

[16] Akarshan Gulhane, " Weaving Resilience Navigating Internal and External Complexities in Modern Supply Chains," 2024/2/1 International Journal of Ingenious Research, Invention and Development Volume 3 Issue 1 https://www.ijirid.in/3-1-24Feb/3-1-16-Akarshan%20Gulhane-Shilpa%20Malge-Eshant%20Rajgure- Pooja%20Deshpande.pdf DOI: 10.5281/zenodo.11491482, https://zenodo.org/records/11491482, https://www.ijirid.in/3-1-24Feb.html

[17] Akarshan Gulhane, " Swipe Controller," International Journal of Research in Engineering and Applied Sciences (IJREAS): Volume 4, Issue 12 pp: 1-7, 2014. https://indianjournals.com/article/ijreas-4-12-001

[18] Akarshan Gulhane, " "Navigating the Quantum Revolution in Logistics: Opportunities and Practical Applications in Supply Chain Management," International Journal of Engineering and Techniques (IJET) Volume 12, Report number 3, Pages 553-556 https://ijetjournal.org/navigating-quantum revolution-logistics/

[19] Akarshan Gulhane, " Quantum Computing for Logistics Optimization: Annealing in Unit Load Device Configuration and Disruption' International Journal of Research Publication and Reviews, Vol (7), Issue (6), June (2026), Page – 4643-4648

https://ijrpr.com/uploads/V7ISSUE6/IJRPR67069.pdf. https://doi.org/10.55248/gengpi.07.0626.16a57

[20] Akarshan Gulhane, " Smart Mobility and Intelligent Transportation Systems: Emerging Trends, Technologies, and Challenges, " International Journal of Scientific Research in Engineering and Management (IJSREM) Volume: 09 Issue:11 |Nov-2025 DOI: 10.55041/IJSREM53436.

[21] Akarshan Gulhane, " Recent Advances in Electric Vehicle Battery Technologies: Materials, Management Systems, and Sustainability Perspectives" International Journal of Scientific Research in Engineering and Management (IJSREM) Volume: 09 Issue:07 |Jul-2025 DOI: 10.55041/IJSREM51198

[22] Akarshan Gulhane, " Quantum Computing in Transportation and Logistics: Current State, Industrial Applications, and Future Directions" International Journal of Scientific Research in Engineering and Management (IJSREM) Volume: 09 Issue:09 |Sep-2025" DOI: 10.55041/IJSREM52469.

[23] Akarshan Gulhane, "Solar-Assisted Electric Mobility: Design Framework And Performance Assessment Of Sustainable Hybrid Vehicle Architectures," Int. J. Engg. Res. & Sci. & Tech. 2025, Vol. 21, No. 3,pp 362-368, https://ijerst.org/index.php/ijerst

[24] Akarshan Gulhane, " Supply Chain Resilience In The Era of Digital Transformation: A Systematic Literature Review And Research Agenda ," Int. J. Engg. Res. & Sci. & Tech. 2025, Vol. 21, No. 4, pp 1058-1068, https://ijerst.org/index.php/ijerst

[25] Padmaja G ,"Performance Analysis of Topological Creative Spaces for Distributional Generalized Transform". International Journal of Engineering Research and General Science. 2020;8(3):12-16. ISSN 2091-2730.

[26] Padmaja G, "Exponential growth of Conventional Topological Spaces with different Kernels," IOSR Journal of Engineering (IOSRJEN), Vol. 10, Issue 3, March 2020, ||Series -II|| PP 19-24.

[27] Padmaja G, " Empirical Analysis of Duality Spaces Connecting Distinct Optical form Transforms," International Journal of Management and Humanities (IJMH), ISSN: 2394-0913 (Online), Volume-4 Issue-10, June 2020, DOI: 10.35940/ijmh.I0840.0641020

[28] Padmaja G ," Different versions of the

Inverse Fourier Stieltjes transform," Archives of Applied Science Research, Vol 4, Issue 3, Pp 1329-1331, 2012

[29] Padmaja G ,"Unifying Transforms for Singular Cauchy Problems in Quantum Logistics, Supply Chain Resilience, and Energy Systems," International Journal of Innovative Research in Engineering, Volume 7, Issue 4 (July - August 2026), PP: 71-76, https://www.doi.org/10.59256/ijire.20260704010

[30] SM Harle, & et al," Artificial Intelligence For Supply Chain Risk Prediction And Mitigation: A Systematic Review, Conceptual Framework, And Future Research Agenda_," International Research Journal of Modernization in Engineering Technology and Science, Vol 08, pp 70-80, July-2026

[31] SM Harle, & et al," Artificial Intelligence-Driven Framework For Village-Level Water Conservation And Groundwater Sustainability," International Research Journal of Modernization in Engineering Technology and Science, Vol 08, pp 31-49, July-2026

[32] SM Harle, & et al," Artificial Intelligence Approaches For Strength Prediction And Optimization Of Composite Concrete Mixtures: A Systematic Review And Future Research Framework ," International Research Journal of Modernization in Engineering Technology and Science, Vol 08, pp 81-97, July-2026

[33] SM Harle, & et al," Artificial Intelligence-Based Pavement Crack Detection: A Comprehensive Review Of Machine Learning And Deep Learning Techniques ," International Research Journal of Modernization in Engineering Technology and Science, Vol 08, pp 50-69, July-2026

[34] SM Harle, & et al," Digital Twins And Artificial Intelligence For Sustainable Textile Raw Material Processing ," International Research Journal of Modernization in Engineering Technology and Science, Vol 08, pp 14-30, July-2026