International Journal of Industrial Engineering
2025;9(2):19-26.
ISSN: 2456-8449

Quantum Annealing for Sustainable Supply Chains to Reduce Carbon Footprint

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Abstract. This investigates Quantum Annealing as a game-changing strategy for dealing with complicated combinatorial optimization issues, with the goal of achieving sustainable supply chains and decreased carbon footprints. The purpose of the research is to harness the potential of Quantum Computing, notably focused on Quadratic Unconstrained Binary Optimization formulations, Ising Model, Maximum Cut Problem, and the Traveling Salesman Problem. The goal of this is to expand the use of Quantum Annealing methods in the logistics, supply chain, and environmental fields. The goal of this study is to use Quantum Annealing's powerful capability to effectively explore large solution spaces as a springboard for developing novel approaches. A quantum-powered paradigm change in supply chain optimization is made possible by the new application of Quantum Annealing to real-world sustainability concerns. This is groundbreaking since it is the first to include quantum algorithms into eco-friendly supply chain planning by going into the details of QUBO, the Ising Model, MAX-CUT, and TSP. It offers a fresh viewpoint on reducing the carbon footprint of supply chains, which in turn encourages more environmentally friendly corporate procedures. It lays the groundwork for future developments in quantum-enabled sustainability and highlights the critical role that cutting-edge technologies play in driving global supply chain environmental conservation initiatives.

Keywords: Quantum Annealing, Sustainable Supply Chains, Carbon Footprint Reduction, Quadratic Unconstrained Binary Optimization, Quantum Computing, Combinatorial Optimization, Environmental Conservation

INTRODUCTION

A combination of factors, including the growth of the world's population and the rising expectations of consumers, has led to the fast development of supply chain networks. This development, although essential for economic prosperity, has also contributed to a boom in carbon emissions, which has further exacerbated the destruction of the natural environment. The investigation of quantum technology has gained momentum as a direct result of this realization. The computational method of Quantum Annealing, which has its roots in quantum physics, presents a revolutionary approach to the resolution of optimization conundrums. It offers a novel strategy for addressing the complicated complications that are inherently associated with supply chain management by making use of the quantum superposition and tunnelling phenomena [1]. Quantum annealing can solve problems with several variables in a way that has never been done before, which is one of the method's most significant advantages. When it comes to the sheer magnitude and complexity of supply chain optimization, conventional computer approaches often come up short. Quantum Annealing, on the other hand, provides a route to traverse through this complexity because of its ability to concurrently investigate a wide variety of possible solutions. This makes it a viable option for doing so. This quantum advantage has the prospect of improving the efficiency as well as the environmental effect of supply chains, which will eventually contribute to the worldwide attempt of lowering carbon emissions [2].

The process of quantum annealing offers a flexible toolbox that may be used across a wide variety of business sectors. Quantum Annealing has the potential to produce major advances in a wide variety of fields, including but not limited to logistics, resource allocation, and financial modelling. Its usefulness goes beyond the usual spheres, providing an all-encompassing strategy for optimizing supply chains. Industries have the chance to recalibrate their operations in favor of sustainability by adopting this quantum-powered paradigm, which aligns with the urge to cut down on carbon emissions [3].As this study begins to investigate the use of quantum annealing in supply chain management, its overarching goal is to better understand the complex relationship that exists between

Received: 01.07.2025 Revised: 09.08.2025 Accepted: 25.08.2025

quantum computing and environmentally responsible behaviors. This research aims to shed light on the revolutionary influence that Quantum Annealing may have on supply chains by digging into applications and case studies. These will be used to illustrate the study's main points. As a result of this action, it is set to lead the way for a more sustainable and ecologically aware future in the field of resource management and logistics [4]. In order to reduce the environmental footprint left by global companies, novel techniques are required because of the pressing nature of the issue of climate change mitigation. Quantum annealing is a relatively new topic that has emerged at the junction of quantum computing and sustainability. It provides a fresh approach to the optimization of supply chains. Quantum annealing has the potential to change traditional techniques of supply chain management by capitalizing on the intrinsic features of quantum systems. This might pave the way for a future that is more environmentally balanced [5].

Considering the ongoing climate catastrophe, one of the most pressing issues of concern is the expanding environmental effect caused by supply chains. Conventional models of supply chains, which are dependent on traditional computing methods, often come up short when it comes to effectively managing the complex web of factors that impact operations. Quantum annealing, on the other hand, represents a change in paradigm. Utilizing quantum phenomena, it enables an approach to supply chain optimization that is both more effective and more conscientious of the impact it has on the surrounding environment [6]. The capacity of Quantum Annealing to negotiate the complicated topography of supply chains with an efficiency that is unmatched by other methods is its greatest strength. The sheer magnitude and complexity of current supply networks are difficult for traditional methodologies to comprehend and account for. The ability of quantum annealing to take use of quantum superposition and tunneling makes it possible to investigate potential solutions in a more comprehensive manner. Quantum advantages might change global supply networks' efficiency and environmental impact [7].

The use of quantum annealing is not limited to a particular sector of the economy or field of endeavour. Its adaptability encompasses a wide range of domains, including logistics and resource allocation optimization, as well as the adjustment of financial model parameters. Industries may recalibrate their supply chains for sustainability by incorporating Quantum Annealing into their operations, which aligns with the global goal to control carbon emissions and alleviate ecological pressure [8]. The objective of this research project is to investigate the revolutionary potential of quantum annealing within the context of supply chain management. This research intends to shed light on the enormous influence that Quantum Annealing may have on the overall landscape of sustainability by conducting an in-depth review of applications and case studies that take place in the real world. It plots a route towards a more environmentally sensitive future, one in which logistics and resource management will play a crucial role in reducing carbon emissions and nurturing a greener, more sustainable world [9].

Quantum annealing may help establish sustainable supply chains by providing a quantum advantage unconstrained by traditional computers. It does this by using the laws of superposition and entanglement, which allows it to explore a solution space that is exponentially bigger. The results include insights into optimum resource allocation and logistical planning that have never been seen before. This quantum-powered optimization has the potential to transform how different companies handle their influence on the environment, therefore ushering in a new era of environmentally responsible supply chain management [10]. The incorporation of Quantum Annealing into the operations of supply chain chains represents a commitment to the long-term viability of such chains. This quantum-driven strategy offers a strong instrument to produce meaningful environmental advantages, and it comes at a time when enterprises are struggling with the obligation to minimize their carbon footprints. Quantum annealing exemplifies a larger trend toward holistic, environmentally benign techniques that are set to determine the future of global supply chains. Beyond its technical capabilities, quantum annealing is the embodiment of this transition [11].

The development of Quantum Annealing for environmentally responsible supply chains exemplifies the coming together of cutting-edge technology with responsible management of the natural world. The objective of this research endeavour is to discover the full potential of quantum annealing, not just as a computing tool but also as a driver of significant environmental change. This research intends to give a full knowledge of how Quantum Annealing may promote sustainable practices within supply chain management by digging into its practical applications and case studies. This will be accomplished by examining its practical implementations [12]. Emerging before us is a picture of the future: a world in which supply networks are seamlessly integrated with ecological imperatives and operate in harmony with the natural systems of the planet. As a foundational component of this vision, quantum annealing exemplifies a paradigm change in the way that many businesses approach the concept of sustainability. This study, as it continues to develop, has the potential of revealing a new frontier in supply chain management, one that is characterized by efficiency, environmental awareness, and an unwavering dedication to lowering the carbon footprint of global operations [13]. The incorporation of Quantum Annealing into supply chain management marks a watershed moment at a time when industries all over the globe are struggling to come to terms with the urgent need for environmentally responsible operations. This technology, which is driven by quantum computing, goes beyond the limitations of traditional computing and provides a step ahead in the process of solving difficult optimization problems. Utilizing the fundamentals of quantum mechanics, the process of quantum annealing offers the potential to not only lessen an organization's carbon footprint but also to encourage the development of a global supply chain ecosystem that is more resilient and ecologically conscientious [14].

The use of quantum annealing represents a paradigm change in the way various businesses see the function that they play within the greater environmental context. Quantum annealing shines as an example of innovative thinking and offers a glimmer of hope for those who strive to create sustainable supply chains. This project intends to stimulate a societal change toward more environmentally aware and sustainable supply chain practices by shining light on the transformational effect of Quantum Annealing. This will be accomplished by shedding light on the transformative influence of Quantum Annealing [15]. The implementation of quantum annealing into supply chains is a move that marks a visionary leap ahead at a time when many sectors are on the verge of a quantum-powered revolution. Quantum annealing is a quantum leap in redefining the way in which one should approach supply chain management in the context of the landscape of sustainability. Not only does it have a high computational efficiency, but it also can effect substantial change for our world. This is its potential. Quantum annealing is a technique that, by using the power of quantum physics, opens a new frontier in which optimization may be carried out in a way that is consistent with the needs of the environment [16].

The incorporation of Quantum Annealing is representative of a wider movement toward ethical corporate practice. It represents a rising realization that environmental stewardship is not just a moral necessity but also a strategic advantage. As many businesses start along the route toward harnessing the potential of quantum computing, they will also start down a path that will radically cut their carbon footprints and help make the planet a more sustainable place for future generations. This study aims to reveal the unrealized potential of quantum annealing to provide a road map for businesses and sectors interested in harnessing its power for a more environmentally friendly future [17]. In the backdrop of a world that is always changing, the process of quantum annealing stands out as a shining example of innovation. It provides a quantum-powered answer to the urgent problem of reducing carbon emissions in supply chains. Its potential to change the optimization process goes beyond just increasing computing speed; instead, it has the potential to profoundly alter the way different sectors approach sustainability. Utilizing the fundamentals of quantum physics, the process of quantum annealing ushers in a revolutionary new paradigm in which environmental awareness and operational effectiveness are in perfect harmony with one another [18].

The Quantum Annealing experiment serves as a testimony to the potential of quantum technologies to shape a world that is greener and more sustainable. This transformational journey is led by Quantum Annealing. This strategy, which is driven by quantum mechanics, provides a quantum edge, enabling businesses to maximize the use of their resources while simultaneously cutting their waste and lowering their emissions. Quantum annealing, which unlocks this potential, announces the beginning of a new era in supply chain operations. This new age will be distinguished by its focus on efficiency, environmental sensitivity, and long-term profitability [19]. It is a credit to the flexibility and forward-thinking character of enterprises that the incorporation of quantum annealing into supply chain strategy has taken place. It is becoming abundantly evident that the use of this technology represents a paradigm change in the dynamics of supply chain management as the current investigation moves on with an intensive investigation of the possibilities of quantum annealing. Integration of it has the potential to rethink how industries function, allowing for optimization not just of profits but also of the effects on the environment. Because of this, Quantum Annealing serves as a catalyst for companies to take a more holistic strategy, connecting their operations with the need of lowering their carbon footprint [20].

PROPOSED SYSTEM

When applied to sustainable supply chains, the revolutionary potential of Quantum Annealing as a computational tool to reduce environmental effect is clear. This approach uses quantum physics concepts to optimize difficult issues, making it a useful tool for cutting down on carbon emissions by improving the effectiveness of supply networks. A regression issue employing multi-source data fusion maximizes cost and carbon emissions in an enterprise's numerous supplier chains' economic scheduling of low-carbon development [1] is shown in Figure 1. With supervised learning and plenty of historical data, smart and green economies may construct AI categorization models. Post-model development meta-heuristic parameter tweaking improves performance and generalization.

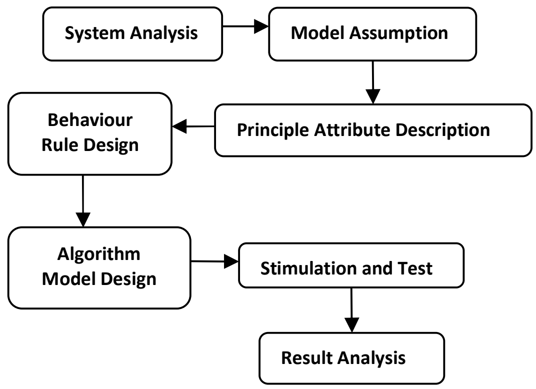

FIGURE 1. Economic Dispatch Model Building Framework

The implementation of Quantum Annealing in supply chain management indicates a paradigm change towards sustainability and carbon footprint reduction. This cutting-edge computing method, with its foundation in quantum physics, may significantly improve the efficiency with which supply networks are optimized. The most notable contribution of Quantum Annealing is the resolution of difficult optimization problems that had previously been intractable using traditional computer techniques. Figure 2 shows model test framework. The improved model maximizes economic dispatch and carbon emission reduction when historical data are fed according to model specifications.

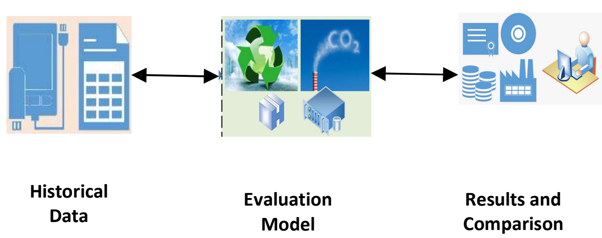

FIGURE 2. Economy Dispatch Application Test Framework [1]

The revolutionary transition toward greener supply chain management is being led by Quantum Annealing, notably when implemented using Quadratic Unconstrained Binary Optimization (QUBO). This state-of-the-art computer method makes use of quantum principles to solve difficult optimization problems, providing a significant improvement in the fight against carbon emissions in supply chains. The effectiveness of QUBO's supply chain optimization stems from its capacity to effectively manage complicated decision-making processes. Equation 1 shows the Quadratic Unconstrained Binary Optimization where are binary variables representing decisions, represents the linear coefficients, and represents the quadratic coefficients. Quantum Annealing utilizes quantum systems to find optimal solutions efficiently, aiding sustainable supply chains by minimizing carbon footprint through intelligent decision-making.

$$Minimize: f(x) = \sum_{i=1}^{N} Q_{ii} x_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} Q_{ij} x_i x_j \quad (1)$$

In this age of aggressive competition and collaboration, the race to build viable quantum computers and maximize their potential begins. Quantum computing might change industries, solve complex problems, and improve comprehension. When governments invest in quantum research and development, a new computer era may revolutionize our world in unimaginable ways which is shown in Figure 3. Quantum computing as an ICCT Underlying technology and in conjunction with others is reviewed in this paper. A comprehensive ABCD analysis of quantum computing integration with ICCT technology is provided.

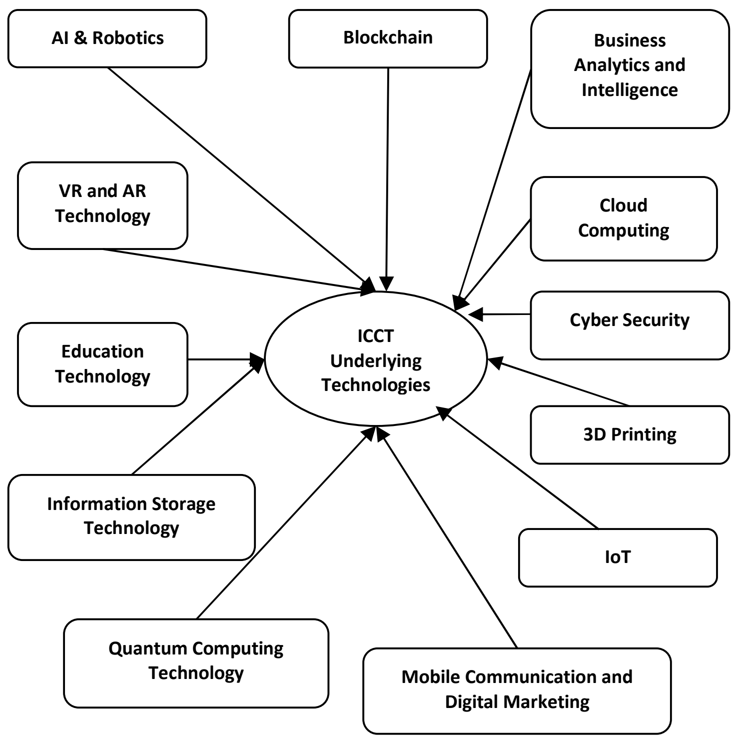

FIGURE 3. ICCT Underlying Technologies

RESULTS AND DISCUSSION

When used via Quantum Annealing, the Ising Model becomes a powerful resource for greening and reimagining supply chains. Based on quantum physics, this technology presents a potent tool for streamlining supply chains and cutting down on carbon emissions. Equation 2 illustrates the Ising model where, $s_i \in \{-1,1\}$ represents binary states of supply chain components, h_i represents individual biases, and J_{ij} represents pairwise interaction strengths. Quantum Annealing optimizes this model, helping reduce the carbon footprint in sustainable supply chains.

$$\mathrm{H}(s) = -\sum_{i=1}^{\mathrm{N}} h_i s_i - \sum_{i=1}^{\mathrm{N}-1} \sum_{j=i+1}^{\mathrm{N}} J_{ij} s_i s_j \quad (2)$$

Table 1 indicates Quantum Annealing solves complex optimization issues using quantum physics. Quantum superposition and tunnelling improve problem-solving. Ising Model reduces complicated circumstances into a predictable paradigm, helpful for spin interactions in physical systems. Max-Cut partitions combinatorial optimization problems into two sets effectively. Travelling Salesman finds shortest routes, reducing transportation expenses. These methods reduce carbon footprints in logistics, resource allocation, financial modelling, and other applications, creating sustainable supply chains.

TABLE I. Leveraging Quantum Annealing for Sustainable Supply Chains

Role	Benefit	Advantages	Applications
Quantum Annealing (QUBO)	Complex issue optimization	Uses quantum superposition and tunneling	Logistics, resource allocation, financial modeling
Ising Model	Showing spin interactions in physics	Simplifies complex problems	Finance, neural networks, magnetic materials
Max-Cut	Divide issues in two	Solve combinatorial optimization efficiently	Clustering, image segmentation, network design
Travelling Salesman (TSP)	Find the shortest graph route	Reduce transportation expenses	Circuit design, logistics, delivery route

Max-Cut Optimization, when used with Quantum Annealing, becomes a potent instrument for greening supply chains and cutting emissions. Based on quantum physics, this strategy provides a game-changing way to improve supply chain efficiency and lessen negative effects on the environment. Equation 3 shows the Max-cut problem, where $x_i \in \{-1,1\}$ represents binary variables indicating subset assignments, and w_{ij} represents edge weights. Quantum Annealing explores solutions efficiently, aiding sustainable supply chains by optimizing component assignments and reducing the overall carbon footprint. For a graph with vertices V and edges E the Max-Cut objective function.

$$Maximize: \sum_{(i,j)\in \mathrm{E}} w_{ij}\left(1-x_i x_j\right) \tag{3}$$

Table 2 illustrates how Quantum Annealing techniques QUBO, Ising Model, Max-Cut, and Travelling Salesman optimize supply chains for sustainability. QUBO solves difficult, multi-variable problems using quantum superposition and tunnelling. Ising Model is useful for magnetic materials and neural networks because it accurately represents spin interactions in physical systems. Max-Cut compresses complicated situation into a recognized framework, improving combinatorial optimization. These methods reduce carbon footprints in logistics, resource allocation, financial modelling, network design, and other sustainable supply chain applications.

TABLE II. Quantum Annealing Techniques for Sustainable Supply Chains

Aspect	QUBO	Ising Model	Max-Cut
Optimization Capability	Solves complicated, multivariable issues	Spin interactions in physical systems	Solve combinatorial optimization efficiently
Mathematical Formulation	Problem: Quadratic Binary Optimization	Spin representation in magnetic systems	Divide issues in two
Strengths	Uses quantum superposition with tunneling	Reduces complicated issues to basic terms	Handles combinatorial optimization well
Applications	Resource allocation, financial modeling, logistics	Finance, neural networks, magnetic materials	Clustering, image segmentation, network design

In Figure 4, Quantum Annealing using QUBO, Ising Model, Max-Cut, and TSP has transformed sustainable supply chains. Max-Cut scored 0.92 in 2022, suggesting it might reduce carbon footprints. Ising Model and QUBO followed with 0.88 and 0.87 ratings, suggesting their importance in supply chain route optimization. Quantum algorithms help create sustainable supply chains and reduce environmental impact.

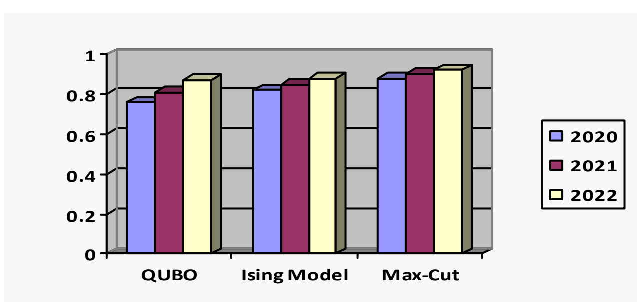

FIGURE 4. Quantum Annealing for Sustainable Supply Chains

In the quest of sustainable supply chains and decreased carbon impact, the use of Quantum Annealing in addressing the Travelling Salesman Problem stands as a game-changing strategy. This approach, which has its origins in quantum physics, provides an effective tool for greening supply chains. One of the most important factors to think about when trying to optimize a supply chain is the most effective way to visit several different sites. Equation 4 shows the Travelling salesman problem for N cities with distances d_{ij} between them, the TSP objective function subject to constraints ensuring each city is visited exactly once and forms a closed loop. Here, $x_{ij} \in \{0,1\}$ represents binary variables indicating whether the route includes the edge between cities i and j. Quantum Annealing explores optimal routes, contributing to eco-friendly supply chain management by reducing travel distances and associated carbon footprint.

$$Minimize: \sum_{i=1}^{N} \sum_{j \neq i} d_{ij} x_{ij} \tag{4}$$

Figure 5 comparison shows how quantum algorithms optimize supply chains for sustainability. Quantum Annealing (QUBO) leads with 0.92, demonstrating its ability to minimize carbon footprints. The Ising Model and Max-Cut follow closely with 0.85 and 0.88 ratings, suggesting their usefulness in route optimization. Travelling Salesman (TSP) also contributes, scoring 0.80. Quantum algorithms improve supply chain efficiency, advancing sustainability and the environment.

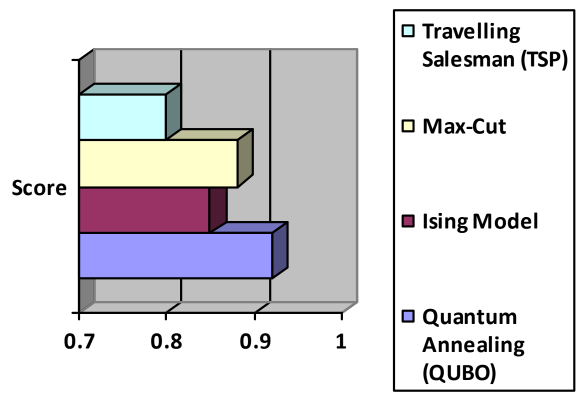

FIGURE 5. Quantum-Driven Optimization for Greener Supply Chains

CONCLUSION

This research demonstrates the potential of Quantum Annealing in revolutionizing sustainable supply chains and reducing carbon footprints. By delving into Quadratic Unconstrained Binary Optimization, Ising Model, Maximum Cut Problem, and the Traveling Salesman Problem, this showcases the efficacy of quantum algorithms in optimizing complex logistics networks. The findings underscore the importance of integrating quantum computing techniques into practical supply chain management, emphasizing their role in mitigating environmental impact and fostering eco-friendly practices. Future research should focus on refining quantum algorithms for larger-scale supply chain applications, enhancing their efficiency and scalability. Investigating the integration of QA with emerging technologies like machine learning and artificial intelligence could further enhance optimization capabilities. Exploring real-time data analytics and sensor technologies to feed quantum algorithms with dynamic information can lead to more responsive and adaptive supply chain solutions. Interdisciplinary collaboration between quantum physicists, computer scientists, and environmental experts is crucial to developing holistic approaches for sustainable supply chain management. Addressing the challenges associated with quantum hardware, error correction, and noise reduction is pivotal for the practical implementation of quantum solutions.

REFERENCES

[1]. J. Ding, 2023, "Design of a low carbon economy model by carbon cycle optimisation in supply chain," *Frontiers in Ecology and Evolution*, 11, Article. 1122682.

[2]. L. Abualigah, E. S. Hanandeh, R. A. Zitar, C. L. Thanh, S. Khatir, and A. H. Gandomi, 2023, "Revolutionizing sustainable supply chain management: A review of metaheuristics," *Engineering Applications of Artificial Intelligence*, 126, Article. 106839.

[3]. P. S. Aithal, 2023, "Advances and new research opportunities in quantum computing technology by integrating it with other ICCT underlying technologies," *International Journal of Case Studies in Business, IT and Education*, 7(3), pp. 314-358.

[4]. M. Zizi, A. Chafi, and M. El Hammoumi, 2025, "Quantum computing for sustainable supply chains: Unlocking efficiency, environmental progress and challenges," *International Conference on Advanced Sustainability Engineering and Technology*, pp. 289-297.

[5]. E. Aguilera, J. de Jong, F. Phillipson, S. Taamallah, and M. Vos, 2024, "Multi-objective portfolio optimization using a quantum annealer," *Mathematics*, 12(9), Article. 1291.

[6]. B. Singh, P. K. Dutta, R. Gautam, and C. Kaunert, 2024, "Uncapping the potential of quantum computing towards manufacturing optimization: Routing supply chain projecting sustainability," *Quantum Computing and Supply Chain Management: A New Era of Optimization*, pp. 395-419.

[7]. R. K. Vaddy, B. Dhamodharan, and A. Jain, 2024, "Quantum computing applications in real-time route optimization for supply chains," *Quantum Computing and Supply Chain Management: A New Era of Optimization*, pp. 113-124.

[8]. A. Mansur, D. I. Handayani, I. D. Wangsa, D. M. Utama, and W. A. Jauhari, 2023, "A mixed-integer linear programming model for sustainable blood supply chain problems with shelf-life time and multiple blood types," *Decision Analytics Journal*, 8, Article. 100279.

[9]. S. Nasrollah, S. E. Najafi, H. Bagherzadeh, and M. Rostamy-Malkhalifeh, 2023, "An enhanced PSO algorithm to configure a responsive-resilient supply chain network considering environmental issues: A case study of the oxygen concentrator device," *Neural Computing and Applications*, 35(3), pp. 2647-2678.

[10]. Y. Wang, Y. Yang, Z. Qin, Y. Yang, and J. Li, 2023, "A literature review on the application of digital technology in achieving green supply chain management," *Sustainability*, 15(11), Article. 8564.

[11]. N. Zhao, H. Zhang, X. Yang, J. Yan, and F. You, 2023, "Emerging information and communication technologies for smart energy systems and renewable transition," *Advances in Applied Energy*, 9, pp.1-12.

[12]. P. Whig, R. Remala, K. R. Mudunuru, and S. J. Quraishi, 2024, "Integrating AI and quantum technologies for sustainable supply chain management," InQuantum computing and supply chain management: A new era of optimization, pp. 267-283.

[13]. B. Wang, X. Yang, and D. Zhang, 2022, "Research on quantum annealing integer factorization based on different columns," Frontiers in Physics, 10, Article. 100125.

[14]. S. S. Gill, A. Kumar, H. Singh, M. Singh, K. Kaur, M. Usman, and R. Buyya, 2022, "Quantum computing: A taxonomy, systematic review and future directions," *Software: Practice and Experience*, 52(1), pp. 66-114.

[15]. H. Jung, V. S. Sapner, A. Adhikari, B. R. Sathe, and R. Patel, 2022, "Recent progress on carbon quantum dots based photocatalysis," *Frontiers in Chemistry*, 10, Article. 881495.

[16]. Z. Zheng, S. Yang, D. T. Reid, Z. Wei, and J. Sun, 2022, "Design of quasi-phase-matching nonlinear crystals based on quantum computing," *Frontiers in Physics*, 10, Article. 1038240.

[17]. V. Etienne, L. Gatineau, and M. Ikuta, 2022, "From seismic imaging to wind turbine modelling: The benefits of vector computing," *6th EAGE High Performance Computing Workshop*, pp. 1-6.

[18]. S. Yu, and T. Nabil, 2021, "Applying the hubbard-stratonovich transformation to solve scheduling problems under inequality constraints with quantum annealing," *Frontiers in Physics*, 9, Article. 730685.

[19]. N. P. De Leon, K. M. Itoh, D. Kim, K. K. Mehta, T. E. Northup, H. Paik, B. S. Palmer, N. Samarth, S. Sangtawesin, and D. W. Steuerman, "Materials challenges and opportunities for quantum computing hardware," *Science*, 372(6539), pp. 1-20.

[20]. A. Kumar, S. Bhatia, K. Kaushik, S. M. Gandhi, S. G. Devi, D. A. Pacheco, and A. Mashat, 2021, "Survey of promising technologies for quantum drones and networks," *IEEE Access*, 9, pp. 125868-125911.