# Quantum-inspired computing in civil engineering – Opportunities, challenges, and visions

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ABSTRACT: Despite its prospective benefits, the application of quantum-inspired computing in civil engineering has not yet been fully explored. This study aims to evaluate the current state of the art of quantum-inspired computing in civil engineering and to identify potential use cases in civil engineering, where quantum-inspired computing could surpass conventional computing methods. Furthermore, this study aims to establish as solid foundation in anticipation of the advancements and increased future availability of quantum computers in civil engineering. A review of quantum-inspired computing is conducted, which, methodologically, accounts for both peer-reviewed, indexed literature, as well as for material not indexed in well-accepted citation databases, such as deliverables, reports, and white papers published by companies that report, e.g., on opportunities, challenges, and visions. The main contribution of this study is a systematic panorama of the current quantum-inspired landscape in civil engineering along with a detailed analysis of potential use cases and applications of quantum-inspired computing in civil engineering. It is expected that the results of this study will serve as a foundation for guiding future research endeavors and practical deployments of quantum-inspired computing in the civil engineering, as quantum computers are expected to become more accessible and advanced in the coming years.

## 1 INTRODUCTION

Quantum computing, capitalizing on the principles of quantum mechanics, offers new computational methods that promise to solve complex problems faster than conventional computing. Many computational complex problems are found in civil engineering, such as numerical calculations, simulation problems, as well as optimization and machine learning problems. However, quantum technology is still in its early research stages and, despite encouraging roadmaps (Gambetta, 2023), many practical challenges remain that render large-scale applications not to be expected soon.

To bypass the current practical limitations of quantum computing, quantum-inspired approaches use ideas derived from quantum computing but run on classical, i.e., conventional computers, representing a promising approach for civil engineering (Ploennigs et al., 2024). This strategy not only has the potential to expedite certain calculations but also enables the preliminary testing of problem formulations. The formulations are likely to prove beneficial for resolution with actual quantum computers in the foreseeable future. In civil engineering, typical problems frequently involve tackling NP-hard problems, necessitating innovative computational approaches for optimal solutions. Moreover, analysis and assessment tasks in civil engineering typically entail solving complex equation systems, which can be cumbersome and time-consuming when employing conventional computing methods. Quantum-inspired computing offers promising avenues for efficiently addressing these challenges, leveraging principles from quantum mechanics to enhance computational power and expedite solution processes. Furthermore, in management tasks within civil engineering, where decisions heavily rely on the collective expertise of individual professionals, quantum-inspired computing may augment decision-making processes by providing advanced data analytics and optimization techniques. In essence, the integration of quantum-inspired computing into civil engineering practices holds immense potential for revolutionizing the field, facilitating more efficient, sustainable, and resilient infrastructure development in an increasingly complex world.

This paper will discuss the current state and future prospective of quantum-inspired computing in civil engineering, which has not yet been sufficiently explored. To address this gap, a multivocal literature review is conducted that, by providing a panorama of the current research landscape, aims (i) to evaluate the current state of research and development in civil engineering and (ii) to identify potential use cases, in which quantum-inspired computing may outperform conventional computing. To provide the readership with sufficient background, the remainder of this paper will first provide the readership with background information on fundamentals and algorithmic concepts of quantum computing and quantum-inspired computing, followed by the multivocal literature review. Upon presenting the review results, opportunities, challenges and visions of quantum-inspired computing will be reported. The paper concludes with a summary and an outlook on potential future research directions, focusing on areas in civil engineering, in which quantum-inspired computing may outperform conventional computing methods.

## 2 QUANTUM COMPUTING

The ultimate goal in quantum computing is to build scalable universal quantum computers, i.e., machines that support all quantum algorithms in a similar way as standard computers support conventional algorithms. An important example of a quantum algorithm is Shor's algorithm (Shor, 1994) for factoring integer numbers quickly (i.e. in polynomial time). Shor's algorithm impressively demonstrates the potential of quantum computing to offer an exponential advantage over conventional computation (i.e. computation performed on bits). However, quantum computations are faced with substantial challenges, due to unavoidable noise in the quantum hardware and the need for large numbers of qubits (quantum versions of conventional bits). Thus, progress on the hardware and the algorithms are essential for scalable universal quantum computation in the long term.

Currently, the focus of implementations lies on intermediate goals. One goal has arguably been reached: The demonstration of quantum supremacy. The term "quantum supremacy" refers to solving computational problems using quantum hardware, which can practically not be solved using conventional computation. Typically, these computational problems are contrived problems without practical relevance. Substantial surge of interest in quantum computing could be observed when Google published their quantum supremacy experiment (Arute et al., 2019), which was quickly met with critical examination. Fundamental concerns about the verification of the experiment (Hangleiter et al., 2019), the introduction of alternative algorithms that could perform similar tasks efficiently using conventional algorithms (Aharonov et al., 2023), and the development of practical, conventional simulation techniques (Pan & Zhang, 2021) brought the claim of quantum supremacy under scrutiny. Other quantum supremacy experiments (Kim et al., 2023; Bluvstein et al., 2023) were accompanied by similar developments with fast conventional simulations based on tensor networks (Patra et al., 2023) and other methods (Maslov et al., 2024). Overall, the ongoing discussions highlight the challenges in proving a clear quantum advantage and stress the need for further innovation in quantum algorithms.

Indeed, the primary upcoming objective is to achieve a quantum advantage that is practically significant, meaning to demonstrate quantum speedup for computational problems of practical importance. This goal is central in the noisy and intermediate scale quantum (NISQ) era, with access to a moderate number of noisy qubits and short quantum computations (Preskill, 2018). Potential applications are simulations of physical systems in quantum chemistry and material science (McArdle et al., 2020; Bauer et al., 2020). Also, combinatorial optimization problems have drawn much attention. The main basic NISQ approaches are quantum annealing (Kadowaki & Nishimori, 1998), used by the D-Wave Systems, and quantum approximate optimization algorithms (Farhi et al., 2014). Quadratic unconstrained binary optimization (QUBO) problems of the form

$$\underset{\in \{0,1\}^n}{\text{minimize}} \sum_{i,j} w_{i,j} x_i x_j, \tag{1}$$

are addressed, where $w_{i,j}$ are real parameters used to capture a combinatorial optimization problem and $x_i$ and $x_j$ are binary variables. Various NP problems can be formulated in this form (Ratke, 2021). It is important to note that quantum computers are not expected to solve NP problems in polynomial time but promise to provide new powerful heuristic approaches for these problems.

Also for classical computation, QUBO problems can be seen as a very useful problem formulation, representing an important example of quantum-inspired computation. First, a combinatorial optimization problem of interest is formulated as a QUBO problem. Then, the QUBO problem is solved with a dedicated solver. Using tensor networks (Orús, 2014) as a tool for conventional computation is another prominent example of quantum-inspired computation. In this context, two types of tensor networks are relevant, (i) matrix product states (MPS), which are sequential tensor networks, and (ii) tree tensor networks (TTN), which are characterized by hierarchical structures (Biamonte & Bergholm, 2017).

## 3 QUANTUM-INSPIRED COMPUTING

Quantum-inspired computing (QIC) applies several innovative ideas from quantum algorithms on conventional hardware, while avoiding the challenges that come along with the development of quantum computers. Essentially, quantum-inspired computing involves running conventional algorithms on either standard or dedicated conventional hardware, using some ideas or inspiration from quantum computing. Yet, QIC cannot achieve the complete potential of full quantum computing.

Historically, the initial challenges of creating functional 2-qubit quantum computers by IBM and MIT

(Chuang et al., 1998) led researchers to explore simpler architectures, giving rise to adiabatic quantum optimization (AQO) and quantum annealing (QA), which caused the need for dedicated, more scalable hardware. D-Wave Systems achieved a significant milestone by launching the first commercial quantum annealing hardware, a 128-qubit system, in 2011 (Johnson et al., 2011). Since then, D-Wave Systems has advanced its technology to include 5,000 qubits, although with certain "connectivity constraints", and, in 2017, has introduced a library specifically designed for QUBO problems. These developments have inspired other contenders, such as Fujitsu, Hitachi, Toshiba and NEC, to develop so-called Ising machines that aim to solve QUBO problems as fast and as accurate as possible. It turned out that traditional binary circuits are best suited for this purpose. Only few benchmark studies have been reported, such as the study published by Kowalsky et al. (2022), comparing the different approaches for QUBO problems. According to findings by Matsubara et al. (2020) and Shaglel et al. (2024), these quantum-inspired solutions can surpass conventional computing techniques, offering the most efficient resolution of QUBO problems with up to 100,000 variables (Nakayama et al., 2021).

Tensor networks represent another important area of QIC research, primarily for modeling and simulating quantum systems on conventional computers, and complex tensor computations on conventional computers have witnessed performance enhancements in the past several years (Orús, 2019). Specifically, matrix product states (MPS) can be used to represent discretized functions and linear operators in a computationally cheap way. Moreover, many linear algebra routines can efficiently be implemented. These insights have been used to develop powerful algorithms for solving complex partial differential equations (PDEs) in computational fluid dynamics (CFD) simulations (Gourianov et al., 2022; Peddinti et al., 2023). The advantage of tensor networks is that many functions can be presented in a way that is exponentially compressed with regard to the discretization size. Here, promising applications can be expected, e.g., augmenting or replacing finite element methods (FEMs) or computational fluid dynamics (CFD) in civil engineering.

Tree tensor networks (TTN) are an extension of MPS and offer advantages in modeling deep neural networks, due to the capacity to manage high-dimensional data, enabling the construction of smaller networks with higher information density of information, as corroborated by Felser et al. (2021), by Wall & D'Aguanno (2021), and in a meta-study published by Wang (2023).

With potential relevance to civil engineering, quantum-inspired algorithms encompass low-rank matrix reconstruction for compressive sensing, as introduced by Gross (2011) and specific training methodologies for deep Boltzmann machines, as discussed by Wiebe et al. (2015), also of importance in algorithms theory where efficient classical variants of quantum algorithms have been developed, which has been coined "de-quantization" (Tang, 2019). It should be noted, however, that not all quantum algorithms are amenable to quantum-inspired adaptations, as some algorithms, such as Shor's algorithm, require full quantum computing capabilities and are not expected to allow for equivalent conventional algorithms, which is particularly relevant for quantum-inspired computing in civil engineering. The literature review of quantum-inspired computing in civil engineering is presented in the following section.

## 4 LITERATURE REVIEW OF QUANTUM-INSPIRED COMPUTING IN CIVIL ENGINEERING

This section presents the review methodology as well as the main results of the review. The main objectives of the review are (i) to evaluate the current state of research and development in civil engineering and (ii) to provide a structured foundation to identify potential use cases of quantum-computing in civil engineering. Therefore, a multivocal literature review (MLR) is conducted, which is favored over other review types as it amalgamates a systematic literature review (SLR), encompassing white literature, with a gray literature review (GLR). The GLR is important for reviewing material not indexed in well-accepted citation databases, such as deliverables, reports, and white papers published by companies. The review methodology involves three phases, (a) a planning phase, in which objectives of the MLR and procedures to achieve the objectives are defined, (b) an execution phase, in which the studies are collected and data is extracted, and (c) a reporting phase, in which the data is analyzed. The phases of the review methodology, each comprising several steps, are presented in the following subsections.

### 4.1 *Planning phase*

The planning phase includes four steps, (i) the definition of the research questions, (ii) the definition of a search strategy to retrieve studies from research and practice, (iii) the definition of inclusion and exclusion criteria to filter and select relevant studies, and (iv) the definition of methods for data extraction and data analysis. In the first step, the following research questions are formulated in compliance with the objectives:

- *Research question 1:* What is the current state of research and development of quantum-inspired computing in civil engineering?
- *Research question 2:* What are potential use cases, applications, and disciplines within civil engineering, in which quantum-inspired computing may outperform traditional computing?

In the second step of the planning phase, the search strategy is defined for the white literature (i.e., for the SLR) and for the gray literature (i.e., for the GLR). As for the SLR, the Scopus database serves as the data source because of its comprehensive coverage, quality assurance, and search tools. Regarding the GLR, to specifically account for studies not included in Scopus, the general-purpose open repository "Zenodo", operated by the European Organization for Nuclear Research, is used as a data source (CERN, 2024). In the third step, inclusion criteria (IC), exclusion criteria (EC), and quality assessment criteria (QAC) are defined. For example, an inclusion criterion dictates that a study has been published in English and an exclusion criterion would be fulfilled if the full text is not available. The quality assessment criteria are scored with either QAC = 0 (a study does not satisfy the quality assessment criteria) or QAC = 1 (a study satisfies the quality assessment criteria). In the fourth step, the methods for data extraction and data analysis are defined. For example, title, document type, year, number of citations, discipline, and research focus are extracted and analyzed.

## 4.2 *Execution phase*

The execution phase encompasses four steps, (v) search, in which the studies are retrieved according to the research questions and the search strategy, (vi) filtering, in which the studies are filtered based on the inclusion and exclusion criteria, (vii) selection, in which the studies remaining after filtering are evaluated according to the quality assessment criteria so as to select relevant studies (hereinafter referred to as "selected studies"), and (viii) data extraction, in which data is extracted from the selected studies.

Regarding the SLR, the corresponding search strings are listed in Table 1. The search step, based on the search strings, initially yields 65,454 studies, which are narrowed down to 24 studies. After filtering and selection, 12 relevant studies are identified. Regarding the GLR, the corresponding search strings are listed in Table 2. In the search step, 5367 studies are initially retrieved, narrowed down, after filtering, to 3 studies. Finally, the total of 15 studies are forwarded to the data extraction step, serving as input for the reporting phase.

Table 1. Search strings and results for the SLR.

| No. | Search string | Results |
|---|---|---|
| $S_1$ | "quantum computing" | 65,454 |
| $S_2$ | "quantum-inspired" | 11,348 |
| $S_3$ | "quantum-inspired computing" | 132 |
| $S_3$ | "quantum-inspired computing" AND PUBYEAR > 2014 AND PUBYEAR < 2025 | 83 |
| $S_4$ | "quantum-inspired computing" AND PUBYEAR > 2014 AND PUBYEAR < 2025 AND ( LIMIT-TO ( SUBJAREA , "ENGI" ) ) | 24 |

Table 2. Search strings and results for the GLR.

| No. | Search string | Results |
|---|---|---|
| $G_1$ | quantum | 5367 |
| $G_2$ | +quantum +inspired | 85 |
| $G_3$ | +quantum +inspired +comput* | 51 |
| $G_4$ | +quantum +inspired +comput* +engineering | 22 |

## 4.3 *Reporting phase*

The reporting phase includes two steps, (ix) data analysis, in which statistical data analysis is conducted, and (x) reporting of the results and recommendations, in which the conclusions regarding the research questions are drawn and recommendations are proposed.

The data analysis step, as the number of 15 studies is not statistically relevant, is limited to identifying the general publication trend for "quantum computing" and "quantum-inspired computing", based on a bibliometric analysis of the results achieved from search string $S_1$ and $S_3$. As can be seen from Figure 1, research in quantum computing started gaining traction in the late 1990s, with a significant increase in quantum computing publications in the late 2010s, while quantum-inspired computing emerged more prominently as a distinct area of research in the early 2020s.

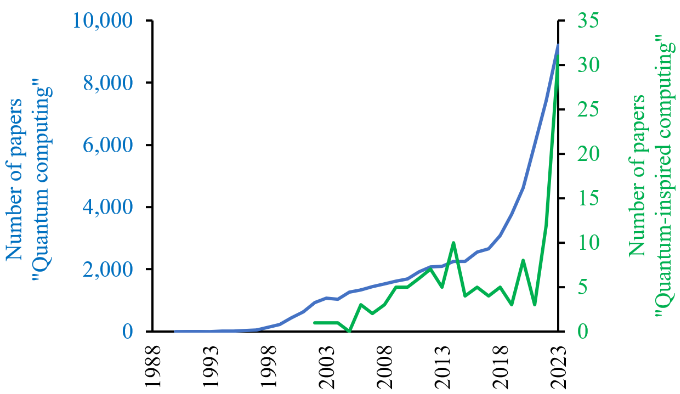


Figure 1. Publication output in quantum computing (search string $S_1$) and in quantum-inspired computing (search string $S_3$).

The reporting step is addressed in the following paragraph, elucidating the results related to research question 1 ("*What is the current state of research and development of quantum-inspired computing in civil engineering?*") as well as in Section 5, which is devised to respond to research question 2 ("*What are potential use cases, applications, and disciplines within civil engineering, in which quantum-inspired computing may outperform traditional computing?*"). Regarding research question 1, drawing from the review results, it can be stated that no review of quantum-inspired computing approaches in civil engineering has been conducted so far, and no concept based on quantum-inspired computing has been proposed particularly for civil engineering problems. Rather, quantum-inspired computing has been applied to solve problems that may occur in civil engineering among other disciplines. For example, a quantum-inspired ant colony optimization approach for improving routing gateways in mobile ad hoc networks has been proposed by Madhloom et al. (2023). A quantum-inspired genetic algorithm for efficient combinatorial optimal decisions in engineering system design and operations has been reported by Zou et al. (2023). A quantum-inspired genetic programming algorithm for crude oil scheduling of a refinery has been developed by Pereira et al. (2020). A review quantum computing in power grids and a discussion of the potential of quantum computing for solving multiple power system problems has been provided by Eskandarpour et al. (2020).

In summary, the fast majority of studies relevant to civil engineering reports on ***quantum-inspired optimization***, primarily quantum-inspired evolutionary algorithms (particularly genetic algorithms), while a few studies report on ***quantum-inspired machine learning***. Overall, research and development in the field of quantum-inspired computing within civil engineering are at an early stage.

## 5 QUANTUM-INSPIRED COMPUTING IN CIVIL ENGINEERING: OPPORTUNITIES, CHALLENGES, AND VISIONS

Addressing research question 2, this section identifies potential use cases, applications, and disciplines within civil engineering, in which quantum-inspired computing may outperform conventional computing, thereby illustrating the opportunities, challenges, and visions of quantum-inspired computing in civil engineering. A broad wealth of use cases in civil engineering have been analyzed, spanning the application areas "simulation", "optimization", and "machine learning". The outcome of the analysis is a mapping that aligns civil engineering disciplines and the application areas with the potential applicability of quantum-inspired computing, as shown in Figure 2. As for the application areas, the main QIC algorithms have been identified as (i) matrix product states used for efficiently solving differential equations ("simulation" application area), (ii) quantum annealing for solving QUBO problems ("optimization" application area), (iii) and tree tensor networks to achieve more compact deep learning networks ("machine learning" application area). The applicability of the QIC algorithms within the civil engineering disciplines is categorized into three levels, "high" (indicated by bold lines), "moderate" (indicated by dotted lines), and "low" (no indication), with expanded details to follow in the subsequent discussion.

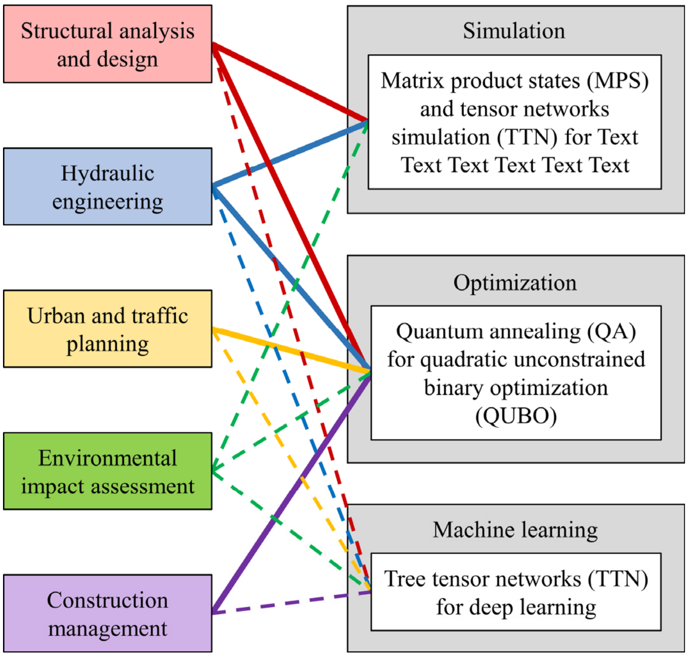


Figure 2. Mapping of civil engineering disciplines and application areas, highlighting the potential applicability of quantum-inspired computing as "high" (represented by bold lines), "moderate" (represented by dotted lines), and "low" (not indicated).

The civil engineering disciplines and the opportunities, challenges, and visions of potential quantum-inspired computing applications will be discussed in the following subsections.

### 5.1 *Structural analysis and design*

Structural analysis and design as well as related and sub disciplines, such as structural health monitoring, largely rely on numerical methods for simulating and analyzing the behavior of engineering structures under various loads. Regarding numerical methods, two main approaches are typically employed, (i) rigid body models, which idealize structures as stiff elements connected by joints, and (ii) finite element analysis (FEA), which discretizes structures into meshes for detailed stress, strain, and displacement analysis. High accuracy of FEA requires significant computational resources, as the number of elements directly impacts the complexity of the calculations. Both numerical modeling approaches may benefit from tensor models, with quantum-inspired MPS methods offering potential for enhanced discretization. Also, optimization problems are common in structural analysis and design to determine to achieve a balance between structural integrity and material efficiency. The optimization approaches are often based on nonlinear programming, genetic algorithms, and simulated annealing, i.e. the application of quantum annealing is promising, with potential applications in generating QUBO problems for more efficient solutions.

### 5.2 *Hydraulic engineering*

Hydraulic engineering typically utilizes computational fluid dynamics (CFD) instead of FEA, simulating fluid systems, such as rivers and dams, by modeling fluid dynamics, including turbulences and fluid-structure interactions. Gourianov et al. (2022) demonstrated the application of quantum-inspired methods in CFD, releasing an open-source Matlab library for the MPS approach proposed in the study. Additionally, hydraulic engineering employs network models for pipes and rivers, suitable for graph-based optimization problems. Speziali et al. (2021) explored sensor placement in water networks using an adiabatic quantum computing (AQC) method, effectively mapping the problem to a QUBO framework. These initial examples shows how QC can be successfully applied in the area and that others should follow.

### 5.3 *Urban and traffic planning*

Urban and traffic planning utilizes simulations for pedestrian and vehicular movement within buildings and transportation networks, capturing complex interactions among people, vehicles, and infrastructure. The main challenge in systems deployed for urban and traffic simulation is the stochastic nature of human decision-making, entailing emergent phenomena in people and traffic flows, which introduces stochastic elements less suited to quantum-inspired algorithms. However, optimizing traffic network designs is a primary goal, involving network flow optimization or logistic routing problems, both of which can be adapted to quantum-inspired solutions. Additionally, site selection for infrastructure facilities, while geospatial, involves complex decision-making that may also benefit from quantum-inspired approaches, despite the higher complexity of constraints and variables involved.

### 5.4 *Environmental impact assessment*

Environmental impact assessment examines the effects of buildings – and the built environment in general – on the natural environment, typically employing CFD or FEA methods (Harish & Kumar 2016), i.e. areas where tensor networks show promise, as previously discussed. While applications such as simulated annealing have been used in building design for energy efficiency, QUBO remain unexplored. However, while many optimization challenges in reducing energy consumption relate to scheduling and control, these specific problems often present limited potential for application of quantum-inspired computing.

### 5.5 *Construction management*

Construction management focuses on optimizing resource allocation and project scheduling, including the efficient distribution of labor, equipment, and materials. These optimization challenges are often conducive to being structured as QUBO problems, rendering QUBO suitable for quantum-inspired algorithmic solutions in construction management.

### 5.6 *Further remarks*

So far, the discussion has primarily focused on mapping the civil engineering disciplines with the application areas of *simulation* and *optimization*, but the vital application area of *machine learning* has not explicitly been addressed in the discussion, as it is widely adopted across all civil engineering disciplines . However, it should be emphasized the specific advantages of quantum computing for machine learning techniques do not fully translate to quantum-inspired computing. Notably, tree tensor networks represent an area where quantum-inspired approaches are considered suitable means, particularly for developing compact deep neural networks in scenarios with strong interlayer correlations. This insight opens potential, e.g., for applications in surrogate models for FEM/CFD or complex graph neural networks, suggesting a nuanced landscape where quantum-inspired computing could be expected to offer distinct benefits.

## SUMMARY AND CONCLUSIONS

The study presented in this paper has illustrated the transformative impact of quantum-inspired computing in civil engineering. Quantum-inspired computing opens new possibilities in computational technology that holds the potential to reshape traditional methodologies and processes in civil engineering. Despite its prospective advantages, the application of quantum-inspired computing and potential use cases in civil engineering have rarely been explored. Therefore, in this study, a multivocal review has been conducted, following two-fold objectives, (i) to assess the current state of research and development in quantum-inspired computing in of civil engineering, and (ii) to pinpoint potential use cases where quantum-inspired computing may surpass conventional computing approaches. Last, but not least, opportunities, challenges, and visions have been summarized to establish a foundation in preparation for the anticipated advancements and increased accessibility of quantum computers in the field of civil engineering.

In conclusion, the vast majority of studies that try to take advantage of quantum-inspired computing focus on quantum-inspired optimization using primarily quantum-inspired evolutionary algorithms (particularly genetic algorithms), while a few studies report on quantum-inspired solutions in the area of simulation and machine learning. Clearly, research and development in the field of quantum-inspired computing within civil engineering are at an early stage. However the potential of quantum-inspired computing to enhance civil engineering disciplines, such as structural analysis and design, hydraulic engineering, urban and traffic planning, environmental impact assessment, and construction management demonstrates its versatility and wide-reaching potential implications. In addition to the application areas of simulation and optimization, machine learning, prevalent across the civil engineering disciplines, highlights a distinct application area, in which quantum-inspired computing could offer benefits to applications in civil engineering.

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