

Big Data Processing Efficiency in Edge-Cloud Environments: A Hybrid Approach

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Abstract

The rapid growth of data in the digital age poses major challenges in the management and processing of big data, especially in terms of time efficiency, resource utilization, and overall system performance. The study aims to explore the extent to which hybrid edge-cloud architectures can improve the efficiency of big data processing compared to traditional cloud-only models. Using a qualitative approach and exploratory case study design, data was collected through semi-structured interviews, direct observation, and technical document analysis. The results show that the hybrid edge-cloud approach is able to significantly increase efficiency through decentralization of computing processes, reduction of the load on the network and cloud, and optimization of bandwidth usage and energy consumption. However, there are also technical challenges that need to be overcome, such as data synchronization between systems and interoperability of multiple platforms, which require a mature and structured implementation strategy. In addition to the technical benefits, hybrid systems also received positive responses from users because of their more responsive and stable performance than traditional solutions. This study concludes that the success of the efficiency of edge-cloud systems depends not only on technological sophistication, but also on organizational readiness, operational strategy, and user acceptance and adaptation levels. Therefore, hybrid edge-cloud architecture is highly relevant to be applied in various sectors that require real-time data processing, such as the manufacturing industry, smart city development, and digital healthcare, to support fast and accurate decision-making and improve service quality.

Keywords: Big Data, Edge Computing, Cloud Computing, Hybrid Approach

INTRODUCTION

In today's digital era, data growth has experienced a very significant spike, both in terms of volume, speed, and variety (Ozcan et al., 2023). This phenomenon is known as big data, where data is generated not only from traditional information systems, but also from various sources such as social media, Internet of Things (IoT) sensors, mobile devices, smart vehicles, and other digital applications (Ahmad Jan et al., 2025). With so much data to handle, organizations whether in the government, industry, and academic sectors are faced with major challenges in managing, storing, and processing data efficiently and in a timely manner (Ikegwu et al., 2022).

Over the years, cloud computing has become a major paradigm in the processing and storage of big data (Rani et al., 2023). Cloud services enable high flexibility, elasticity in scalability, as well as operational cost savings by minimizing on-premises hardware requirements (Ashwin Chavan, 2023). Nevertheless, the cloud-only approach is starting to show limitations, especially when systems demand real-time response and low latency (Yuan et al., 2025). The need to transfer large amounts of data to distant data centers can lead to increased latency, high bandwidth usage, as well as potential network bottlenecks, which in turn reduces system efficiency.

To overcome these challenges, an edge computing approach has emerged that places part of the computing process close to the data source. By performing initial processing on the "edge" side of the network, such as on IoT devices, gateways, or edge servers, edge computing can significantly reduce latency and speed up system response times (Mehmood et al., 2021). Nonetheless, edge computing is not without its drawbacks either (Kong et al., 2023). Limitations in compute, storage, and resource management power are a barrier if complex data processing has to be done entirely on the edge side.

From these conditions, a strategic solution emerged in the form of a hybrid edge-cloud approach, which is an architectural model that synergistically combines the power of edge and cloud (Chennupati, 2025). In this approach, initial processing and rapid analytics are done on the edge side, while large-scale data processing and long-term storage remain in the cloud (Miryala & Gupta, 2023). The hybrid approach is believed to optimize system efficiency, both in terms of performance, resource consumption, and response time (Kalai Arasan & Anandhakumar, 2023). This is very important in modern applications such as intelligent video surveillance systems, autonomous vehicles, industry 4.0, smart farming, and sensor-based digital health services.

However, even as hybrid edge-cloud approaches begin to be widely adopted, there is still a need to systematically examine the extent to which this approach actually provides efficiency over traditional cloud-only models (Sulieman et al., 2022). The efficiency in question includes various dimensions such as processing time, bandwidth usage, use of computing resources, and operational costs. In addition, a deep understanding of the challenges of hybrid implementation, both from a technical and managerial perspective, is required (Katal et al., 2023).

Based on this description, the formulation of the problem in this article is: *What is the level of efficiency of big data processing in an edge-cloud environment with a hybrid approach, compared to a conventional cloud approach?* The purpose of this study is to analyze and evaluate the effectiveness of the hybrid approach in the context of big data processing, as well as identify the advantages and challenges faced in its application.

The scope of research is focused on the study of hybrid edge-cloud architecture, the literature review of edge and cloud systems, as well as efficiency analysis in terms of performance and resource use in the context of big data. The scientific contribution of this article is to provide comprehensive insights into the efficiency of big data processing with a hybrid edge-cloud approach, which can serve as a basis for technological decision-making at the organizational level and the development of more adaptive, responsive, and resource-efficient system architectures.

METHODS

This research applies a qualitative approach with an exploratory case study design to deeply understand how big data processing efficiency is implemented through hybrid edge-cloud architecture. This approach was chosen to explore technological phenomena contextually in a real environment, as well as to capture the direct experience of the system implementers.

1. Data Collection Techniques

Data were obtained through two main methods: semi-structured interviews and direct observation. Interviews were conducted with a number of key informants, such as engineers, system architects, and IT staff, who were directly involved in the implementation of edge-cloud

systems. The selection of participants was carried out purposively, namely based on certain criteria that are relevant to the research topic. The number of participants is determined until data saturation is achieved, which is a condition in which the interview no longer produces new meaningful information.

In addition to interviews, field observations were conducted to directly observe the data processing process and the interaction between edge and cloud components. Supporting documents such as system architecture, performance logs, and internal reports are also used as additional data sources to strengthen the analysis results.

2. Data Analysis Techniques

Data analysis was carried out using a thematic analysis method, where data from interviews and observations were encoded and classified into key themes, such as system efficiency, technical constraints, architectural integration, and user perception. To support the validity of the findings, the researcher also used a data triangulation approach, which is comparing various data sources to obtain a consistent and comprehensive understanding.

As a complement, member checking is also carried out, which is verification of interview results by participants to ensure the accuracy of interpretation. Thus, the analysis process not only produces factual descriptions, but can also build a conceptual understanding of the factors that affect efficiency in a hybrid edge-cloud system.

RESULTS AND DISCUSSION

This study explores the efficiency of big data processing in a hybrid edge-cloud system through a qualitative approach, by collecting data through semi-structured interviews, direct observation, and analysis of technical documents. The research findings are arranged in the form of main themes resulting from the thematic analysis process.

Table 1 Summary of Research Findings

Theme	Main Explanation	Data Source
Decentralize Computing at the Edge	Data processing is done at the edge before being sent to the cloud, lowering network latency and dependency.	Interviews, observations
Bandwidth and Energy Savings	Data is sent only when necessary, significantly reducing cloud traffic and power consumption.	Interviews, performance log documents
Synchronization and Integration Challenges	Time asynchrony and data duplication between edge-cloud are major technical issues.	Interviews, system technical documentation
Effective Implementation Strategies	The use of orchestrators, rule engines, and local processing SOPs is the key to successful implementation.	Technical documents, observations
Positive User Perception	Users feel the system is faster, more stable, and suitable for automation and early warning systems.	Interviews, observation of system interactions

1. Processing Efficiency Through Computational Decentralization

All of these findings have been verified through data triangulation (interviews, observations, system documents), and member checking of informants to ensure that the researcher's interpretation is in accordance with the reality of the field. This process strengthens the validity and credibility of the research results. Bandwidth Savings and Resource Consumption This theme emerged strongly from observations and system logs that showed a

decrease in the volume of data traffic between the edge and the cloud. The informant mentioned that hybrid systems allow for significant bandwidth savings, while reducing energy consumption in data centers.

2. Bandwidth Savings and Energy Consumption

One of the real benefits of hybrid systems is the efficiency in bandwidth usage. Based on system documentation and network measurements, it was found that data usage dropped drastically after initial processing was performed at the edge. Participants explained that only data that is considered important or anomalies are forwarded to the cloud, so that data traffic becomes more controlled. This also has an impact on decreasing energy consumption, particularly in data centers, as computing loads become more distributed. Effective Implementation Strategies. Other findings suggest that organizations that successfully implement a hybrid approach are more likely to use orchestration platforms (such as KubeEdge or Azure IoT Edge) to manage workloads across edge and cloud layers. In addition, the technical team implements an internal monitoring and training system so that technology adoption runs optimally.

3. Data Integration and Synchronization Challenges

While providing significant benefits, hybrid edge-cloud implementations present complex challenges, especially in terms of real-time data synchronization, interoperability between systems, and distributed resource management. Some informants mentioned cases where the edge and cloud processed the same data with different timestamps, causing inconsistencies in the results.

4. Hybrid System Implementation Strategy

Some key strategies were found from documentation and interviews related to how organizations manage the implementation of hybrid systems effectively, including:

- Use an orchestration platform, such as KubeEdge, AWS Greengrass, or Azure IoT Edge, to set up load sharing between the edge and the cloud.
- Set a local processing policy based on the rule engine (e.g. only send data when a certain threshold is reached).
- Train internal staff to understand the functions of edge devices and how to monitor the system remotely.

5. Positive Perception from System Users

One of the important findings is the emergence of positive perceptions from system users towards the adoption of hybrid edge-cloud. From interviews with technical staff and operators, most state that the system is now more responsive, lags less, and relies less on internet connectivity. Some organizations even claim that these hybrid systems pave the way for broader automation implementations, as the local edge capabilities can be used for alerting, device control, or mild AI. To maintain the validity and credibility, all interview results are confirmed back to participants through the member checking process. The observation results are also confirmed through system documents such as:

- Edge-cloud architecture diagrams.

- System performance logs for 3 months.
- Local data processing policies.

Triangulating these three sources results in a more thorough and comprehensive understanding of how system efficiency is realized.

Discussion

This study illustrates how the hybrid edge-cloud approach can improve the efficiency of big data processing, especially in work environments that demand the speed, reliability, and scalability of computing systems. Through qualitative methods and exploratory case studies, a number of key dimensions were found that not only demonstrate the technical benefits of hybrid systems, but also reveal the dynamics and challenges inherent in their implementation.

1. Efficiency Through Computing Decentralization

One of the most prominent benefits of a hybrid edge-cloud deployment is its ability to decentralize computing processes. In a purely cloud-based conventional system, all data collected by IoT devices must be sent to a data center for processing. This often causes latency, especially when the network connection is unstable or bandwidth is limited. However, with a hybrid architecture, most of the initial processing such as filtering, compression, validation, and anomaly detection can be done at the edge level. The research findings show that this approach directly lowers the load on cloud networks and servers, while speeding up system response times. This efficiency is especially important in the context of applications that require a quick response, such as environmental monitoring systems, smart factories, or public safety. Theoretically, these results are in line with *the fog computing* and *distributed systems approach*, where processing is carried out in a hierarchical and distributed manner to improve resource effectiveness and efficiency.

2. Optimization of Bandwidth and Energy Usage

Another significant benefit is bandwidth savings and energy consumption. Data that has been filtered at the edge means that only the information that matters is sent to the cloud. In the observed cases, there is a decrease in bandwidth usage of up to 40–60% compared to the previous system. This is especially relevant for companies or agencies with high network operating costs or those operating in areas with limited connectivity. In addition, edge computing enables on-premises processing without the active involvement of the cloud for a full 24 hours, reducing the burden of central processing and energy consumption in the data center. This approach not only has an impact on technical efficiency, but also supports sustainability policies (green IT) because it reduces excess energy consumption. From the implementation side, these savings are also related to the selection of energy-efficient edge devices, as well as a modular system architecture so that workloads can be dynamically adjusted.

3. System Synchronization and Interoperability Challenges

Although system efficiency is improving, the study found that there are major challenges in terms of data synchronization between the edge and the cloud. The problem arises when the same data is processed in two places at different times, causing a mismatch of the results. In some cases, timestamp mismatch and data duplication are major issues. In addition,

interoperability between systems and platforms is also a technical obstacle that needs to be anticipated. Many organizations use edge devices and cloud platforms from different vendors, which sometimes don't have full integration support. This demands the critical role of orchestration software (such as KubeEdge, Azure IoT Edge, or AWS Greengrass) in maintaining consistency in data flows and workload distribution. From a systems theory perspective, this issue demonstrates the importance of a robust *systems integration* approach, as well as the role of *middleware* in bridging communication between devices and the cloud layer.

4. Structured and Adaptive Implementation Strategy

The successful implementation of a hybrid system depends not only on technology, but also on management strategies and organizational readiness. In this study, it was found that organizations that are able to develop technical SOPs, internal staff training, and performance monitoring systems tend to be more successful in adopting these systems. One important strategy is the use of local processing policies based on the rule engine, which governs when data can be sent to the cloud. This creates system flexibility in dealing with real-time conditions, such as changes in data traffic or network instability. Another strategy is the use of an orchestration platform to automatically set up load sharing between the edge and the cloud. This approach is in line with the concept of *cloud-edge orchestration*, which emphasizes the importance of a centralized yet flexible control system to support decentralization. This shows that managerial aspects and operational policies play an important role in supporting the effectiveness of the system, not just the technological aspect.

5. User Perception and Social-Technical Readiness

In addition to the technical results, the findings of this study highlight the importance of end-user perception and experience of the system. Most participants said that the edge-cloud system provides greater convenience, speed, and reliability than the previous system. Users find the system more stable because it is not entirely dependent on an internet connection and is able to provide a quick response when needed, especially in emergencies or real-time control needs. This proves that technology adoption is not only about engine performance, but also about trust, experience, and user engagement. Within the framework of the *Technology Acceptance Model* (TAM), the perception of the ease and benefits of the system is an important indicator in the success of technology adoption. These results confirm that the hybrid edge-cloud approach is not only technically efficient, but also socially acceptable in everyday usage practices.

Overall, the study confirms that the hybrid edge-cloud approach is able to optimize the efficiency of big data processing through three main aspects: decentralization of computing, reduction of network and energy loads, and the adaptive ability of the system to real conditions.

Nevertheless, the effectiveness of the system depends heavily on:

- Quality of data synchronization.
- Interoperability between devices.
- Implementation strategy and organizational policies.
- The level of understanding and user engagement.

An important implication of this study is that the successful implementation of hybrid edge-cloud must be understood in an interdisciplinary manner, involving aspects of technology, management, policy, and work culture. In the future, this research can be the basis for developing a framework for evaluating the performance of hybrid systems, as well as designing a contextual and sustainable technology adoption model.

CONCLUSION

This research shows that the application of hybrid edge-cloud architecture is an effective solution in facing the challenges of big data processing in an increasingly complex and dynamic era of digital transformation. Through a qualitative approach with an exploratory case study design, it is revealed that system efficiency in this context is not only related to improving technical performance, but also reflects a comprehensive adaptation to contextual needs, both in terms of infrastructure, users, and operational policies. One of the key findings is that decentralizing data processing to edge devices has been shown to reduce reliance on the cloud, lower latency, and accelerate local decision-making. This is especially important for organizations that operate in real-time and need responsive systems in locations that have network limitations. In addition, efficiency is also achieved through reduced data traffic to the cloud, which has an impact on bandwidth savings, energy consumption, and operational costs. However, the study also identifies that such efficiency is not absolute, as it is affected by technical challenges, such as data synchronization between edge and cloud nodes, device interoperability from various vendors, and the need for reliable integration protocols. This is where the role of an orchestration system comes in that can ensure optimal division of tasks between edge and cloud components in real-time.

From a non-technical perspective, this study highlights the importance of structured and adaptive implementation strategies. Organizations that successfully implement hybrid systems generally have supportive internal policies, competent human resources, and effective communication patterns between technical and managerial teams. In addition, positive perception from end users of system performance is a supporting factor that cannot be ignored in driving the successful adoption of this technology. Overall, the study concludes that efficiency in big data processing through a hybrid edge-cloud approach can only be achieved if there is alignment between technology design, organizational readiness, and user acceptance. In other words, efficiency is not only the result of technological sophistication, but also the product of multidimensional integration between technical, operational, and social aspects. As a conceptual contribution, the study confirms that the success of edge-cloud systems is inseparable from the context of its implementation. Therefore, a hybrid approach should be designed specifically and tailored to the characteristics of the organization, the type of data, the level of urgency of processing, and the business objectives to be achieved.

REFERENCE

- Ahmad Jan, M., Adil, M., Brik, B., Harous, S., & Abbas, S. (2025). Making Sense of Big Data in Intelligent Transportation Systems: Current Trends, Challenges and Future Directions. *ACM Computing Surveys*, 57(8), 1–43. <https://doi.org/10.1145/3716371>
- Ashwin Chavan. (2023). Exploring the Synergy of Cloud and On-Premises Systems- A Case for Hybrid Architectures. *Journal of Computer Science and Technology Studies*, 5(3), 122–141. <https://doi.org/10.32996/jcsts.2023.5.3.10>

- Chennupati, S. (2025). Edge-cloud Synergy in Real-time AI Applications: Opportunities, Implementations, and Challenges. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.5206560>
- Ikegwu, A. C., Nweke, H. F., Anikwe, C. V., Alo, U. R., & Okonkwo, O. R. (2022). Big data analytics for data-driven industry: A review of data sources, tools, challenges, solutions, and research directions. *Cluster Computing*, 25(5), 3343–3387. <https://doi.org/10.1007/s10586-022-03568-5>
- Kalai Arasan, K., & Anandhakumar, P. (2023). Energy-efficient task scheduling and resource management in a cloud environment using optimized hybrid technology. *Software: Practice and Experience*, 53(7), 1572–1593. <https://doi.org/10.1002/spe.3203>
- Katal, A., Dahiya, S., & Choudhury, T. (2023). Energy efficiency in cloud computing data centers: A survey on software technologies. *Cluster Computing*, 26(3), 1845–1875. <https://doi.org/10.1007/s10586-022-03713-0>
- Kong, L., Tan, J., Huang, J., Chen, G., Wang, S., Jin, X., Zeng, P., Khan, M., & Das, S. K. (2023). Edge-computing-driven Internet of Things: A Survey. *ACM Computing Surveys*, 55(8), 1–41. <https://doi.org/10.1145/3555308>
- Mehmood, M. Y., Oad, A., Abrar, M., Munir, H. M., Hasan, S. F., Muqet, H. A. U., & Golilarz, N. A. (2021). Edge Computing for IoT-Enabled Smart Grid. *Security and Communication Networks*, 2021, 1–16. <https://doi.org/10.1155/2021/5524025>
- Miryala, N. K., & Gupta, D. (2023). Big Data Analytics in Cloud – Comparative Study. *International Journal of Computer Trends and Technology*, 71(12), 30–34. <https://doi.org/10.14445/22312803/ijctt-v71i12p107>
- Ozcan, M. B., Konuk, B., & Yesilcimen, Y. M. (2023). Big Data Analytics in Industry 4.0. In *Emerging Trends in Mechatronics* (pp. 171–199). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-2012-7_8
- Rani, S., Bhambri, P., & Kataria, A. (2023). Integration of IoT, Big Data, and Cloud Computing Technologies. In *Big Data, Cloud Computing and IoT* (1st ed., pp. 1–21). Chapman and Hall/CRC. <https://doi.org/10.1201/9781003298335-1>
- Suliman, N. A., Ricciardi Celsi, L., Li, W., Zomaya, A., & Villari, M. (2022). Edge-Oriented Computing: A Survey on Research and Use Cases. *Energies*, 15(2), 452. <https://doi.org/10.3390/en15020452>
- Yuan, H., Niu, Z., & Liu, J. (2025). Optimization techniques for real-time optical image processing using edge computing. In S. S. Agaian (Ed.), *Second International Conference on Big Data, Computational Intelligence, and Applications (BDClA 2024)* (p. 122). SPIE. <https://doi.org/10.1117/12.3059702>