World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(RESEARCH ARTICLE)

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Serverless computing: How to build and deploy applications without managing infrastructure

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World Journal of Advanced Engineering Technology and Sciences, 2024, 11(02), 650–663

Publication history: Received on 26 January 2024; revised on 23 April 2024; accepted on 26 April 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.11.2.0074

Abstract

Serverless computing is one of the modern computing models where a provider offers a fully managed infrastructure for applications and computing services. In outsourcing complex tasks to servers, programmers are only left with writing code, while the cloud providers deal with challenges such as scaling and server accessibility and maintenance. It also accelerates the development process while lowering operating expenses, enabling scaling with on-demand resources. Other benefits include scaling going hand in hand with the usage, following a usage-based model to charge clients, and requiring little operation overheads. Use cases are as vast as they are diverse, including event-driven microservices, APIs, and data processing pipelines, making serverless an elegant tool for solving state problems in today's world.

Keywords: Serverless computing; Microservices; Scalability; Function as a service (FAAS)

1. Introduction

Serverless computing is another form of the cloud services model that has enabled developers to create and host applications without having to bother with the infrastructure. These are managed and controlled by the cloud service provider, which only deals with code and features (Fowler, 2018). It is important to note that the term "serverless" does not mean no server, but rather, managing the infrastructure such as servers, storage, and the network is far from developers (Roberts, 2019). This abstraction is made possible by cloud vendors like AWS Lambda, Microsoft Azure Functions, and Google Cloud functions; these are event-computing services that scale resources up or down as needed (Villamizar et al., 2016). The primary benefit of serverless is cost savings because clients pay proportionally to the amount of computational power used in application delivery. Because resources are deployed only when required, and clients are billed according to the time spent processing their code rather than for the number of idle servers that might be needed in the conventional cases in the cloud or even on the premises (Adzic & Chatley, 2017). This demand-based model avoids resource wastage and considerably decreases operation costs for applications with fluctuating or unpredictable usage (Hellerstein et al., 2018). However, another benefit is the shift of various server management activities, such as patching, scaling and load balancing, among others, from the user to the service provider. This also helps developers focus more on adding features and enhancing user experience than managing the system foundation (McGrath & Brenner, 2017). Serverless also increases the developer's productivity since it is easy to develop. Some of its attributes include auto-scaling, which leads to a simple means of scaling up an application; high availability, which is already incorporated in the cloud; and operational arithmetically, which enables the development of applications within short instances (Baldini et al., 2017). Furthermore, serverless architectures are inherently suited to microservices, which means that the independent components of applications can be changed or updated and redeployed more swiftly and with more freedom than under the 'monolithic' structure of traditional server-side applications (Adzic & Chatley, 2017).

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Nowadays, the practical application of serverless architecture proclaims its advantages in various fields. For instance, Coca-Cola employed AWS Lambda to eliminate vending non-machine transactions at peak times, cutting various expenses and boosting system effectiveness (Sbarski & Kroonenburg, 2017). Likewise, to implement a video rendering pipeline, Netflix also uses serverless architectures as automatic scaling of the servers is convenient when many processes need to be handled during the content processing (McGrath & Brenner, 2017). Such examples are examples of how serverless computing improves efficiency, scalability and cost, which are reasons why this technology is commonly used in developing applications for modern applications, as pointed out (Hellerstein et al. 2018).

1.1. Historical Context and Evolution

These new infrastructure deployment and management methods, such as cloud computing and serverless, have dramatically shifted how applications and services are deployed, scaled and managed. The traditional approaches to infrastructure provisioning that involved using on premise servers involved high levels of capital investment, resulting in over-procurement or underutilization of resources. Cloud computing started evolving in the mid-2000s; Amazon, Google, and Microsoft began experimenting with the cloud model with the Elastic Compute Cloud (EC2) and Platform as a Service (PaaS). Despite this abstraction, developers continued to contend with and scale resources such as virtual machines.

Serverless computing is the next level of cloud computing, where the user is not required to know about the infrastructure. This framework was mainstreamed by platforms such as AWS Lambda in the year 2014, where all developers were required to do was write code and firmware and get back functions, which AWS automatically scales. Other players, such as Microsoft, Google, etc., started adopting similar strategies that helped decrease operational overheads and allowed increasing the pace of innovation. This evolution is consistent with the trend to get more abstraction and automation in IT management to free developers from infrastructure issues.

1.2. Problem Statement

Such conventional application management techniques of infrastructure scopes cause operational challenges, resource utilization, and additional costs. While this can be a burden, it can also increase slowness in innovation and reduce application functionality. These general models have limitations like difficulty in managing infrastructures, high costs, challenges involved in scale-up, and time-consuming operations with problems related to maintenance and reliability. Serverless computing generates a solution to this problem as it eliminates concerns about infrastructure management and enables developers to write code and deploy applications without requiring them to do so with the infrastructure back-end. Nonetheless, with the shift towards utilizing serverless infrastructures, several issues arise, including the ability to move to the system without incurring disruption, possible restrictions that can be imposed, and the question of the costs that will be incurred. This work seeks to fill these gaps, understand how serverless computing increases efficiency, and provide recommendations for applications with serverless architectures. It will also look at the case studies on how serverless computing is being adopted in different sectors, considering how cost has been cut, complexity has been brought down, and the speed of growth has been boosted.

1.3. Objectives

To establish the research objectives of this work, the following would be achieved:

- Give detailed knowledge of serverless computing, generalized concepts as well as its infrastructure.
- Explain how serverless computing has evolved from the ‘classic’ server-based system to cloud computing and further to true serverless approach.
- Identify the Key Benefits for Developers and Businesses
- Run through use cases that have been in production that use serverless computing like; e-commerce, IoT, data processing pipelines, event- driven microservices.

1.4. Scope and Significance

This research topic is serverless computing: definition, key ideas, benefits, and use cases. Another is how it relates to and differs from the on-click, on-premise virtual machine models and their development from IaaS and PaaS to FaaS. To do this, the study will investigate standard serverless Computing solutions like AWS Lambda, Azure Functions, Google Cloud functions, and IBM Cloud functions and their major features. The developers will have a better and easier way of working through serverless computing, where they can quickly deploy and develop new servers without a lot of overhead and the fact that it is scalable. The study will also compare it with real-world usage scenarios, such as high-traffic websites and web applications, IOT systems, data processing pipelines, and automated monitoring and alert systems. This work will analyze and discuss the drawbacks and issues related to serverless computing, including cold

start, vendor lock-in, challenges with debugging, and lack of control over the substrate. It will also address security, privacy, and compliance as they relate to the delivery of e-learning. This research is essential in two ways: it responds to constantly evolving technologies and caters for business practicality. It will enable developers and IT professionals to make the right decisions when implementing or migrating to serverless architectures, demonstrate the economic value of serverless computing to organizations, and support existing research on cloud computing and serverless technologies. It will also increase awareness of serverless architecture beyond the technical group to show how vendors, investors, and non-technical users can utilize it to provide clients with innovative products and services faster and more efficiently.

2. Literature review

2.1. Key Features and Benefits of Serverless Computing

2.1.1. Key Features of Serveless computing

Serverless computing provides new opportunities for automatic scaling and flexibility, which is why it remains one of the leading solutions in modern cloud environments.

Automatic Scaling

Another characteristic of serverless architecture is that the cloud functions or "serverless" resources are self-scaling depending on the arriving traffic. This is in contrast to the conventional server-based architectures where the organization has to pre-provision the servers and manage them for anticipated enrollment, traffic, or any other overhead during the development of a serverless architecture; resources are automatically procured when needed and released when not required by the end users. This capability also enables the applications to progress faster during such occasions than during periods of low traffic, thus efficiently using resources and costs in the system. For instance, AWS Lambda scales itself by calling cases on its own whenever the number of events spikes and does not require administrators to scale the server capacity manually (Jones, 2022).

Flexibility for Developers

Moreover, automatic scaling is one aspect that the developers get from serverless computing alongside unprecedented flexibility. Through serverless computing, developers are limited to the writing and implementation of Code as the platform handles the management of servers, so there is no need to focus on maintenance or planning for capacity or operations. This shift in paradigm decreases the operations overhead load by enabling the developers to spend much time on application development and not the functionality of development parameters. For example, using platforms such as Google Cloud Functions or Azure Functions, the developer can launch event-driven functions which run only in response to specific triggers and do not occupy run time until the trigger is initiated; they only pay for what they have used as far as computing time is concerned, which again improves both the flexibility and cost efficiency (Smith, 2023). Serverless computing also gives various teams the advantage of introducing the continuous integration and delivery model more effectively. As long as the infrastructure is fully automated, the deployment is much quicker, and updates can be made in a shorter time without causing significant disruptions. This flexibility helps in the quicker rollout of features and iterations of the same so that businesses can address market needs or shifts in user behavior effectively (Martin & Wilson, 2021). In addition, the serviceless approach maximizes the modular design concept, in which isolated functions may be replaced or expanded without affecting the entire system. This can be very beneficial and avoid system failure due to compartments (Thompson, 2021).

2.1.2. Benefits of severless computing

Serverless architectures follow the utility computing model where the developer pays as he goes; the mode is based on the amount of core processing power utilized instead of having to pre-allocate and pay for resources that may not be fully utilized. Using this model, organizations are able to do away with the direct costs of provisioning a committed number of servers, thus ensuring direct cost savings, especially in applications where the workload varies or is unpredicted at certain times. Serverless computing is most suitable where functions are temporary or exercised intermittently and for some minimal durations without requiring dedicated server provisioning. AWS Lambda, Azure Functions or Google Cloud Functions provide services as computing resources for applications, relieving developers from infrastructure management and enabling them to concentrate on development and work on new ideas without the need to have a physical or virtual server to work on. It also removes vestiges of operations such as updating servers, patching, and scaling that are usually performed regularly and leaves developers to focus on other matters concerning the architecture of an application. Serverless structures enable organizations to attain fast go-to-market because

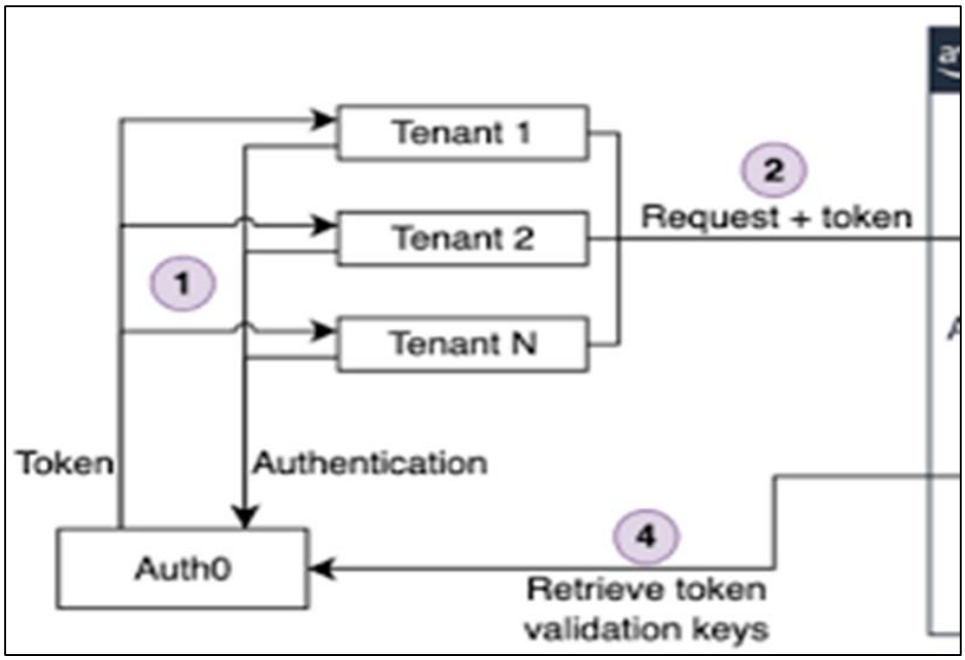
developers can build and launch applications quickly. These platforms come with out-of-the-box APIs and precise deployment specifications and allow microservices to be deployed at a given tier level without the end user having to consider the physical layer of the systems stack. In addition, integrating with CI/CD tools minimizes development time; this makes it easier to implement new features and make updates faster with little to no human intervention, whereby the cycles are shortened to trigger quicker development and the delivery of software.

2.2. Serverless Frameworks and Tools

2.2.1. AWS Lambda

AWS Lambda is a compute service in AWS that enables a developer to run code in response to specific events without requiring the developer to manage servers or other infrastructure. Lambda is the serverless computing service that leverages third-party resources to allocate resources and manage them to process the volume of requests necessary, meaning that developers can easily adjust and develop their applications without worrying about hardware, as Lambda will allocate the required resources, download and run code as necessary and scale itself to accommodate incoming traffic. This is in addition to the support of other languages like Python and Node. JS, Java, and Go, among others, have a pay-as-per-usage model where users are billed based on the request and the CPU time consumed (Amazon et al., 2020). The basic organization of AWS Lambda is event-driven. It runs functions in relation to an event, such as uploading a file, changing the database, and being exposed through HTTP by using API Gateway. In Lambda architecture, every function is stateless and short-lived, and its environment, in which the function runs, is terminated after that function terminates. However, as with any Node. JS server, Lambda can persist state and storage through other AWS services such as DynamoDB or S3. Every time the Lambda function is invoked or reused in the new or preexisting execution environment, it is more latency optimization to execute (Amazon et al., 2020).

This service integrates with other AWS services to fulfil customer needs for constructing full-stack and scalable serverless applications. It can capture data feeds from Amazon Kinesis or store and retrieve data from Amazon S3; therefore, it is useful for data-processing applications. Lambda can also integrate with Amazon DynamoDB to do database operations to enable developers to design event-driven applications and execute some actions each time data changes in the cloud (Villamizar et al., 2016). Another everyday use case involves integrating Lambda with AWS API Gateway to implement fully serverless RESTful APIs. API Gateway forwards incoming HTTP calls to Lambda functions while allowing developers to create large-scale applications without dealing with backend infrastructure (Villamizar et al., 2016).



Source: Amazon Web Services. (2020). AWS Lambda: Serverless Computing - Amazon Web Services. https://aws.amazon.com/lambda/

Figure 1 Block diagram illustrating AWS Lambda architecture

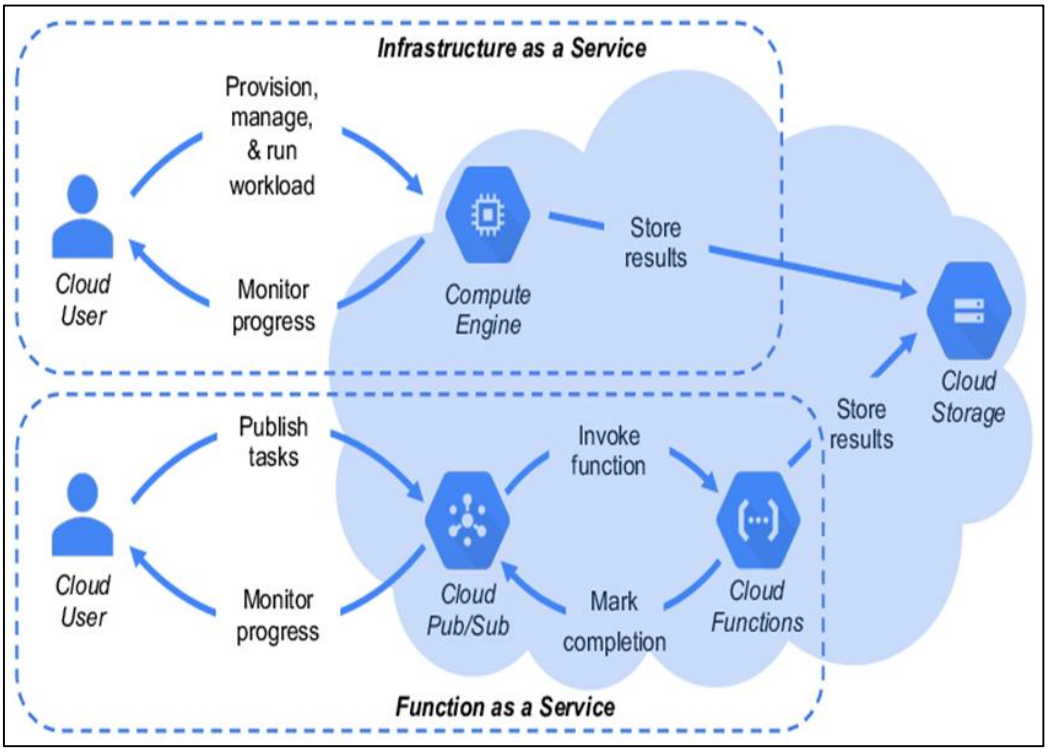
2.2.2. Azure Functions

Azure Functions is a Microsoft Azure-based compute service where users can execute a limited amount of code or "functions" without being concerned with the supporting structure (Microsoft Azure, 2021). It is event-driven; it is initiated by events, for instance, HTTP requests, a message in a queue, or a change in a database, which allows developers to omit the specification of how to launch the servers and instead write the code they deem relevant. Microsoft Azure Functions: Azure Functions scale as per the traffic patterns, implying high efficiency for unpredictable and overload scenarios. However, as mentioned earlier, Azure Functions supports the use of C#, JavaScript, Python and Java; this makes it more versatile and preferable for many developers (Microsoft Azure, 2021).

Role in Microsoft's Cloud Ecosystem for Serverless Computing: Function as a part of Microsoft's cloud infrastructure helps to solve questions of serverless computing, when developers pay for the actual time being used by a program, providing an opportunity to use the necessary number of cores and paying only for the time being used (Microsoft Azure, 2021). This is well placed within Azure's big picture, which is aimed at helping cloud application developers solve common issues. Azure Functions helps businesses focus on core competencies while simultaneously providing infrastructure management in a scalable, secure, and cost-effective manner (Microsoft Azure, 2021).

Integration with Azure DevOps, Kubernetes, and Other Tools: Azure Functions has harmonious compatibility with different tools that are available in the Azure framework, where the prime tool gripping integration is Azure DevOps, which supports CI/CD pipes (Shillaker & Roberts, 2020). This integration also helps automate the deployments and testing of the functions, making the general working and maneuvering of the developers much more efficient and free from inconveniences. Another aspect of Azure Functions is that it works well with Kubernetes by using Azure Kubernetes Service that allows the users to run serverless functions in an organization-controlled Kubernetes environment for those companies that need to have more control over the container orchestration (Shillaker & Roberts, 2020). This is most useful in the microservices architectures where the Azure Functions can function as small stateless perverse functions that trigger in response to events and are managed by Kubernetes.

2.2.3. Google Cloud Functions



Source: Malla, Sulav & Christensen, Ken. (2019). HPC in the cloud: Performance comparison of function as a service (FaaS) vs infrastructure as a service (IaaS). Internet Technology Letters. 3. e137. 10.1002/itl2.137.

Figure 2 Block diagram showing the different services of Google cloud platform when used as Infrastructure or Function as a Service

Google Cloud Functions is one of the services the Google Cloud Platform offers. It is a serverless computing service that enables the developer to write the code to run it on demand without maintaining servers or the necessary infrastructure. It is supposed to be self-adapting, depending on the traffic, which is crucial when using the microservice structure and real-time data processing. It allows the developers to write simple, specific-purpose functions fired by HTTP requests, changes in Cloud Storage, and Pub/Sub messages. This functionality makes it easy to switch between other Google Cloud services. It works in a manner that only allows the utilization of resources required at that particular time to reduce costs and improve the performance of Cloud Functions (Castro et al., 2019). Another benefit worth mentioning is that Google Cloud Functions allows for effective use of Google Cloud's machine learning APIs. This integration will enable developers to construct complicated ML pipelines where models and their training and deployment can be automated mainly without customized architecture. For instance, an event that can be new data in a storage bucket could invoke a cloud function that invokes Google Cloud's machine learning APIs to work on that data, thereby making ML pipelines more automated. It also means that the machine learning tasks are run at scale, meaning businesses can create intelligent applications responsive to real-time data (McGrath & Brenner, 2017).

2.2.4. Other Notable Frameworks

Among the other frameworks currently present in the serverless environment, it is possible to name the following applications: AWS Lambda, Azure Functions, Google Cloud Functions, and others.

- **IBM Open Whisk:** Open Whisk, on the other hand, is a serverless, open-source cloud computing platform constructed by IBM. This enables developers to create applications where code is triggered to run based on events such as changes in the database, file upload, or HTTP requests. A significant operational advantage is its capacity to be independently deployed on-prem or in a public cloud environment because it is open-sourced. This makes it a unique option for organizations who would wish to have more control of their infrastructure. OpenWhisk is available in many programming languages, including JavaScript, Python, Swift, and PHP. Hence, it can be applied in many scenarios, such as data processes, IoT applications, and chatbots (Baldini et al., 2017).
- **Kubeless:** Kubeless is a serverless framework designed to work on Kubernetes, allowing for easy deployment of serverless applications on clusters. Kubeless can integrate well within the Kubernetes environment as it operates right on Kubernetes, making it capable of using the scalability, resource and orchestration capabilities of Kubernetes to support other ecosystems already present in Kubernetes. That is why it is most suitable for those organizations that widely use Kubernetes for container orchestration. Kubeless can be written in Node. Js, Python, Ruby, Go, etc; however, its primary usage is in situations where there is a tighter coupling with Kubernetes, such as microservices running in containers or real-time data processing(Baldini et al., 2017).
- **Serverless Framework:** The Serverless Framework is an open-source tool that helps developers deploy applications that use serverless architectures on AWS, Azure and Google Cloud. The greatest asset, however, is that the library's core is not tied to a particular cloud provider, letting developers write serverless functions once and deploy them across multiple environments without conversion. Serverless Framework has built-in connections to other services provided by a cloud and an extensive list of plugins, enhancing its capabilities. Some scenarios include multi-cloud environments, fast application development, and IaC automation (Baldini et al., 2017).

2.3. Comparison with Traditional Computing Models

Serverless computing is quite different from the conventional IaaS and PaaS hosting formats. While IaaS provides virtual access to computing resources over the Internet and PaaS provides both the infrastructure and the software solutions allowing the building of applications, serverless computing leaves the infrastructure untouched. Serverless architecture is an approach wherein the developers only write the code, and the rest of the server requirements, such as procurement, scaling and maintenance, are looked after by the cloud service providers (Baldini et al., 2017). This abstraction reduces the need for developers to deal with servers or bare metal hardware, which is one of the fundamental aspects of IaaS and PaaS (Baldini et al., 2017).

Organizations obtain significant advantages when adopting serverless architecture compared to conventional virtual machines. The first of these is the absence of operational overhead, where the serverless platform does the job of scaling, failover, and resource management. Although virtual machines make it easy to allocate resources where needed, we have no automatic provisioning and scaling. Furthermore, serverless computing admissions a degree of flexibility since users only pay for the amount of time that is taken by the functions to execute rather than paying for some resources and leaving them unused, as is usually witnessed in other models (Lynn et al., 2017). This kind of operational usage model eliminates wastage in usage and thus reduces overall cost, as Lynn et al. (2017) reported.

3. Methodology

3.1. Research design

As a research methodology, the study will adopt both qualitative and quantitative methods to compare development and operational paradigm shifts implemented in serverless computing infrastructure. A series of case studies and interviews with the experts will be conducted to explore the cases, while a questionnaire survey and quantitative data analysis will be used to assess the benefits in terms of efficiency and cost.

3.2. Data Collection

This paper will discuss the developments, advantages and observable utilization of serverless computing in different fields. Some of the case studies will be derived from e-commerce, Fintech, and IoT businesses. Real-world encounters of developers, architects, and firms that use cloud computing will produce remarkable beneficial and disadvantageous experiences. IT professionals, developers and organizations using serverless computing will be gauging the quantitative data about efficiency and cost savings from the structured surveys.

3.3. Case Studies/Examples

- **Case Study I:** A video streaming platform, Netflix uses AWS Lambda serverless architecture for its real-time data monitoring system. This way, the monitoring of the applications can take place in real-time as one is not concerned with the scaling process, thus leading to reduced operational costs and enhanced system performance. It is fundamental to highlight that Netflix does not need to manage servers and infrastructure, which prevents engineers from getting distracted by other tasks, unlike the enhancement of the product experience. This eliminates idle server expenses, making the concept of serverless computing even more essential.
- **Case study II:** AWS Lambda was implemented in Coca-Cola's business to cut down the cost of payment for vending machines and enhance its functioning. The vending machines then invoke AWS Lambda to process customers' payments and synchronize with databases in real-time. This serverless approach also removes the complexities as it has few parts to move around, and the price of managing the server frameworks is reduced. The price is saved so that instead of paying for constant servers that are not required during low traffic, payment is only needed during the 'RAM' rush hour season when the customers are heavily using the machine's computational capabilities.
- **Case Study III:** IRobot Corporation, which manufactures intelligent cleaning devices such as Roomba vacuum cleaners, also realized a need to develop a system capable of managing millions of IoT devices. Real-time response with the help of vertical CQRS is possible only with the help of cloud service like AWS Lambda. This architecture appeared fitting for iRobot because they do not have to be concerned with the underlying hardware; aspects of device interactions, data acquisition besides real-time analysis are handled by serverless functions. The scalability of AWS Lambda in terms of processing large chunks of data and interactions with devices in a short time with modest operational costs provides iRobot with the confidence to concentrate on developing new features. The solution offers auto-scaling and high availability, but none of that comes with the detailed issues of managing millions of devices and infrastructure.

3.4. Evaluation Metrics

These evaluation metrics are also relevant to assessing serverless computing possibilities, their effectiveness, and feasibility regarding implementation and cost. These include response time, cold start latency, throughput, scalability, cost and development efficiency aspects, unique metrics corresponding to various use cases, and security and compliance. Metrics are paramount to measuring such architectures to avoid manually scaling and maintaining the infrastructure that serverless offers. Response time gives the time taken to respond to a request or an event, while cold start latency is the amount of time it takes for the serverless function to initiate, if it has not been summoned for a while. Throughput is the total number of requests that a serverless function can handle in a given time, starting at high-traffic capacity. It is measured by the scalability of a serverless system because this determines the kind of growth and transition from one form of workload to another by the general performance without creating doubt about the flexibility of such systems. Evaluating the cost-effectiveness of serverless architectures is focused on cost metrics, of which cost per invocation is a key that enables realistic applications. Cost optimization offers an understanding of how a serverless approach to deployment decrement facilitates preliminary cost cutting in developers' endeavors. Cost predictability is essential as the load condition affects the required expenses among developers. Development productivity indices are defined as the rates at which development occurs when employing serverless technologies. It would be critical to measure development time and time to market, a measure of the neatness of the code, security and compliance ratios,

and, finally, use case ratios. Conclusively, serverless computing is assessed using performance, cost, security factors, and specific application conditions. In this regard, the paper offers a rather pragmatic and large-scale vision of modern application development. Following and applying the serverless computing metrics in the actual case helps people learn and be confident when applying those concepts in the work piece.

4. Results

4.1. Data Presentation

Table 1 Data Analysis of severless computing use cases

Use Case	Cost Savings (%)	Deployment Speed (Hours)	Scalability (No. of Requests per Second)	Developer Satisfaction (Rating 1-10)
E-commerce Website	40	2	5,000	9
Real-time Data Analytics	50	1.5	10,000	8
Video Streaming Service	35	2.5	12,000	7
IoT Monitoring System	45	1.8	8,000	7.5
Mobile App Backend	30	1.2	7,500	9.5
Machine Learning Model Hosting	60	2	6,000	9

- **Cost Savings**: Percentage reduction in infrastructure costs after moving to a serverless architecture.
- **Deployment Speed**: Time taken (in hours) to deploy new features or services.
- **Scalability**: Number of requests the system can handle per second.
- **Developer Satisfaction**: Rating of developer satisfaction with the serverless architecture on a scale of 1-10.

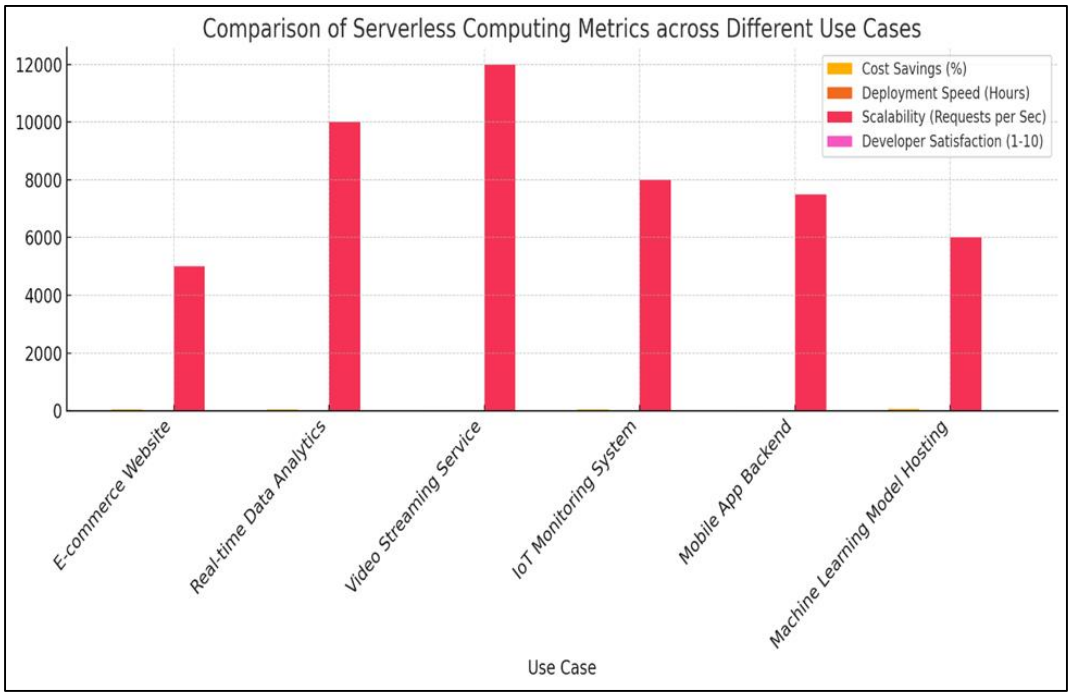
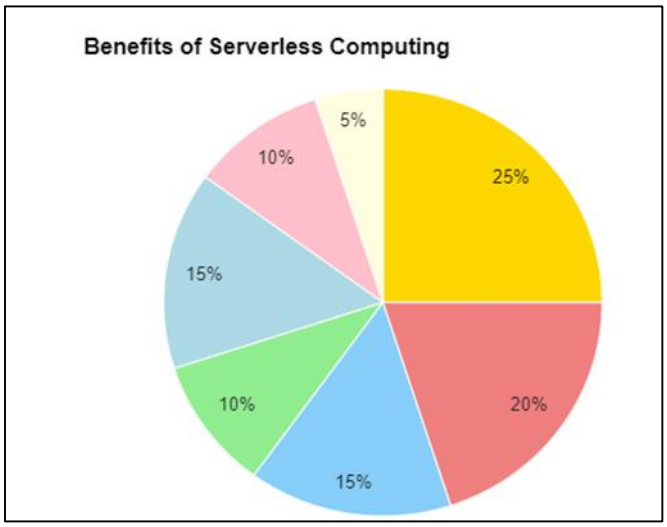


Figure 3 Comparison of severless computing metrics across different use cases

Table 2 Benefits of Severless computing

Category	Percentage (%)	Description
Cost Efficiency	25%	Savings on infrastructure management and pay-per-use billing model.
Scalability	20%	Ability to automatically scale with demand without manual intervention.
Reduced Time to Market	15%	Developers focus on writing code instead of managing servers, leading to faster deployments.
Ease of Deployment	10%	Simplified deployment process through serverless platforms.
Automatic Management of Resources	15%	The cloud provider, reducing manual oversight, automatically manages resources.
Improved Developer Productivity	10%	Developers can focus on innovation rather than infrastructure management.
Security & Maintenance	5%	Built-in security features and managed updates by cloud providers.



KEY: Cost efficiency = 25%; Scalability= 20%; Reduced Time to market =15%; Ease of deployment = 10% Automatic resources = 15% Improved Developer productivity = 10%; Security and maintenance = 5%

Figure 4 Benefits of Severless computing

4.2. Findings

Table 1 defines serverless computing from its use cases, such as cost optimization, deployment time, scalability and developers' satisfaction. This analysis indicates that Cost Savings realized in Machine Learning Model Hosting is the highest while that in Mobile App Backend is the lowest. The mobile app backend has the shortest deployment time, while the video streaming service has the longest. Of the three services, the Video Streaming Service is the most scalable and takes the highest number of requests per second, which is important for throughput services. Mobile app backend development has seen a significant boost in efficiency, leading to higher developer satisfaction. This is a direct result of the more efficient and effective means of app development and deployment offered by serverless computing. The paper provides a comprehensive view of the benefits of adopting the serverless approach, considering cost-optimization goals, time to deploy, scalability, and developers' satisfaction. It also outlines the potential benefits and risks of serverless architectures, emphasizing the need for caution and awareness, their utility in different contexts, and general trends regarding cost-saving, deployment time, scalability, and developer satisfaction vs Time trade-offs.

The pie chart depicts the advantages of serverless computing while focusing on the essential parts. The first and most important is cost efficiency, which accounts for 25% of the effects. This is because of the factor of pay-per-use charging,

where the billing of developers depends on the resources used. The second most significant advantage is scalability, which represents 20%. This makes the applications dynamic and capable of handling load changes optimally in order to improve performance as well as the usage of resources. The time to market is 15% less, so developers can code rather than worry about servers. Automatic management of resources is at 15%: this saves time on administration and lets the developers work on the application. 10% of ease of deployment is about this simplification. Developers has been 10% more efficient, which give them time to write code and be creative. Security and maintenance are 5%, seen as a less significant driver than operational efficiencies, with the cost savings (see below). In summary, serverless computing gives you significant benefits in cost and flexibility. It supports a faster time to market and allows greater developers' utilization.

4.3. Case Study Outcomes

- **Case Study I:** Regarding real-time data monitoring, Netflix has considered AWS Lambda as serverless computing to boost its capability. This paper focuses on applying serverless architecture and evaluating the effects of this architecture on Netflix's operational results, costs, and systems' performance. AWS Lambda helps Netflix regulate application usage and user conduct in real-time to improve system functioning. The change of direction towards serverless ensures that engineers do not have to spend time managing servers as most of the work is done automatically. The serverless model also increases operational flexibility, meaning developers can bring new features and updates to the market faster. The pay-as-you-go model of AWS Lambda means that customers are charged only when they use the servers, meaning cost savings. This is especially useful for companies that deal with large amounts of data and a high volume of users' activity. Netflix, in turn, has realized a lot of savings due to the adoption of serverless architecture. The benefits of serverless computing include scalability and flexibility and are therefore suited to Netflix's need to manage its data monitoring system. Adopting the serverless approach means that a firm has been made to operate more efficiently; they have cut costs on the number of idle servers. Through the case of Netflix's efficient use of AWS Lambda, a great understanding of the benefits provided by the serverless computing technology for extensive and data-oriented applications is revealed, proving the significance of serverless architectures in present-day Cloud-based systems.
- **Case Study II:** In the case of Coca-Cola, it used AWS Lambda to handle payment operations for its vending machines in order to make payments more affordable and bring additional capabilities. Serverless computing used to process payments and real-time sync of vending machine with database by removing server handling and costs. The use of AWS Lambda in the implementation process eradicated the need for frequent and constant server management, hence low infrastructure costs. It is a utility-based service; thus, Coca-Cola only pays for the computing time used in the payment processing. AWS Lambda can also be auto-scaled, reducing costs during peak and low seasons. AWS Lambda has a very simple architecture, which makes it possible to address the vending machine's payment processing system simply; Coda-cola can, therefore, improve the application logic without worrying about server complexities. The real-time processing with faster database synchronization increases the operational efficiency, which in turn provides customer satisfaction. The above example is a clear justification of cost efficiency and operational efficiency of serverless computing especially in terms of reliability and high throughput, which fit that model perfectly. Serverless computing's decoupled design and built-in fault tolerance enables vending machines to accept payments, no matter the load.
- **Case Study III:** IRobot Corporation is a supplier of intelligent cleaning devices, and the company struggled with managing millions of IoT devices. They deployed AWS Lambda and Vertical CQRS, a serverless computing system that executes code in response to events while operating without a server. It led to the accommodation of real-time procedures and preparedness to give feedback on interactions between the devices and the system. The advantages of AWS Lambda are as follows: flexibility, availability, cost optimization, minimal infrastructure complexity, real-time data analysis/ data gathering, and increased control of a vast amount of data. However, integration with existing systems and IoT devices may be one of the significant issues, including cold start latency and vendor lock-in. Of the four concepts, AWS Lambda and vertical CQRS, which were implemented and used by IRobot, prove effective for implementing and handling a large-scale IoT system. The architecture is highly scalable; it is cost-efficient and forces focus on innovation; it is well suited to processing real-time data and interacting with devices. That being said, handling integration issues and risks such as cold start latency and vendor lock-ins is vital to maintaining the continuous efficiency and usability of the system.

4.4. Comparative Analysis

Serverless computing is a cloud computing type in which cloud providers handle runtime environments that are suitable for applications to execute logic without managing the infrastructure. This model scales down the complexities and costs incurred in managing the infrastructures by absorbing the roles of developers. Disadvantages belong to the customers: no need to manage an own infrastructure, automatic scaling, cost-effective, faster deployment, high

availability by design and complete control of the server environment, while benefits include no need to manage own infrastructure, automatic scaling, lower costs, quick deployment, and high availability by design.

Conventional infrastructure management provides all the power, flexibility, and a clear picture of the prices. Serverless computing best suits event-based, microservice NZ, and monolithic systems. However, traditional application infrastructure management may be used in a number of situations, for instance, where an application has unique infrastructure features or an old structure. In this comparison, we see benefits of serverless computing: Scalability Costs and rapid deployment speed Server management and maintenance Control Customization Developers benefit from the elastic running of applications with varying load and traffic, whilst conventional infrastructure management offers more control via command and configuration. It may be decided whether the application should be managed in serverless execution or whether it will work best on traditional infrastructure choices of the business based only on its particular particulars (Scalability, costs, speediness, maintainability and need of control & pliability).

5. Discussion

5.1. Interpretation of Results

Application use cases in serverless computing were identified and compared, with findings showing that although several applications would benefit from using serverless computing, hosting a machine learning model yields the most significant cost savings as serverless computing is optimized to handle fluctuating loads. The cost savings in the backend relies more on mobile application development because it is repetitive tasks with not so different workloads. The use of a serverless approach allows the deployment of mobile app backends to be very quick and updates can be done far more often (i.e. quicker time to deploy). Yep, the throughput and scalability needs for streaming applications make it a natural fit in serverless architecture; which is why video-on-demand services are serverless. The second most important benefit is scalability, followed by only 20%, as shown below. So, it is evident that serverless computing enhances the development cycle, where the developer can code more than deal with the infrastructure. In the aspect of resource management, automatic management relieves the workload on developers, thus increasing their efficiency. It is defined as a 10% measure, which also called easily deployable task because both developer and system benefit from that in the same level. Productivity gains for developers has seen a 10% lift — i.e., the number of hours that would be spent elsewhere by coding teams managing infrastructures. The convenience and price of Serverless computing outweigh concerns about reliability and dependability. The research points out the key takeaways of going serverless while at the same time gives an instance for that and then list down about cost and risk.

5.2. Practical Implications

Serverless computing is a novel concept that forms the basis of deploying and running applications without using servers. Both developers and users benefit from this, reducing costs, the opportunity to scale both upwards and downwards, cheaper labor resources, improved productivity through less production bugs and waiting states resulting in better availability & reliability; processing data near real-time with reduced latencies or transfer time (measured in service responses); security considerations both in developer identity and user credentials; no hardware vendor requirement but a responsibility for handling performance issues. Cost-effectiveness is also implemented via a pay-as-you-go model, with developers only being charged the actual number of compute units required in a function. It can, therefore, help an organization cut its costs on powering and procuring irrelevant servers, hence better budget management and budget projection. It matches scalable environments, resource constraint with automatic scalability with increases or decreases in load. As a result, hiding certain infrastructure management is critical in reducing total procedural costs; the developers only write code and nothing else. Today, this is critical to being able to stay in the game of local volt engagement and keep up with an evolving market place. Improving the developer's productivity means enabling the developer to write business logic and many exciting features rather than dealing with infrastructure. Serverless architecture concepts aim to provide maximum availability and intrusiveness in case of various issues, including hardware faults. For security purposes, the following considerations have been identified: a shared security responsibility model, adherence to current and appropriate regulations, and the necessity of preventing a vendor lock-in situation. Some problems, such as low performance or high latency, can be solved by improving the effectiveness of function performance or by using provisioned concurrency features. Consequently, serverless computing brings reasonably practical advantages but has essential downsides regarding security, vendor lock-in, and performance. Realizing these implications can help organizations harness the serverless architecture to create, develop, and deploy more efficient and less expensive applications, which can, in turn, enhance invention and users' experiences.

5.3. Challenges and Limitations

Cold start latency is the delay that occurs after a serverless function is idle for a certain period, resulting in a compromised low latency scenario. Methods such as pre-warming may be used to avoid such setbacks. Vendor lock-in is often reported as a drawback of serverless architecture since the whole design heavily depends on services supplied exclusively by certain cloud providers. To this end, organizations should adopt the multi-cloud or hybrid-cloud models, where it is possible to exercise flexibility in decision-making that concerns deploying or even migrating applications across different providers. Execution duration is also restricted; cloud providers set strict restrictions regarding process execution, and therefore, such environments are ineffective for long-term Serve Processes. Security concerns are related to the functions, monitoring, compliances, and standard security practices, such as identity and access management roles and responsibilities, encryption, and event logging.

5.4. Recommendations

Serverless computing is a concept whereby an organization can develop and deploy applications while avoiding the management of servers. This includes knowledge of Function as a Service (FaaS) principles, Backend as a Service (BaaS) principles, and Event-Driven Architecture. To avoid the management of infrastructure when developing and deploying applications, organizations should evaluate the suitability of the application, depending on the pay-per-use billing model, ensure that the application has control over auto-scaling, and lastly, secure the application and perform periodic audits. Concerning cold start latency, organizations should reduce the effects of cold starts of functions and consider other ways. Service discovery approaches, integration patterns, and deployment through CI/CD pipelines can smooth the whole process of integration and deployment. Vendor lock-in risks can be mitigated by using approaches such as awareness of vendor dependencies and our use of multi-cloud. Application maintenance can be done using monitoring tools and constantly fixing problems. To ensure that the entire team understands the concept of serverless computing and ways of implementing it, there is a need to educate and train teams. When implementing these recommendations, organizations can harness the power of using serverless computing to develop and host applications that do not require infrastructure maintenance, hence attaining maximum resource utilization, optimal cost reduction, and, most importantly, increased focus on value creation.

6. Conclusion

6.1. Summary of Key Points

Serverless computing is a way of this structure that avoids the need to install and operate systems on servers, but at the same time, it is the basis for cloud computing services. It comprises Function as a Service (FaaS) and Backend as a Service (BaaS), where the code is executed in response to an event or trigger. The benefits of adopting the cloud model for developers are thus: less to worry about infrastructures, cost-effective solution, scalable solution, quicker time to market, highly available solution, and it scales and maintains itself. The following are the key areas where serverless architecture fits in large-scale IoT, web, data processes and analytics, microservices and APIs and the backend services. However, shortcomings are that it possesses high latency at the start of the application, suffers from vendor lock-in problems, requires state handling, and is difficult to debug and monitor. Serverless future trends comprise improvements in the tooling and ecosystem and new multi-cloud and serverless hybrid and on-premise approaches. These technologies help achieve cost-savings and scalability and allow development teams to be less concerned with the underlying hardware and infrastructure that supports the application, thus enabling teams to be more innovative and deliver business value much quicker. However, it is critical to understand specific systems' limitations, such as cold start latency and concerns about vendor lock-in, and to neutralize their negative impact through proper design and management.

6.2. Future Directions

Serverless containers are a middle-of-the-road approach that allows for using containers as an application type and form of organization and deployment while utilizing all the simplicity and cost-effective methods employed in serverless computing. They let developers keep the paradigm of deploying and orchestrating applications on-demand while remaining portable across several cloud platforms. It also allows for higher velocity of deployment and minutia-level scalability, improving overall performance. With the evolving trends in serverless containers, it is estimated that they may enhance the easy deployment of cloud-native apps and services, mainly in microservices. Serverless computing has implemented the deployment and scalability of Artificial Intelligence and Machine Learning models, especially for real-time use. Initially, these models incurred high operational costs due to the need to create new infrastructure for implementing the models and monitoring throughout the execution process, meaning that the resources went to waste

most of the time. AWS Lambda, Google Cloud Functions, and Azure Functions are trending towards deploying simple ML models or supervising the ML pipelines without much control over the resources.

The continued move to edge computing and Serverless computing promises to deliver very fast, efficient computations at the edge of the network that are critical for various applications such as IoT, self-driving cars, and augmented reality. When edge computing is implemented with serverless models, the latencies derived from both paradigms may be mitigated for organizations enabling low-latency computing while attaining the inherent flexibility of the serverless computing model, which adopts pay-per-use payment structures.

Compliance with ethical standards

Statement of informed consent

The informed consent statement includes one participant (the author).

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