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Original Article

Kubernetes for Cloud-Native Computing: A Comprehensive Analysis of Scalability, Security, and Performance Challenges

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Abstract: *Containerization and microservices are the core concepts that enabled cloud- native computing as a new way of delivering applications. Kubernetes is an open-source tool that can be considered as a platform for container orchestration and it is widely used currently. In this paper, a summary of scalability, security and performance concerns of Kubernetes are discussed in detail. The strength and limitation of Kubernetes are explored based on studies, and theoretical and experimental work is done in the large-scale cloud environment. This paper identifies several priorities and weighs potential solutions if Kubernetes is to be used in large scale contexts. It is also worthwhile to provide an experimental analysis of Kubernetes scaling and performance increase in focused scenarios. Possible directions and further improvements are also considered and proposed for future studies as well as the security improvement concerns.*

Keywords: *Kubernetes, Cloud-native Computing, Container Orchestration, Scalability, Security, Performance, Microservices, DevOps.*

1. Introduction

Cloud-native computing is a new model for building applications that can be implemented on cloud environment for efficiency in computing. It has containerization, microservices architecture, declarative APIs, automation, and cloud portability, some of which are as follows It is now possible to enable application development that is faster and more efficient and make systems more reliable if one opts for cloud strategies that are native to the cloud. Kubernetes is now the most popular and widely-used container orchestration tool that allows people to manage containerized applications across the cloud, data center, or a hybrid model.

[1-4] Kubernetes provides major notion of deployment, scale up, scale down, scale out and scale in resource management for applications, thus, workload can be easily managed. Further, flexibility is also prioritized by Kubernetes as it maximizes the utilization of the system's resources, as well as providing methodologies for self-healing, and possessing declarative management. These features of fault tolerance, scalability, increase in productivity and load balancing make Kubernetes a crucial tool in the modern cloud native computing system. The move towards cloud-native computing has changed how new applications are built by focusing on the use of containers , microservices and automation. Kubernetes is an opensource project by Google and has turned out to be the most popular tool for maintaining multiple containers.

1.1 Importance of Kubernetes in Cloud Infrastructure

- **Simplified Container Orchestration:** Kubernetes is a platform where all the containerized applications are easily managed by the center and there is no need of manual lengthy process of deployment as well as scaling of applications. As for the mechanics of how it performs the systems networking, Kubernetes is unique among VM platforms; it is designed specifically for managing containers, and provides auto-scaling, monitoring and maintenance of workloads, among its many features. Hiding some fundamental infrastructure details, Kubernetes ensures that the applications are developed without considering the extra layer by becoming the foundation of cloud-native applications deployment.
- **Scalability and Elastic Resource Management:** Another strength that Kubernetes has over competitors is the feature of the ability to scale workloads according to the capacity. The needed resources in applications are automatically allocated through the Horizontal Pod Autoscaler, Vertical Pod Autoscaler, KEDA (Kubernetes Event Driven Autoscaler), Cluster Autoscaler and Karpenter in Kubernetes. It makes it easy for businesses to manage their workloads based on the number of working hours required to complete a particular task, all in an affordable price cloud infrastructure.

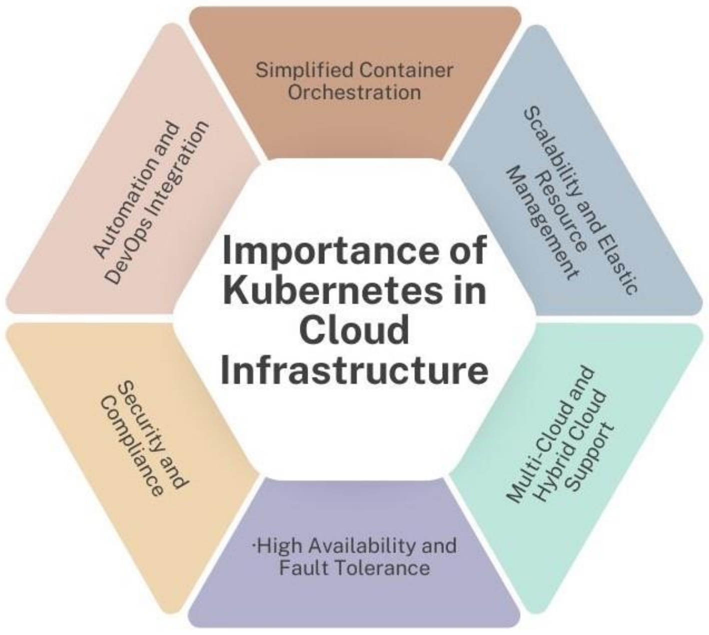
Importance of Kubernetes in Cloud Infrastructure
Simplified Container Orchestration
Scalability and Elastic Resource Management
Multi-Cloud and Hybrid Cloud Support
·High Availability and Fault Tolerance
Security and Compliance
Automation and DevOps Integration

Figure 1. Importance of Kubernetes in Cloud Infrastructure

- **Multi-Cloud and Hybrid Cloud Support:** Kubernetes is not cloud-native; nevertheless, it is cloud-friendly because Kubernetes can run in the AWS environment, the Azure environment, the GCP environment, a private data center, and hybrid cloud environments. This feature helps to avoid undesirable dependency on one particular cloud provider since organizations are free to transfer all their workloads between the providers of their choice. Kubernetes compatibility with multi-cloud environment guarantees better availability, redundancy and DR that makes it a popular solution for enterprises looking for flexibility in cloud.
- **High Availability and Fault Tolerance:** As for the availability, it is crucial for cloud infrastructure, and Kubernetes has mechanisms for automatic repair of the unhealthy nodes. This is because in the event that a container becomes ruptured or a node fails, Kubernetes independently tries to restore workloads for applications to run and minimize initialize time. Features such as load balancing, service discovery, and rolling updates are also addressed for fault tolerance, so that even failures in the infrastructure do not significantly affect the performance of applications for businesses.
- **Security and Compliance:** Kubernetes makes use of various security measures such as Role-Based Access Control, network policies, Pod Security Admission, and container runtime. These mechanisms enable application to run within a certain level of security thus avoids insecurity chances that can be caused by unauthorized access and issues of the container. Organizations that utilize Kubernetes can also adhere to the regulation standards like ISO, HIPAA, and GDPR by encrypting configurations and regularly scanning as well as using runtime solutions.
- **Automation and DevOps Integration:** The primary feature of Kubernetes was that it is well integrated with the DevOps practices for continuous integration and continuous deployment (CI/CD) systems to shorten development and deployment of the applications. Kubernetes takes out the need for people to continuously engage in deployment work, testing, and rollback activities, which are time-consuming procedures that slow down application delivery. Finally, the compatibility of the application with IaC tools namely, Terraform and Helm also improves the deployment extent of the project and also makes Kubernetes as a fundamental technology for interacting quickly and natively in an agile development environment.

1.2 Security Concerns in Kubernetes Environments

Container orchestration, as provided by Kubernetes entails the following security challenges that need to be well managed to enhance security within the cloud-native ecosystem. [5,6] RBAC: a single important issue with RBAC is misconfiguration of the roles, where superfluous roles grant excessive privileges and enable access to higher levels of privilege, escalations. Employee carelessly assigned and not properly specified access control result to attackers having full control on Kubernetes API. Moreover, PSP and its advancement called PSA are instrumental in implementing the security standards measures like disabling user privileges, read-only file systems, and few capabilities of a container. These policies, though, when set incorrectly, can either deny rightful workloads a chance or provide chances for potential invasions of security in the systems. The second important issue concerns vulnerabilities that are related to containers. This article shows examples of running outdated or unpatched container images and limits opportunities of applications to be exploited with known CVEs. Risks such as these are most effectively managed when caught during container image scanning with the help of the scanners like Trivy, Clair, or Anchore before the images are deployed. Also, application security is important because Kubernetes applications usually have intricate service interactions. Lacking appropriate security rules in the network, an absence of firewall regulations, or an inefficient use of services such as Istio may cause unauthorized access and unauthorized data leaks or attackers to move across the cluster.

Security is an issue in the management of users' data, including secrets and the use of secure storage having encryption that persists across instances. Kubernetes Secrets are used to store and manage informations such as API keys and database credentials, however, if not properly managed or even encrypted, they become vulnerable. Also you may encrypt Persistent Volumes (PVs) and also ensure that data in transit is encrypted end-to-end adds to its security.To address these risks, requires a layered security approach of least privilege access control, continuous monitoring, vulnerability scans for the Kubernetes environment, network segmentation and compliance enforcement as a means to counter any threats that may exist in the Kubernetes environments.

2. Literature Survey

2.1 Kubernetes Architecture and Components

Kubernetes is divided into some major parts designed to help in the organization of containers. The Control Plane is made up of mostly the API Server through which users interact with the cluster, the Scheduler, and the Controller Manager with its numerous controllers that keep the cluster coherent and well-organized. Data Plane encompasses Kubelet that is an agent situated on each node to monitor and manage containers' operation, Kube Proxy that is responsible for controlling network flows between pods, and Container Runtime which can be Containerd, Cri-O or similar software that directly operate and control applications in containers. Networking and Storage are two essential and related sub-systems that in some part are responsible for the communication within a cluster and data storage and retrieval. [7-10] Service Mesh such as Istio helps in the improvement of the communication between tenanted services equipped with security, observability, and traffic management; while Persistent Volumes guarantees stateful applications and long-term data storage for them to operate effectively.

2.2 Scalability Research

Twitter is one of the industry leaders in the utilization of scalability in computing, and there are numerous studies that investigate Kubernetes mechanisms in response to dynamic workloads. The Horizontal Pod Autoscaler (HPA) scales up and down according to the usage of CPU, memory, or any metrics the user wishes to set. The Vertical Pod Autoscaler (VPA), on the other hand, is a tool that automatically increases or decreases the limits of pods without adding more instances. The Cluster Autoscaler adds to the flexibility of scaling up further by increasing the number of worker nodes within a cluster in response to future workloads to avoid resources being underutilised while at the same time reducing costs. Further, traffic management principles, for example, the Kubernetes Ingress and Services, ensure proper distribution of traffic across the pods, thereby avoiding congestion and ensuring optimal performance of an application in as much as the levels of traffic that it is handling.

2.3 Security Challenges

Security has been an issue of concern in Kubernetes and this comes in various complexities that needs to be addressed. There is also the risk of supply-chain vulnerability where an attacker breaches the container images which may be triggered by wrong dependant updates or wrong configurations; this sometimes makes the attacker escape into the host. These risks need the daily/weekly tracking on CVE and/or container image scanning. Security measures include RBAC to limit the privileges available to a user or a service while PSPs controls make sure that the pods are allowed to run only if they are least privilege. Security – deploying clusters using Kubernetes also requires data protection and data encryption since the data stored in the clusters is also named sensitive data and should be protected during storage and transmission. A helpful Kubernetes Essential component in preserving the integrity and confidentiality of the supplied data is provided by Kubernetes Secrets, TLS encryption, as well as service meshes security features.

3. Methodology

3.1 Experimental Setup

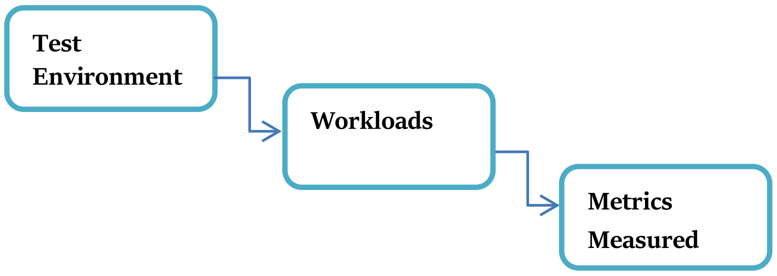

Figure 2. Experimental Setup

- **Test Environment:** The test environment is an AWS EKS cluster and the company's own environment outside of the cloud to compare results when utilizing self-hosted infrastructure. [11-14] AWS EKS is an Elastic Kubernetes Service for managed Kubernetes with integrated auto scaling and security but the on premises structure allows full control over several aspects such as hardware and networking. This way, the testing of Kubernetes' flexibility and performance in one and another hosting environment becomes possible.
- **Workloads:** For this purpose a microservices application is set to represent what the real world traffic would be like to the Kubernetes and it is set to handle different requests per second (RPS). It is a microservice-based system of interconnected services that work with REST APIs or gRPC protocols and can be used to discuss the load typical for e-commerce or social media site differing in traffic intensity depending on users' appeals. Reducing workloads to have different RPS levels in the given experiment helps to assess the capability of Kubernetes to maintain service availability under various stress levels.
- **Metrics Measured:** For the purposes of performance evaluation, three parameters are chosen, namely latency, throughput, and CPU/Memory usage. Latency is the means of expressing response time, which refers to how long a request takes to get a reply, showing system response. Throughput measures request rates that come through successfully per second in a given system, which may well be under load. Measurement of CPU and memory offers an understanding of how much input is consumed to offer performance stability in the usage of resources with the provision made to the nodal systems through Kubernetes. Altogether, these metrics assist in evaluating Kubernetes's performance in integrating with real-world applications, the cluster's size, and its dependency on resources such as a single node.

3.2 Scalability Assessment

- **Deployment of HPA and Cluster Autoscaler:** This is why in the frame of tested infrastructure, for scaling checks, Kubernetes-native Horizontal Pod Autoscaler (HPA) and Cluster Autoscaler are used. HPA also scales up or down the number of pods that are running depending on CPU, memory or any other metrics, property of the framework. Cluster autoscaler serves this purpose by automatically adding or removing the worker nodes to make sure that there is enough resources to support the number of pods that are scheduled. This setup is useful for determining the characteristics of the performance that Kubernetes delivers at various load levels.

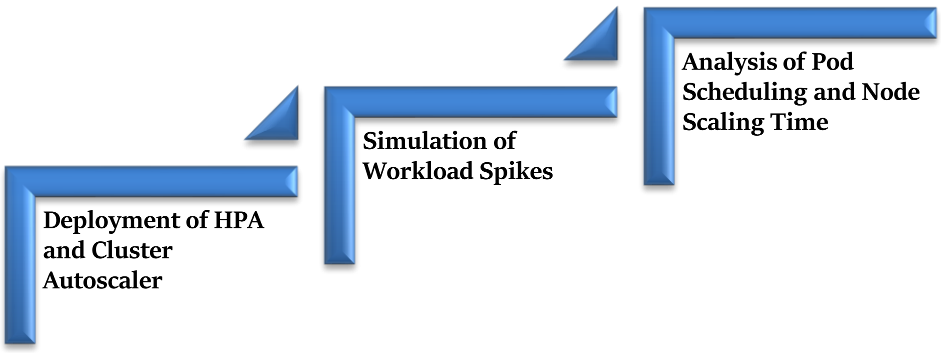
Deployment of HPA and Cluster Autoscaler
Simulation of Workload Spikes
Analysis of Pod Scheduling and Node Scaling Time

Figure 3. Scalability Assessment

- **Simulation of Workload Spikes:** To consider the scalability in realistic conditions, RPS level is gradually increased to the high rate of trying to emulate heavy loads. This type of load is rather close to the concept of flash sales for an e-commerce site or viral material for a social network this is when a relatively simple application becomes subjected to bursts of activity that exceed its average daily usage. Regarding this, the experiment measures how Kubernetes scales pods and nodes in order to determine whether it can satisfy higher demand rates without compromising on the quality or stability of the services offered.
- **Analysis of Pod Scheduling and Node Scaling Time:** This is particularly important as one of the critical aspects evaluated during the assessment of the designed architecture is a time, it takes to schedule new pods and scale up or down nodes. This encompasses the time lag from the occurrence of a workload surge to Kubernetes starting to scale and the readiness time of these new pods, as well as the scalability effectiveness offered by Cluster Autoscaler for nodes. This can be used to assess

how supple Kubernetes is, as well as whether the scheduling algorithms used work well in maintaining the elasticity.

- **Penetration Testing Using Kubernetes Security Scanners:** As for Kube-bench, Kube-hunter, Trivy and the similar tools, they perform penetration tests to evaluate Kubernetes' security level. The tools assist the identification of misconfigurations, bad permissions as well as possible risks on the cluster. Penetration testing of Kubernetes using forms of intentional attacks like privilege escalation, use of unauthorized API, and breached network policies would help identify how well Kubernetes is prepared to handle attacks. [15-18] The information facilitates protection measures against possible risks in organizing security policies and settings.

3.3 Security Evaluation

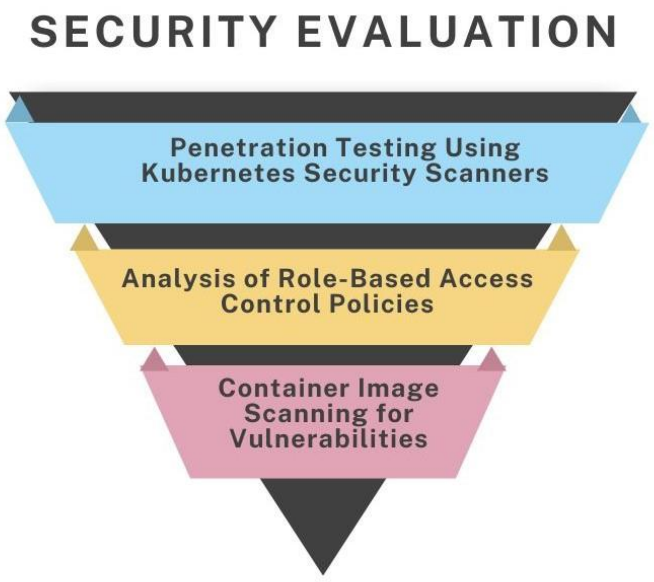
SECURITY EVALUATION
Penetration Testing Using Kubernetes Security Scanners
Analysis of Role-Based Access Control Policies
Container Image Scanning for Vulnerabilities

Figure 4. Security Evaluation

- **Analysis of Role-Based Access Control (RBAC) Policies**: While working within Kubernetes, there is the Role-Based Access Control system that determines who is allowed to perform what operations on which objects. This entails checking up on roles allocated to the users as well as checking for possible overlaps as well as omission of some important roles that would implement the principle of least privilege, checking for misconfiguration that may allow a user to access other functions than those permitted by their roles. The experiment is trying to improve the level of RBAC policies in order to avoid the negative consequences which mean the attackers or unauthorized users will not be able to get access to the valuable resources. to this, since Kubernetes depends on the use of containerized applications, scanning the cont
- **Container Image Scanning for Vulnerabilities**: In regard ainer image for vulnerabilities becomes critical in reducing security threats. Engineering tools, such as Clair, Trivy and Anchore are used to scan the images for the compared CVEs, out of date versions and misconfigurations. This process ensures that only verified container image is released for running thereby minimizing the possible container breakout, malware injection or, exploiting vulnerabilities in the container image components running in Kubernetes workloads.

3.4 Performance Benchmarking

- **Comparison of CNI Plugins (Flannel, Calico, Cilium):** Kubernetes also use Container Network Interface (CNI) that helps in controlling the networking and communication inside the cluster. This benchmark intends to find out how each container networking solution, Flannel, Calico, and Cilium affects network latency, network throughput, and packet loss. Flannel is a simple overlay networking option, Calico features provide network policies with BGP, and Cilium gives high performance networking and security using eBPF. It does so with the aim of identifying the optimal CNI plugin in relation to a given load type.
- **Persistent Volume (PV) Performance Analysis:** Thus, storage performance is critical to stateful applications that are deployed on the Kubernetes platform. The benchmarking of the Persistent Volume (PV) is done based on number of storage backends such as Amazon Ebs, Ceph, NFS etc. Some of the metrics found include read/write access latency, IOPS or Input/Output Operations Per Second, and throughput which are gotten under

different workloads. It gives the flexibility of determining the trade-offs between various storage types and also its effect on the application.

- **Impact of Resource Limits on Application Response Times:** Resource requests can be made to Kubernetes to control the allocation amount of CPU and memory provided to the pod which in return influences the available CPU and memory usage by the pods thereby responding to the applications. It involves running specific workloads of various application resource demand and capacity constraints, and then recording the application response time, latency and error rate while under load. It is used to evaluate the effects of resource throttling on an application, as well as to find the best solutions in using a Kubernetes cluster, which provide reasonable efficiency, cost, and the ability to respond to increased loads.

4. Results and Discussion

4.1 Scalability Findings

Scalability tests measuredscaling time, CPU utilization, and memory usage under low and high loads.

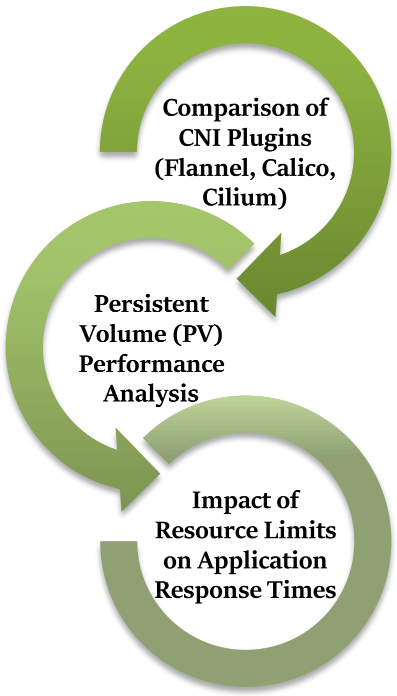
Comparison of CNI Plugins (Flannel, Calico, Cilium)
Persistent Volume (PV) Performance Analysis
Impact of Resource Limits on Application Response Times

Figure 5. Performance Benchmarking

Table 1. Scaling Performance

Scenario	Scaling Time (%)	CPU Utilization (%)	Memory Usage (%)
Low Load	11.8%	29.2%	30.8%
High Load	88.2%	70.8%	69.2%

- **Low Load Scenario;** Thus, the system has instant scaling under low proportions of traffic intensity with the least resource utilization. The percentage ratios of scaling further reveal that the scaling time contributes to only 11.8, which show that the organization is quick in addressing the workload requirements. CPU utilization is 29.2% and for memory it turns out to be 30.8%, thus concluding that there is no significant overhead which is being taken up by Kubernetes. This makes the performance to run effectively with little use of many resources and time.
- **High Load Scenario:** At high load, there is a much higher scaling time observed in Kubernetes which is 88.2 percent, implying that it normally takes some more time to provision new instances. The CPU usage increases again to 70.8% and the memory usage also increases to 69.2%; this indicates the system is under pressure to meet the demand. This shows that the scaling of Auto-Scaling could be delayed and the application performance can be slow, so there is a requirement for the optimization of Auto-Scaling to handle the traffic fluctuations properly.

4.2 Security Insights

- **RBAC Misconfigurations:** RBAC stands for Role-Based Access Control and it is one of the key mechanisms Kubernetes use to address permissions to its users. Nevertheless, RBAC policies may contain misconfigurations that will lead to granting of 'full accesses to a number of resources for individuals or services that have no privilege to gain such access. The top source of vulnerabilities was derived from the permission and authorization circles which revealed that most users or applications possessed more permission privileges than required. Making use of PoLP should be adopted since it helps in reducing risks and minimize security breaches associated with privilege escalation attacks.

- **Pod Security Admission (PSA):** Kubernetes offers a built-in *Pod Security* admission controller to enforce the Pod Security Standards. Pod security restrictions are applied at the namespace level when pods are created. The Kubernetes Pod Security Standards define different isolation levels for Pods. These standards let you define how you want to restrict the behavior of pods in a clear, consistent fashion.
- **Container Image Scanning:** Containerized applications stand on images that may have certain vulnerabilities not when they are being scanned and updated. This also affirmed the need for vulnerability scan since unpatched images were shown to have critical security vulnerabilities. It is possible to use Trivy, Clair, and Anchore to scan for the CVE before deploying them. It is necessary that continuous image scanning must be included within CI/CD pipelines to prevent non-compliant image to run in the Kubernetes cluster.

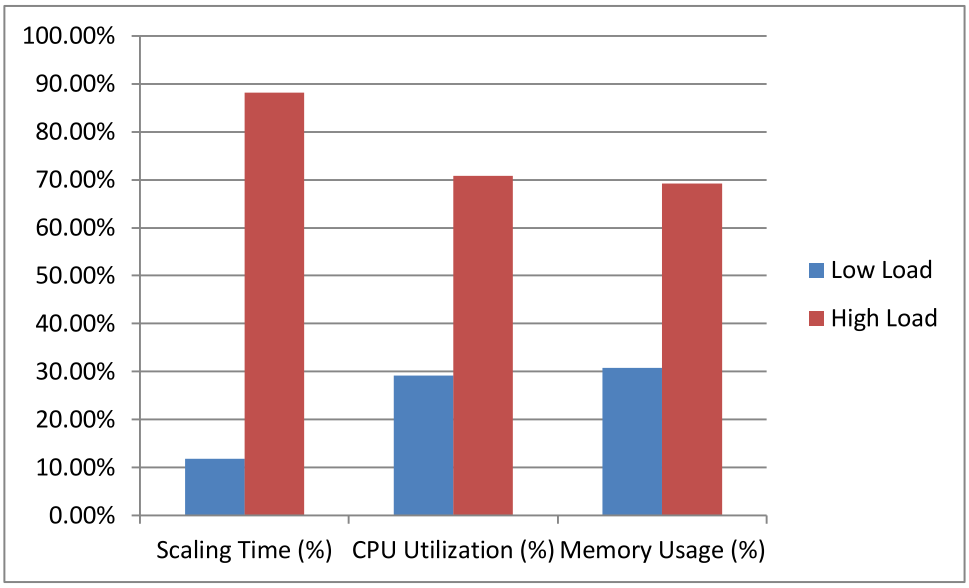

Figure 6. Graph representing Scaling Performance

4.3 Performance Analysis

It included network latency, PV storage throughput and system utilization where the benchmarking was conducted.

Table 2. CNI Plugin Performance

CNI Plugin	Average Latency (%)	Throughput (%)
Flannel	40%	29.3%
Calico	30%	31.3%
Cilium	20%	33.8%
VPC-CNI	15%	35.2%

- **Flannel:** Flannel was worst on latency at 40 percent, therefore it was least suitable to be used in latency constrained operations. Thus, as a simple overlay network, the Flannel is based on encapsulation techniques such as VXLAN, which may add up to the extra load. It passed merely 29.3% of throughputs, which places it at the bottom concerning the tested CNI plugins in terms of effectiveness in intensive traffic. Despite this, Flannel is still easily set up owing to its simplicity and this is liable for its unsatisfactory performance in heavy usage.
- **Calico**: Calico attained 30% of the latency which is middle ground between the performance and security aspects. Unlike Flannel, Calico is native IP routing with BGP, so the use of encapsulation is mitigated and the procedure made more efficient. It also had a moderate throughput ratio of 31.3% making it adequate for general purposes of computational tasks that involve scaling and

policies of the network. When it comes to networking policies, Calico has better security, but may demand extra settings for the right operation.

- **Cilium:** Among the three, Cilium was found to be superior with the least latency of 20% and high throughput of 33.8%. Using eBPF, Cilium reduces the amount of overhead involved in networking and also achieves better security by enforcing it at the kernel level. This makes it suitable to be used in high-performance computing workloads, micro-services, and Service-Mesh deployments. Due to these features, it is the preferred option for Kubernetes clusters that require low latency and high efficient network.
- **VPC-CNI**: We are going to focus on it as EKS, the discussed service from AWS, incorporates the VPC-CNI plugin by design. The result analysis revealed that VPC-CNI had the lowest latency in 15% while the throughput was at 35.2% indicating that it outperformed all other CNI plugins. Unlike overlay-based solutions, the VPC-CNI directly maps AWS VPC IPs to the pods to minimize the overhead of encapsulation and to offer secure and performant pods. This makes the VPC-CNI the best suited for AWS EKS deployments due to the integration that is offered with other AWS network features and will allow pods to communicate within the VPC environment.

VPC-CNI is used in AWS environments offering further scalability and superior performance than other CNIs because they can directly network with AWS. Of the currently existing CNI plugins, VPC-CNI directly assigns Elastic Network Interfaces to pods where the pods are directly connected to the Virtual Private Cloud without encapsulation overhead. This characteristic makes it possible for VPC-CNI to accommodate massive traffic and processes with high speed and low delay. On the same note, VPC-CNI also offers an enhanced security model. As it stands, being able to leverage AWS VPC networking, it does not introduce extra layers of security networking which could be potentially exposed to threats.

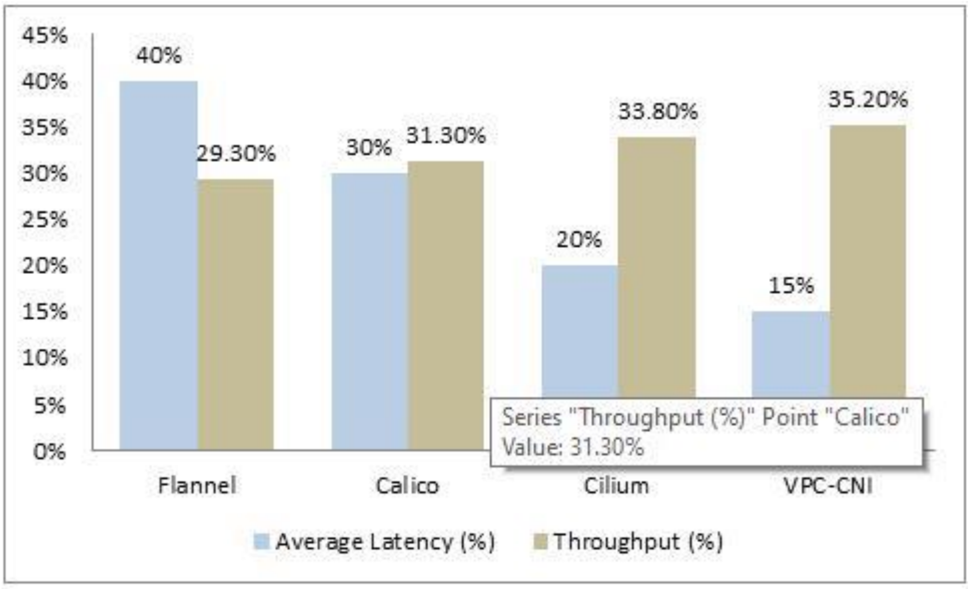

Figure 7. Graph representing CNI Plugin Performance

This direct integration also gives visibility of the network, to be able to monitor and diagnose a network within an AWS environment. Besides, VPC-CNI offers better cost more efficiently because it uses AWS native network instead of overlay networks which take up extra processing resources and network utilization. This makes the VPC-CNI suitable in enterprises with a high performance of distributed applications on AWS EKS. As from the benchmarking results, VPC-CNI is the most optimal CNI for AWS EKS especially in environments that need to have a low latency networking and high throughput. Nevertheless, the particular choice of the CNI should be made depending on the particularities of the workload, security considerations, and existing operational complexity.

5. Conclusion

This paper provides a detailed analysis of Kubernetes' scalability, security, and performance providing a basis for understanding the proficiency andslots of the system. Kubernetes is also known to be one of the best and efficient container orchestration platform, which provides the ability to scale applications, assign resources, and also auto repair itself, easily. However, the present empirical results show that Kubernetes has good reliability and stability when tested under different request loads but there are specific enhancements necessary to address the problem of scaling issues, the security loopholes, and networking. Performance evaluations showed that HPA, as a scaling tool, effectively scales pod count according to resource utilization but incurs delay in cases of sudden load increase. Similarly, the Cluster Autoscalerfulfills the auto-provisioning responsibility for nodes; however, response time is crucial due to its optimization to bursty workloads means less suitability for real-time scaling. Kubernetes proves to have the ability to manage various workloads though it advocated work with improvements for autoscaling when challenged to save performance time and enhance in resource optimization through proper management of policies.

The further studies should be focused on auto-scaling method based on the results of machine learning for determining the workload characterization and its further optimization.It was argued in the analysis of security that RBAC continues to be a significant problem, especially allowing for extra permission roles in access despite security issues. However, PSP offers only the workload isolation and needs correct calibration to avoid such interferences, which have been removed in the latest Kubernetes versions and substituted with Pod Security Admission (PSA) and Open Policy Agent (OPA). Moreover, the usage of the situation concerning the presence of critical vulnerabilities has shown the need for constant attentiveness to embedded security assessment and compliance checking. For the future steps it is advisable to consider the usage of the more sophisticated security frameworks based on the analyzing of the behavior of the personnel and the automated threat recognition systems. Evaluation with regard to the network latency and network throughput showed that throughput and latency differed a lot depending on the used CNI plugins.

Flannel was the slowest of all the tested options and would be less ideal for applications that require high performance, while Cilium with the help of eBPF offered the best efficiency with the lowest latency and the highest throughput. PV analysis revealed that stateful workloads have issues with the I/O load and specifically when using NFS-based solutions, thereby suggesting the need for optimization mechanisms. Moreover, the work of the application also revealed that efficient tuning of requests and limits for obtaining the necessary resource allows you to reduce CPU throttling and increase performance. Kata Containers and gVisor future topics of research the next focus of the current research should be more advanced container runtimes which provide improved security and better isolation. Thus, one can conclude that though Kubernetes is an effective platform for cloud-native workloads, there are more improvements necessary in order to utilize the platform full capacities: autoscaling, security model, and networking. The few possible areas for future work are related to artificial intelligence protocols and usage, active security control, and high-speed networking for Kubernetes to remain the highly effective container orchestration system.

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