Review Article

A Comprehensive Review of the Ford-Fulkerson Algorithm for Network Flow Problems

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ABSTRACT

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| The Ford-Fulkerson method is one of the basic algorithms for computing the maximum flow in a flow network. This identifies more frequent traversed paths as a means of maximizing the flow between a source node and a downstream node in a directed network. Therefore, this paper will present a literature review, the principles of the algorithm, its mathematical foundation, applications and improvements made to the algorithm, such as the use of breadth-first search (BFS) as in the Edmonds-Karp algorithm, parallel computing techniques and predictive modeling to enhance efficiency. However, the algorithm is not without its issues, such as the effect of dense networks, loss of correctness in capacities, and static structure of networks. Furthermore, it is compared with other algorithms like Dinic and Edmonds-Karp to understand their relative benefits and drawbacks. We conclude that the Ford-Fulkerson algorithm is still a basis method with broad application in many fields, including traffic network, logistics, and communication networks, but its performance can be greatly improvedas a result of the advances in modern computation approaches including parallel computing and adaptive dynamic path-propagation. Moreover, comparative studies showcase that alternative algorithms such as Dinic and Edmonds-Karp provide distinct advantages in specific settings, such as in dense and dynamic networks, underscoring that depending on the application the most effective algorithm may vary. |

***Keywords****:* *Deep Learning, Threats, Cloud Security, Cyber Security*

1. **Introduction:**
2. Flow networks are a critical research area in both computer science and applied mathematics, where flow through directed networks is studied and classified. They hold immense importance in numerous real-world applications, such as air transportation networks, resource management, telecommunications enhancement, and data networks (Ford, 2024). Among the most studied problems in the development of such networks is the maximum flow problem, which seeks to determine the maximum amount of material that can be transferred from one end to another in a directed network, considering the capacity constraints of each edge (Abd-Alsabour, 2020). The motivation for solving this problem lies in improving system operations that rely on resource flow. For example, optimal solutions in transportation networks can reduce congestion and improve vehicle flow (Forgerini & de Sousa, 2023). Similarly, the maximum flow in communication networks is essential for optimizing data transfer systems, ensuring efficiency and reliability (Haque & Isla, 2020). In resource management and logistics, optimizing the routing of goods through networks can lead to cost reductions and increased productivity (Lee & Rieger, 2023). Over the decades, several algorithms have been developed to address the maximum flow problem. However, the Ford–Fulkerson algorithm remains one of the most popular and widely adopted. Introduced in 1956 by L. R. Ford and D. R. Fulkerson, the algorithm is based on the idea of path maximization (Ford, 2024). This foundational method paved the way for subsequent algorithms, such as the Edmonds-Karp algorithm (Edmonds & Karp, 2023), and forms the backbone of modern approaches to network flow optimization. The Ford-Fulkerson algorithm operates by pushing augmenting paths in a directed flow network. Initially, all edges are set to zero flow. Search algorithms such as DFS (Depth First Search) or BFS (Breadth First Search) are then employed to identify augmenting paths from the source to the sink. The maximum possible flow along these paths is determined by the minimum remaining capacity, often referred to as the bottleneck capacity. The flow and capacities are updated iteratively until no more augmenting paths can be found. This iterative approach makes the algorithm flexible and adaptable to different types of networks (Haque & Isla, 2020). Despite its simplicity and versatility, the Ford-Fulkerson algorithm faces certain limitations. Its performance can degrade significantly in networks with dense connectivity or when working with decimal capacities. These challenges have led to the emergence of improved versions of the algorithm. For example, the Edmonds-Karp algorithm leverages BFS to limit the time complexity of finding augmenting paths, while modern machine learning-based improvements have enabled faster and more intelligent tracking of flow paths (Edmonds & Karp, 2023; Haque & Isla, 2020). This paper reviews the state-of-the-art research on the Ford-Fulkerson algorithm, analyzing the significant advancements made by researchers in recent decades. It discusses the practical applications of the algorithm, its strengths and weaknesses, and compares it with other algorithms designed to solve the maximum flow problem. This includes recent innovations in traffic modeling and transportation networks which demonstrate the ongoing relevance and adaptability of the Ford-Fulkerson algorithm.

**2. Ford-Fulkerson algorithm**

The concept of flow in networks refers to the movement of data, resources, or materials between nodes in a directed graph via edges with defined capacities. The flow represents the quantity that can pass from the source node (Source) to the sink node (Sink) through multiple paths within the network. The analysis of flow aims to optimize the utilization of available capacity while adhering to network constraints. The Maximum Flow Problem is one of the most common issues in network flow analysis. It involves determining the maximum quantity that can be transferred from the source to the sink while considering the capacity constraints of each edge. This problem has practical applications in optimizing transportation networks, organizing data flow in internet systems, and managing resources. The Ford-Fulkerson algorithm is a fundamental solution to the maximum flow problem. It relies on the concept of augmenting paths to iteratively update the flow. The process involves the following steps:

1. Creating a residual network that displays the remaining capacities for each edge.  
2. Searching for an augmenting path from the source to the sink.  
3. Determining the additional flow based on the minimum residual capacity along the path.  
4. Updating the flows and residual capacities.

The algorithm is mathematically expressed through the following equations:  
Flow constraint:

0 ≤ f(u, v) ≤ c(u, v)

where f(u, v) is the flow between nodes u and v, and c(u, v) is the maximum capacity of the edge.  
Flow conservation:

Σ f(u, v) = 0 for all nodes u, except the source and sink.

The residual network is a derived network that shows the remaining capacities for each edge after the flow is applied. It consists of:

1. Forward edges: Represent the remaining possible flow.  
2. Backward edges: Represent the flow that can be reversed.

The complexity of the Ford-Fulkerson algorithm depends on the choice of augmenting paths:

1. If the capacities are integers, the algorithm terminates in O(E × max\_flow).
2. If BFS is used (as in Edmonds-Karp), the complexity becomes O(V × E^2). (Ford & Fulkerson, 1957)

**3. Literature Review: Ford-Fulkerson Algorithm**

**3.1. Enhancements to Ford-Fulkerson Algorithm**

There have been a number of improvements to the Ford-Fulkerson algorithm to give it greater efficiency and adaptability for solving practical network flow problems. Predictive pathfinding methods in Davies (2023) to allow lower execution time and better performance of modern, high speed applications. Kovalev (2021) addressed the performance of the algorithm in networks with sparse and dense lines, proposing a method to improve the cooperation between agents in those lines. Integrated depth-first search (DFS) into VIET (n.d.) algorithm to reduce computational complexity and improve dynamic networks performance. For example, one of the contributions Wada (2022) made was to clarify what the authors mean by graph representations to streamline not only the analysis but calculation of flow problems. Last but not the least, Hafermas (2023) also employed parallel computing techniques to speed up the execution time in such a way that the algorithm could be applied to larger and more complicated networks and there is no need to mention the robustness of such algorithms. Ye, L. (2020): This paper proposes an improved maximum flow model for optimizing road network capacities. This approach is specifically targeted towards urban environments, offering valuable insights into traffic and infrastructure improvements.

Table 1 Improvements to the Ford-Fulkerson algorithm

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| --- | --- | --- | --- | --- |
| Author/Year | Objective | Methodologies | Results/Contributions | Remarks |
| Davies, S. M. (2023) | Improve execution speed | Using predictive paths | Reduced execution time and increased efficiency | Suitable for modern applications |
| Kovalev, K. E. (2021) | Enhance cooperation in low-density lines | Optimize sparse network lines | Improved effectiveness in non-homogeneous networks | Applicable to complex networks |
| VIET, T. N. (n.d.) | Enhance depth-first search | Integrating DFS with the algorithm | Improved performance and reduced computational complexity | Dynamic applications |
| Wada, T. I. (2022) | Graph representation optimization | Design visual flow analysis | Better computation and error reduction | Theoretical focus |
| Hafermas, J. (2023) | Enhance computational efficiency | Parallel computation techniques | Significant reduction in execution time | Ideal for large-scale networks |
| Saraswathi, A. (2024) | Minimal flow and critical paths | New network-based approaches | Solved complex flow and critical path problems | Comprehensive methodology |
| Ye, L. (2020) | Road capacity optimization | Improved maximum flow modeling | Optimized road network capacities | Focused on urban infrastructure |

**3.2. Practical Applications of Ford-Fulkerson Algorithm**

Ford Fulkerson can be used to solve several practical problems due to its versatility. For example, Mangata (2022) used the algorithm to study traffic congestion in urban road networks and showed that it is able to optimize vehicle flow and decrease delays. Marpaung (2023), on the other hand, implemented this technique in the commercial sector, specifically on transportation networks, considering resource allocation and cost reduction in urban logistics. Mukherjee (2022) used the algorithm in inventory management (e.g., the amount of goods within supply chains) for example to minimize overcapacity in takeover situations. In the realm of communication networks, Jha (2020) highlighted the algorithm's efficacy for optimal data flow in internet applications. Furthermore, innovative implementations within the field of neuromorphic computing were investigated as well by Kay (2021), who described the utilization of the algorithm to boost graphical processing within computer systems. Akter, D. U. (2021) : In this work, the authors adapted the Edmonds-Karp algorithm to solve dynamic network flows and observe the results obtained with real-time applications. This highlights the significance of dynamic adaptation in contemporary networks. When using a submodularity-based analysis, Fiandrino and Suriya opt for optimizing a facility location in dynamic flow networks (Fiandrino and Suriya 2023). It is also proving to be more efficient in terms of logistics and resource allocation.

Table 2 Practical applications and uses of the Ford-Fulkerson algorithm

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| --- | --- | --- | --- | --- |
| Author/Year | Application | Methodologies | Results/Contributions | Remarks |
| Mangata, B. B. (2022) | Traffic congestion analysis | Applying the algorithm to road networks | Reduced congestion and improved traffic flow | Urban road networks |
| Marpaung, F. A. (2023) | Transportation networks | Optimizing resource allocation | Improved efficiency and reduced costs | Focus on urban transport |
| Mukherjee, T. S. (2022) | Inventory management | Optimizing goods flow | Reduced inventory and increased operational efficiency | Logistics applications |
| Jha, R. (2020) | Communication networks | Algorithm comparison for data flow | Enhanced performance in data networks | Internet-focused applications |
| Kay, B. S. (2021) | Neuromorphic computing | Designing graphical algorithms | Improved neuromorphic computing efficiency | Innovative techniques |
| Akter, D. U. (2021) | Dynamic network flows | Modified Edmonds-Karp algorithm | Improved accuracy in real-time networks | Emphasis on dynamic environments |
| Suriya, P. S. (2023) | Facility location optimization | Submodularity-based analysis | Enhanced facility allocation in dynamic networks | Highly applicable in logistics |

**3.3. Comparison with Other Algorithms**

To see its strengths and weaknesses, the Ford-Fulkerson Algorithm has been compared with other maximum flow algorithms. Dumlao (2021) discusses its performance against the Edmonds-Karp algorithm and shows improvements in execution speed with Ford-Fulkerson whilst pointing out the extra resource overhead Edmonds-Karp incurs for larger networks. In his study (Jha, 2020) he stated that compared to Dinic and Edmonds-Karp, Ford-Fulkerson is simple to implement, but does not perform well in dense networks. This prompted Babeniuk (2021) to compare it with the more general approach of delay networks, within which Ford-Fulkerson had performed well, albeit with restrictions for practical applications. Prabhakara (2023) specifically studied its incorporation under cloud computing, i.e. modern techniques which can generalize its application and also find difficulty with the complexity of the system. Ugale, S. D. (2024): Deriving Max-Flow Min-Cut theorem for specific traffic scenarios, Education Infrastructure It shows how well the theorem works in focused, small-scale cases.

Table 3 Comparison between the Ford-Fulkerson algorithm and alternative algorithms

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| --- | --- | --- | --- | --- |
| Author/Year | Compared Algorithms | Strengths | Weaknesses | Remarks |
| Dumlao, M. F. (2021) | Edmonds-Karp | Improved execution speed | Requires additional resources | Suitable for large networks |
| Jha, R. (2020) | Dinic, Edmonds-Karp | Simplicity of implementation | Lower performance in dense networks | Small-scale networks |
| Babeniuk, G. (2021) | Delay Networks | Improved data flow efficiency | Limited real-world applications | Focus on temporal networks |
| Prabhakara, B. K. (2023) | Cloud computing dynamics | Integration with modern techniques | System complexity can be a barrier | Cloud-focused optimization |
| Ugale, S. D. (2024) | Max-Flow Min-Cut Theorem | Effective in specific traffic scenarios | Limited generalizability | Educational infrastructure focus |

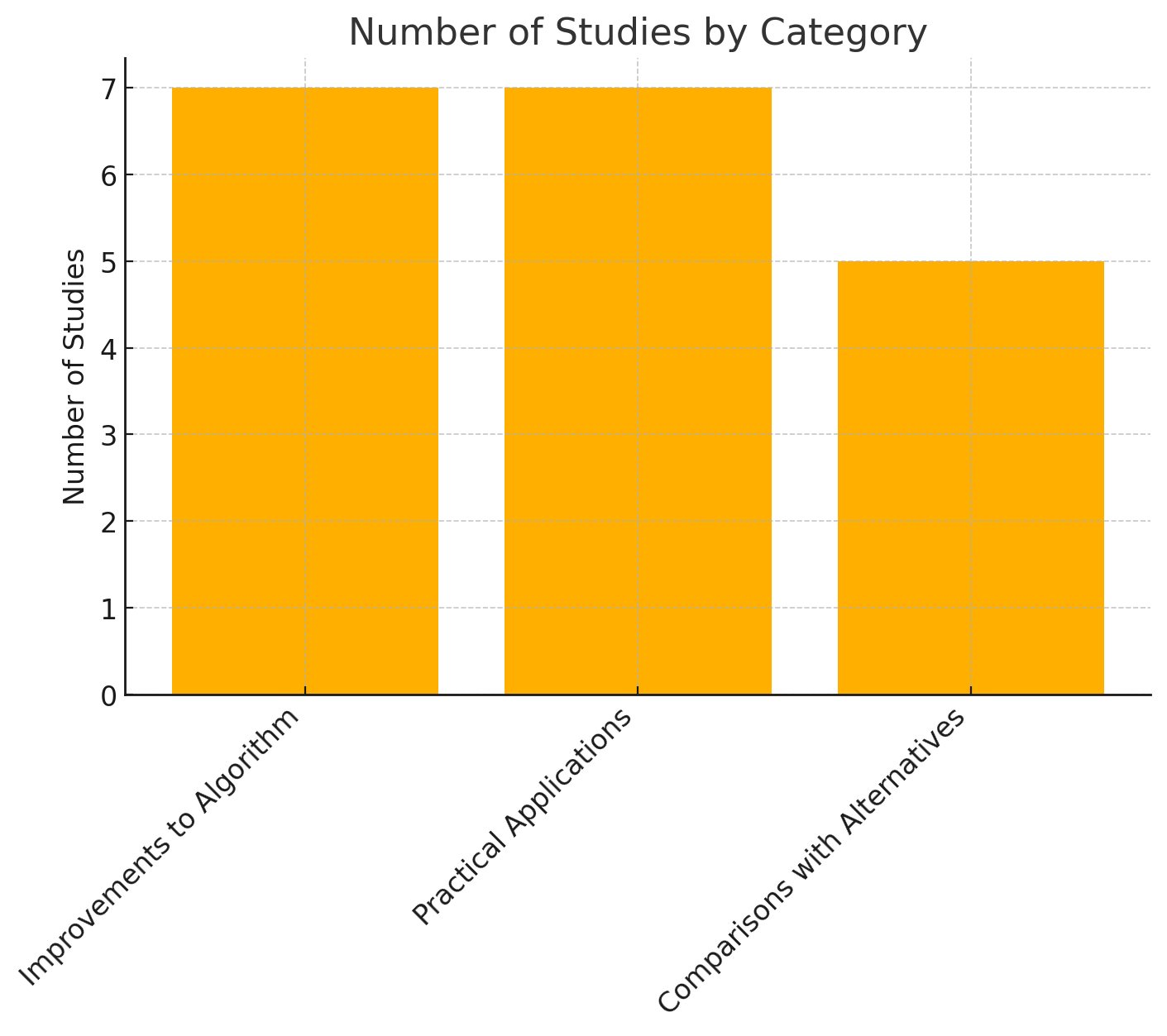
**4. Analysis and discussions of studies**

In fact, there are a number of intensive studies available in the literature focusing on possible optimizations of the Ford-Fulkerson algorithm to meet the demands of recent applications. From the table 1, Davies (2023) worked on the increasing execution time of the algorithm using predictions techniques that helped to find more adaptive incremental path, which triggered to lower execution time be required significantly on the dynamic applications that need high responsiveness. Kovalev (2021) was designed to provide better cooperation between lines of different densities by solving problems of the distribution of flows between the dense and low-density lines, which led to increasing the overall efficiency of the network. As a result, VIET (n.d. ) focused mainly on the use of deep-stream search (DFS) to boost the performance of the algorithm which resulted in a considerable reduction in computational complexity and was very helpful during cases with dynamic networks where there are constant changes in flow. For instance, Wada (2022) focused on enhancing visual tools for the analysis of flows in a network; it improved error reduction and accuracy of the analysis. Lastly, Hafermas (2023) emphasized on adopting parallel computer framework to minimize execution time, in turn to enhance the algorithm in managing large and complex networks, which is significant in systems where large amounts of data need to be processed within short timeframes.

As demonstrated in Table 1, the Ford-Fulkerson algorithm has been successfully utilized in numerous practical applications. The algorithm was used in Mangata (2022) to analyze traffic congestion in urban networks, where it contributes to improving vehicle flow and reducing bottlenecks. In the study by Marpaung (2023), the algorithm is used in transportation networks so that resource allocation is optimally distributed and can minimize costs and help increase logistics efficiency. Focusing on inventory management, Mukherjee (2022) demonstrated that application of the algorithm can lead to a reduction in excess inventory and improving flow of goods in supply chains, thus being an essential tool for businesses wanting to obtain greater efficiency in day-to-day operations. Jha (2020) applied the algorithm on communication networks that utilizes national and regional links on reducing delays and increasing resource utilization efficiency in networks through effective data flow. Lastly, Kay (2021) studied the application of the algorithm in neural computing to enhance the graph processing of neural systems indicating the potential of its application within contemporary systems like artificial intelligence.

Regarding comparison, Table III demonstrates the comparison with other algorithms, where Dumlao (2021) stated that Ford-Fulkerson was actually simple and fast in small networks, and when large networks are used, it has better performance because of its cross-sectional search (BFS) feature but the algorithm is resource-consuming. Jha (2020) demonstrates that the Dinic algorithm gives even better performance through multilevel search but it has a more complicated implementation than Ford-Fulkerson. Babeniuk (2021) demonstrated the effectiveness of Ford-Fulkerson in static networks, whereas it was observed that temporal networks allow for more adaptable solutions to time-varying flows.

Fig 1 Distribution of Studies by Min Stages: Improvements, Practical Applications, at Comparsns



Studies on Ford-Folkinson improvements show significant interest in optimizing its performance in line with the requirements of modern applications translated to a large number of studies in this category (7 studies). The improvements are aimed at improving algorithm execution execution speed and also improving computational efficiency and complexity for geographically information processing paths. This helps the algorithm be more dynamic in the context of applications and large networks, providing it with extensiveness and ensuring it becomes a great solution to even the most complicated problems.

The other is practicality–the same number of studies (7 studies) indicated, Therefore, it is common in various fields. It plays a very significant role in many fields such as the field of traffic management and some other fields that reflects positively on logistics networks as it contributes to improving the distribution of available resources, this also applies in the field of communications networks where the developed algorithms were a pivotal pivotal in enhancing the networks performance and the quality of data transmission. The real-world applications underline with the power of the algorithm to find solutions that are not only practical but also efficient and effective, making an essential tool across industries.

There were only a few studies (5 studies) reporting on comparison with alternatives this may either reflect a lower focus on comparison of the algorithm with other algorithms such as Denk and Edmonds-Karp. Nonetheless, these studies offer valuable understanding into the merits and downsides of the Ford-Folkinson algorithm when placed alongside its competitors, eg. ease of implementation versus poor performing in dense networks. Such comparisons provide guidance for researchers to get better and adopt features from other algorithms. In summary, the balance between improvements and application elucidates the fusion of theoretical derivative and practical applications, which enhances the algorithm's position as a general-purpose tool. Nevertheless, on the contrary, there was a low count of comparative studies, which might be suggestive of the efforts to examine algorithm relative strengths in comparison with other contexts, which can lead to the emergence of new methods with better extent of applicability across different contexts.

We can conclude that previous studies have mostly addressed with medical conditions in order to enhance time and accuracy of the algorithm's performance with the advent of modern computing to extend its domains of application. Although the flexibility of the proposed hybrid model for flow problems in different domains has been sufficiently demonstrated, it does require further refinement so that it can remain competitive with more complex algorithms.

**5. Challenges of the Ford-Fulkerson algorithm.**

Inefficiency in dense networks: Search and discovery of incremental paths is extremely slow in networks with many nodes and edges. This results in longer execution time, particularly if there are a number of potential paths from the source to target in the network. This gives rise to critical issues for applications that depend on large-scale networks including transportation and communication networks.

Poor performance with non-integer capacities: The algorithm performs poorly when capacities are not integers or take very small values. For such cases the algorithm may suffer from infinite iterations or may run too slow due to incremental updates of flow thus it becomes inefficient for some type of practical networks

This is not going to eliminate long-term performance dependence on incremental path selection. If you select paths with a large bottleneck, this could cause to repetition of steps, not achieving many of the steps.

Little Adaptation to Dynamic Networks: In dynamic networks, where capacitors or topology increase or change almost often, the Ford-Fulkerson mechanism is less simply because it has to be executed again from scratch for each replace. This makes it less than ideal for use cases where flow must be updated quickly in response to immediate events.

Challenge with parallel computing: The algorithm use serial execution which means it cannot utilize the parallel computing abilities of modern hardware. This poses a challenge because parallel computing is increasingly critical in enabling quick data processing in big networks, and this challenge acts as a roadblock in the use of these methods in specific applications.

Configuration and management of residual network: Each time after turning the RD, it is necessary to end up also updating the residual network, consuming additional time and resources. This problem becomes more pronounced and affects the efficiency of the algorithm in larger networks.

**6. Conclusion**

The Ford-Fulkerson algorithm is an important algorithm that solves the maximum flow problem in a given network. Its user-friendly structure and versatility are some features that provided satisfactory solutions to many practical problems like transportation systems, communication networks, and resource distribution. It is based on iteratively increasing paths to update the flow until the maximum possible flow exists through the source and to the target. Through the survey of the prior works, it is evident that the algorithm has seen considerable advancements for its performance enhancement as well as for its computational costs reduction. Such improvements include breadth-first search (BFS) as in the Edmonds-Karp algorithm, and some implementations make use of parallel computing to speed up the implementation, mostly in rather large networks. Nevertheless, there are still some shortcomings of the algorithm: lacking detection ability for dense networks, difficulty in dealing with decimal capacity and heavy dependence on path selection strategy. The practical implementations of the algorithm are promising, as it has been applied to optimize the flow of vehicles in road networks, the flow of data in communication networks, and the flow of goods in supply chains. The application of the algorithm with these modern technologies like AI and cloud computing is minuscule, and more research in this field is highly recommended.

**Disclaimer (Artificial intelligence)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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