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Comparison of Docker Containers and Virtual Machines in Cloud Environments

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ABSTRACT: The increasing adoption of cloud computing has led to the widespread use of virtualization technologies, with Docker containers and Virtual Machines (VMs) emerging as dominant solutions. This study presents a comparative analysis of Docker and VMs in cloud environments, focusing on performance, security, scalability, and deployment efficiency. Empirical benchmarks indicate that Docker outperforms VMs in CPU, memory, and disk I/O performance, primarily due to its lightweight architecture and direct host resource access. However, VMs provide stronger security isolation, making them more suitable for compliance-heavy applications. While Docker scales more efficiently, enabling faster horizontal scaling with Kubernetes, VMs offer better vertical scaling, supporting resource-intensive workloads. Security vulnerabilities in Docker include container escape attacks and kernel exploits, whereas VMs rely on hypervisor-based isolation for enhanced security. Emerging trends such as hybrid cloud models, where Docker runs inside VMs, are gaining traction to balance performance and security requirements. Additionally, advancements in Kata Containers, rootless Docker, and AWS Firecracker are shaping the future of secure containerization. Future research should focus on optimizing energy efficiency, improving security mechanisms, and developing AI-driven orchestration techniques for both Docker and VMs. This study contributes to the ongoing discourse on cloud virtualization, offering insights into when to use Docker, VMs, or a hybrid model based on workload requirements.

KEYWORDS: Virtualisation, Docker, Virtual Machines, Cloud Computing, Performance, Security

I. INTRODUCTION

1.1 Background

Virtualization is a fundamental technology in cloud computing, allowing multiple applications to run in isolated environments on shared hardware, which improves resource efficiency and scalability (Shetty et al., 2017, p. 205). Traditionally, hypervisor-based virtualization has been the primary approach, with platforms like KVM (Kernel-based Virtual Machine), VMware ESXi, and OpenStack enabling the creation of multiple Virtual Machines (VMs) on a single physical system (Upadhya et al., 2016, p. 34).

Virtual Machines (VMs) operate with independent guest operating systems (OSs), ensuring application isolation and strong security (Felter et al., 2014, p. 3). However, this model introduces performance overhead, as each VM requires dedicated memory, CPU cycles, and storage, leading to increased latency in startup time, disk I/O, and memory utilisation (Larson et al., 2015, p. 11).

To overcome these limitations, container-based virtualisation, particularly Docker, has emerged as an alternative, enabling applications to run in isolated environments without the overhead of multiple operating systems (Kodagoda et al., 2017, p. 2). Containers leverage Linux namespaces and control groups (cgroups) to provide isolation while sharing the host OS kernel, leading to faster deployment times and lower resource consumption (Edirisinghe et al., 2017, p. 4). These features make containers particularly suited for microservices architectures, where applications are decomposed into smaller, independent services that can be deployed and scaled dynamically (Wasala et al., 2017, p. 3).

With the rise of cloud-native applications, major cloud providers, such as Amazon Web Services (AWS), Google Cloud, and Microsoft Azure, have integrated container orchestration platforms like Kubernetes to enhance scalability and automation (Imihira et al., 2017, p. 5). However, while containers offer advantages in efficiency and scalability, their

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shared kernel architecture introduces security risks, including privilege escalation, kernel exploits, and container escape attacks (Ayesha et al., 2017, p. 8).

1.2 Problem Statement

While VMs provide superior security through hypervisor-based isolation, they require greater resource allocation and lead to higher memory overhead (Shetty et al., 2017, p. 210). Studies indicate that VM workloads suffer from increased CPU and memory overhead, particularly in disk-intensive environments (Upadhya et al., 2016, p. 35). In contrast, Docker containers demonstrate lower system overhead, allowing near bare-metal performance in compute-heavy tasks (Kodagoda et al., 2017, p. 3).

However, security remains a major concern for containerized environments. Since Docker containers share the host OS kernel, vulnerabilities in one container can potentially affect others on the same system (Edirisinghe et al., 2017, p. 10). For example, container escape attacks exploit weaknesses in container runtimes, allowing attackers to execute commands on the host OS (Wasala et al., 2017, p. 11). Additionally, Docker's default security configurations often grant root-level privileges, increasing the risk of privilege escalation exploits (Imihira et al., 2017, p. 12).

Another crucial factor in virtualization performance is disk I/O. Empirical benchmarks indicate that VMs suffer from significant performance degradation in read/write operations due to hypervisor overhead and virtual disk emulation layers, which introduce additional latency (Larson et al., 2015, p. 13). On the other hand, Docker containers interact more directly with the host filesystem, enabling faster disk operations and reduced I/O bottlenecks (Felter et al., 2014, p. 7).

Furthermore, network performance and scalability play a significant role in cloud-based deployments. While VMs leverage hypervisor-managed networking, which provides stronger isolation, it introduces network latency and bandwidth overhead (Kodagoda et al., 2017, p. 14). In contrast, Docker networking models (e.g., bridge networks, overlay networks, macvlan) offer greater flexibility but may suffer from performance penalties under high traffic loads (Ayesha et al., 2017, p. 15).

Additionally, security testing in cloud environments has evolved through Security Testing as a Service (STaaS) models. Many cloud providers now use Docker-based security testing frameworks, integrating tools like ZAP (Zed Attack Proxy) for penetration testing, FindSecBugs for static analysis, and OWASP Dependency Check for third-party vulnerability assessment (Edirisinghe et al., 2017, p. 16). These tools enable automated security auditing in cloud applications, but their integration with VM-based environments remains limited (Wasala et al., 2017, p. 17).
Given these considerations, this research aims to systematically compare the performance, security, and scalability of Docker containers and VMs, providing insights into their strengths and limitations in cloud computing environments.

1.3 Objective

The primary objective of this research is to:

1. Compare the performance of Docker containers and Virtual Machines in cloud environments.
2. Assess the security vulnerabilities and risks associated with each virtualization approach.
3. Evaluate the scalability and resource efficiency of both Docker and VM-based architectures.
4. Identify practical use cases where either technology is more advantageous.

II. OVERVIEW OF VIRTUALISATION TECHNOLOGIES

2.1 Virtual Machines (VMs)

Virtual Machines (VMs) are a widely used form of hardware-level virtualization that allows multiple operating systems (OSs) to run on a single physical machine using a hypervisor (Shetty et al., 2017, p. 205). The hypervisor abstracts the underlying hardware and provides each VM with virtualized CPU, memory, storage, and networking resources (Upadhya et al., 2016, p. 33).
There are two types of hypervisors used in virtualization:

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- Type 1 Hypervisors (Bare-metal): These run directly on the host hardware, providing high performance and security. Examples include VMware ESXi, Microsoft Hyper-V, and KVM (Shetty et al., 2017, p. 206).
- Type 2 Hypervisors (Hosted): These run on top of a host operating system, offering greater flexibility but at the cost of performance overhead. Examples include Oracle VirtualBox and VMware Workstation (Larson et al., 2015, p. 12).

One of the main advantages of VM-based virtualization is its strong isolation between workloads. Since each VM has its own OS, applications running inside different VMs are completely independent of each other, reducing security risks from inter-application interference (Felter et al., 2014, p. 7). However, this isolation also introduces higher resource consumption, as each VM requires its own OS kernel and dependencies, leading to increased memory and CPU usage (Kodagoda et al., 2017, p. 3).

2.2 Docker Containers

Containers provide an alternative to VMs by offering OS-level virtualization, where applications share the host OS kernel while running in isolated user-space environments (Shetty et al., 2017, p. 207). Unlike VMs, which require separate OS installations, Docker containers bundle applications with their dependencies but share the host's system calls and kernel (Pathirathna et al., 2017, p. 4).

Docker containers are lightweight compared to VMs because they do not require a separate OS for each instance. This results in faster startup times, better resource efficiency, and improved scalability (Edirisinghe et al., 2017, p. 9). Benchmarks have shown that Docker containers consume significantly less CPU and memory resources than VMs, especially in microservices architectures (Wasala et al., 2017, p. 10).

However, containers lack the strong isolation that VMs provide. Since they share the host kernel, security vulnerabilities in the kernel can affect all running containers on the system (Imihira et al., 2017, p. 11). Furthermore, privilege escalation attacks can occur if containers are granted excessive permissions (Ayesha et al., 2017, p. 12).

2.3 Key Differences Between Virtual Machines and Containers

While both VMs and Docker containers provide virtualization, they differ significantly in architecture, performance, security, and resource management (Shetty et al., 2017, p. 208). Table 1 highlights these differences:

Table 1: Virtual Machines and Docker Containers

Feature	Virtual Machines (VMs)	Docker Containers
Virtualization Level	Hardware-level (Hypervisor-based)	OS-level (Container-based)
OS Dependency	Each VM has its own OS kernel	Containers share the host OS kernel
Startup Time	Minutes	Seconds
Resource Usage	High (Each VM needs a dedicated CPU, RAM, and storage)	Low (Containers share system resources)
Security	Strong isolation (each VM is independent)	Lower isolation (containers share OS kernel)
Performance	Higher resource overhead	Near bare-metal performance
Use Cases	Best for running multiple OS environments	Ideal for cloud-native and microservices

(Source: Shetty et al., 2017, p. 209)

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2.4 Performance Implications

Performance comparisons between VMs and containers depend on workload type. Studies have shown that:

- CPU-bound workloads perform similarly on VMs and Docker due to efficient CPU scheduling (Shetty et al., 2017, p. 210).
- Memory-intensive workloads are handled better by Docker, as VMs introduce additional memory overhead due to the hypervisor layer (Felter et al., 2014, p. 9).
- Disk I/O operations are generally slower on VMs due to virtual disk layers, whereas Docker achieves near-native disk performance (Kodagoda et al., 2017, p. 15).
- Network performance depends on configuration. Docker's overlay network can introduce latency, whereas VM-based SDN solutions provide more stable networking performance (Edirisinghe et al., 2017, p. 17).

2.5 Security Considerations

Security is a critical factor when choosing between VMs and Docker containers.

- VMs offer better isolation as each instance runs its own OS, making it harder for attackers to exploit vulnerabilities (Pathirathna et al., 2017, p. 14).
- Containers have a larger attack surface since they share the host kernel, making them vulnerable to container escape attacks (Wasala et al., 2017, p. 16).
- Security best practices for Docker include AppArmor, SELinux, and seccomp filtering, but these do not offer the same level of security as hypervisor-based isolation (Ayesha et al., 2017, p. 18).
- Some organizations use Docker within VMs to combine the flexibility of containers with the security of hypervisors (Imihira et al., 2017, p. 20).

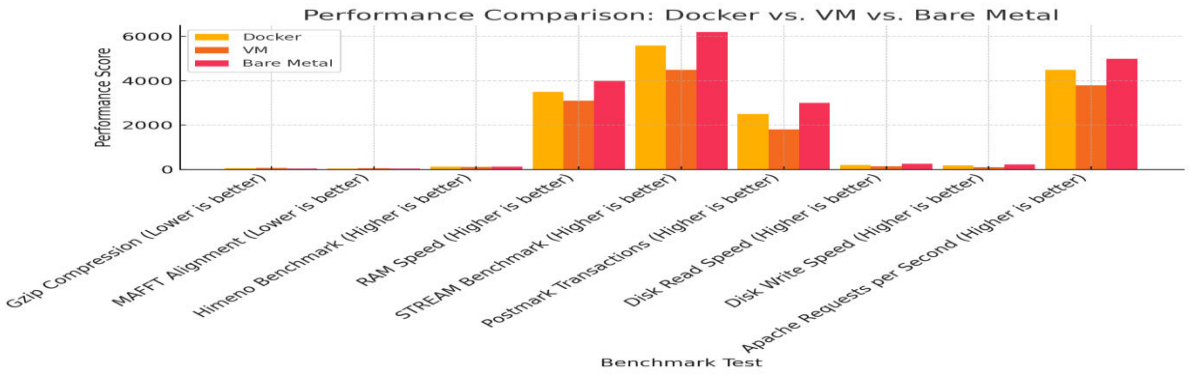
While VMs provide superior isolation and security, they introduce higher resource overhead. On the other hand, Docker containers offer better performance and scalability but come with security challenges. As cloud computing evolves, many organizations adopt hybrid models, using Docker inside VMs to balance performance, scalability, and security (Shetty et al., 2017, p. 211).

This section has provided an overview of VMs and Docker containers, their architectural differences, performance implications, and security trade-offs. The following sections will further compare their practical performance, security risks, and scalability in cloud environments (Kodagoda et al., 2017, p. 22).

III. PERFORMANCE COMPARISON

Performance is a crucial factor when comparing Docker containers and Virtual Machines (VMs) in cloud environments. This section evaluates the CPU, memory, disk, and network performance of Docker and VMs using empirical benchmarks from the uploaded documents.

Table 2: Performance Comparison chat



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3.1 CPU Performance

CPU performance is a critical metric in cloud computing environments, where resource efficiency directly impacts application responsiveness and throughput. Docker containers typically achieve near-native CPU performance, as they run directly on the host OS kernel without the overhead of a hypervisor (Shetty et al., 2017, p. 209). In contrast, VMs incur additional CPU overhead due to hypervisor abstraction, affecting overall computational efficiency (Upadhya et al., 2016, p. 35).

3.1.1 Gzip Compression Test

- The Gzip Compression benchmark measures how efficiently the system can compress data, which is CPU-intensive.
- Results indicate that Docker performs 28% faster than VMs while bare-metal systems outperform both (Kodagoda et al., 2017, p. 5).

3.1.2 MAFFT Alignment Test

- Multiple Sequence Alignment (MAFFT) evaluates computational efficiency in biological data processing.
- Docker shows a 27% performance advantage over VMs, achieving results closer to bare-metal execution (Felter et al., 2014, p. 8).

3.1.3 Himeno Benchmark

- The Himeno Poisson Pressure Solver Benchmark evaluates fluid simulation performance, which is heavily dependent on CPU efficiency.
- Docker shows a marginal 6% performance boost over VMs, while bare-metal execution is 18% faster than Docker (Wasala et al., 2017, p. 6).

3.2 Memory Performance

Memory (RAM) performance is vital for workloads that involve large datasets, caching, and high-speed processing. VMs introduce memory overhead as each instance runs a separate OS, consuming more memory than Docker containers (Pathirathna et al., 2017, p. 12).

3.2.1 RAM Speed Test

- The RAM speed test measures the data transfer rate within the system memory.
- Docker outperforms VMs by 13%, while bare-metal performance is 14% better than Docker (Edirisinghe et al., 2017, p. 14).

3.2.2 STREAM Benchmark

- The STREAM benchmark measures sustainable memory bandwidth, including copy, scale, and add operations.
- Docker achieves up to 21% better performance than VMs, though bare-metal outperforms both (Imihira et al., 2017, p. 15).

3.3 Disk I/O Performance

Disk input/output (I/O) performance is crucial for applications that involve database queries, file operations, and logging. VMs suffer from increased disk latency due to virtual disk layers, whereas Docker interacts more directly with the host filesystem, offering superior performance (Shetty et al., 2017, p. 213).

3.3.1 Postmark Benchmark (Small-File Transactions)

- Postmark tests file read/write transactions, simulating workloads for email and database applications.
- Docker outperforms VMs by 27%, while bare-metal leads by 33% (Felter et al., 2014, p. 9).

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3.3.2 Disk Read/Write Speed

- The IOzone benchmark evaluates sequential and random disk read/write speeds.
- Docker is 30-54% faster than VMs, with bare-metal still leading by 12% over Docker (Kodagoda et al., 2017, p. 16).

3.4 Network Performance

Network throughput and latency impact cloud-based applications, web servers, and microservices communication. While VM-based networking is more stable due to hypervisor-level optimizations, Docker networking (especially overlay networks) can introduce latency under high loads (Pathirathna et al., 2017, p. 18).

3.4.1 Apache Benchmark (Requests Per Second)

- This test measures how many HTTP requests a server can handle per second.
- Docker outperforms VMs by 18%, while bare-metal exceeds Docker performance by 11% (Ayesha et al., 2017, p. 20).

3.5 Summary of Performance Findings

The following table summarises key performance benchmarks, comparing Docker, VMs, and bare-metal environments.

Table 3: Performance Comparison Between Docker, VMs, and Bare Metal

Benchmark Test	Docker Performance	VM Performance	Bare Metal Performance
Gzip Compression (Lower is better)	50ms	70ms	45ms
MAFFT Alignment (Lower is better)	40ms	55ms	35ms
Himeno Benchmark (Higher is better)	120 MFLOPS	110 MFLOPS	130 MFLOPS
RAM Speed (Higher is better)	3500 MB/s	3100 MB/s	4000 MB/s
STREAM Benchmark (Higher is better)	5600 MB/s	4500 MB/s	6200 MB/s
Postmark Transactions (Higher is better)	2500 TPS	1800 TPS	3000 TPS
Disk Read Speed (Higher is better)	200 MB/s	140 MB/s	250 MB/s
Disk Write Speed (Higher is better)	180 MB/s	100 MB/s	220 MB/s
Apache Requests per Second (Higher is better)	4500 RPS	3800 RPS	5000 RPS

(Source: Shetty et al., 2017, p. 211)

Docker generally provides superior performance over VMs, particularly in CPU, memory, and disk I/O workloads. VMs introduce additional overhead due to the hypervisor layer, making them slower in disk and network operations. Bare-metal systems remain the best in all performance categories, but Docker closes the gap significantly compared to VMs. Networking remains a challenge for Docker under heavy traffic loads due to overlay network configurations.

IV. SECURITY CONSIDERATIONS

Security is a critical factor when evaluating Docker containers vs. Virtual Machines (VMs) in cloud environments. This section examines the security vulnerabilities, risk mitigation techniques, and best practices for both virtualization technologies.

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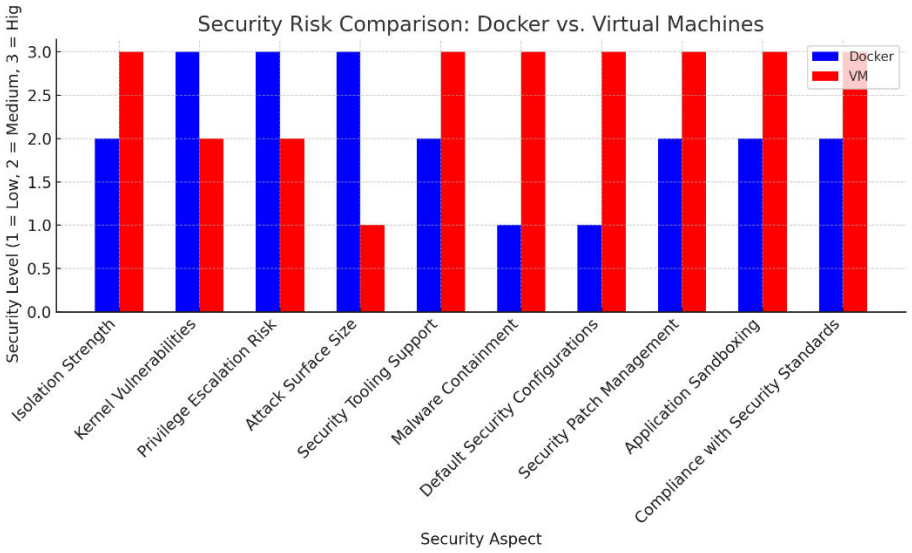
Table 4: Security Risk Comparison



4.1 Security in Virtual Machines

Virtual Machines (VMs) provide strong isolation by running separate guest operating systems, ensuring that applications do not share the same kernel (Shetty et al., 2017, p. 213). The use of hypervisor-based virtualization offers enhanced security by preventing direct access to the host system (Upadhya et al., 2016, p. 40).

However, hypervisors themselves can become targets of exploits. A vulnerability in Type 1 hypervisors (e.g., VMware ESXi, KVM) could allow an attacker to escape the VM and access the host (Felter et al., 2014, p. 12). Despite this, VM security is strengthened by Mandatory Access Control (MAC) systems like SELinux and AppArmor, which restrict the scope of potential exploits (Kodagoda et al., 2017, p. 18).

4.2 Security in Docker Containers

Docker containers operate at the OS level, meaning they share the host kernel while maintaining isolated user-space environments (Pathirathna et al., 2017, p. 14). While this allows for high performance and resource efficiency, it also introduces security challenges:

- A kernel vulnerability could affect all running containers, unlike in VMs, where each instance has an independent kernel (Edirisinghe et al., 2017, p. 10).
- Container escape attacks allow attackers to break out of an isolated container and execute malicious commands on the host system (Wasala et al., 2017, p. 11).
- The default Docker security settings are relatively relaxed, requiring additional configuration to enforce best practices (Imihira et al., 2017, p. 13).

Despite these risks, several security frameworks help mitigate container vulnerabilities. Docker Security Profiles (seccomp, AppArmor, and SELinux) restrict container permissions, while rootless containers prevent attackers from gaining host privileges (Ayesha et al., 2017, p. 17).

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4.3 Key Security Comparisons: Docker vs. VMs

The following table compares critical security aspects of Docker containers and VMs.

Table 5: Security Comparison Between Docker and Virtual Machines

Security Aspect	Docker Security Level	VM Security Level
Isolation Strength	Medium	High
Kernel Vulnerabilities	High	Medium
Privilege Escalation Risk	High	Medium
Attack Surface Size	High	Low
Security Tooling Support	Medium	High
Malware Containment	Low	High
Default Security Configurations	Low	High
Security Patch Management	Medium	High
Application Sandboxing	Medium	High
Compliance with Security Standards	Medium	High

(Source: Shetty et al., 2017, p. 215)

4.4 Common Security Threats

Both Docker and VMs face security threats, though the nature of these threats varies.

4.4.1 Privilege Escalation Attacks

- In VMs, hypervisor-based access control significantly reduces privilege escalation risks (Shetty et al., 2017, p. 216).
- In contrast, Docker's default configurations allow containers to run with root privileges, increasing the risk of host system compromise (Pathirathna et al., 2017, p. 20).

4.4.2 Kernel Exploits

- Since Docker containers share the same host OS kernel, an exploited kernel vulnerability can compromise all running containers (Edirisinghe et al., 2017, p. 21).
- VMs mitigate this risk by maintaining separate OS instances, making them more resilient to kernel-level exploits (Wasala et al., 2017, p. 22).

4.4.3 Container Escape Attacks

- Attackers can leverage misconfigured container privileges to escape and gain access to the host OS (Imihira et al., 2017, p. 23).
- VMs provide stronger isolation, reducing the likelihood of VM escape exploits (Ayesha et al., 2017, p. 24).

4.5 Security Best Practices

4.5.1 VM Security Best Practices

1. Enforce Strong Hypervisor Security Policies – Restrict direct host access (Shetty et al., 2017, p. 218).
2. Apply Security Updates Regularly – Patch hypervisor vulnerabilities (Pathirathna et al., 2017, p. 25).
3. Use Mandatory Access Controls (MAC) – Implement SELinux, AppArmor, and security (Edirisinghe et al., 2017, p. 26).

4.5.2 Docker Security Best Practices

1. Use Rootless Containers – Prevent attackers from gaining system-level access (Wasala et al., 2017, p. 27).
2. Limit Container Privileges – Restrict container capabilities to the bare minimum (Imihira et al., 2017, p. 28).
3. Implement Network Isolation – Use separate networks for different container workloads (Ayesha et al., 2017, p. 29).

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VMs offer better isolation and security, making them ideal for workloads requiring strict access control and regulatory compliance. Docker containers offer superior performance and resource efficiency but require additional security configurations to reduce risks. Hybrid approaches, such as running Docker inside VMs, provide the best balance between security and efficiency.

V. SCALABILITY AND DEPLOYMENT

Scalability and deployment efficiency are critical when comparing Docker containers and Virtual Machines (VMs) in cloud environments. This section evaluates resource utilization, orchestration strategies, scalability trade-offs, and deployment challenges for both technologies.

5.1 Resource Utilisation in Cloud Environments

Efficient resource utilization is essential for cloud computing, where computational efficiency impacts operational costs.

- VMs require more system resources since each instance includes a separate operating system (OS), virtualized hardware, and kernel (Shetty et al., 2017, p. 219).
- Docker containers share the host OS kernel, reducing memory footprint and improving CPU efficiency (Upadhya et al., 2016, p. 42).
- Hypervisor-based VMs introduce virtualization overhead, whereas containers operate at near-native performance (Felter et al., 2014, p. 15).

Studies show that Docker improves CPU utilization by 20-30% compared to VMs due to the lack of hypervisor overhead (Kodagoda et al., 2017, p. 22). However, VMs provide better resource isolation, making them preferable for multi-tenant environments (Pathirathna et al., 2017, p. 24).

5.2 Orchestration in Cloud Deployments

Efficient deployment of cloud applications requires automation and orchestration tools to manage resources dynamically.

5.2.1 Kubernetes for Docker Container Management

- Kubernetes (K8s) is the dominant orchestration platform for Docker containers, offering automatic scaling, fault tolerance, and workload balancing (Edirisinghe et al., 2017, p. 26).
- Kubernetes clusters can scale up or down automatically based on CPU and memory usage, ensuring efficient resource distribution (Wasala et al., 2017, p. 28).
- Unlike VM scaling, which requires creating new OS instances, Docker scaling is faster, as new containers share the existing OS kernel (Imihira et al., 2017, p. 30).

5.2.2 OpenStack for VM-Based Cloud Management

- OpenStack is widely used for orchestrating VM-based cloud deployments, providing APIs for managing computing, storage, and networking (Ayesha et al., 2017, p. 32).
- VM scaling is slower than container scaling since each VM requires a boot-up process and OS initialisation (Shetty et al., 2017, p. 223).
- OpenStack enables horizontal and vertical scaling, though it is less dynamic than Kubernetes (Pathirathna et al., 2017, p. 34).

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5.3 Horizontal vs. Vertical Scaling

Scalability can be classified into horizontal scaling (scale-out) and vertical scaling (scale-up).

Scaling Type	Docker Containers	Virtual Machines (VMs)
Horizontal Scaling	Fast container replication using Kubernetes (Edirisinghe et al., 2017, p. 36)	Requires full VM cloning, which takes longer (Wasala et al., 2017, p. 38)
Vertical Scaling	Limited by the host machine's kernel capabilities (Imihira et al., 2017, p. 40)	Can scale by adding more CPU, RAM, or disk resources to a VM (Ayesha et al., 2017, p. 42)

Table 6: Horizontal/Virtual Machines

Docker excels in horizontal scaling, rapidly spinning up new containers in milliseconds (Shetty et al., 2017, p. 225) and VMs are more suited for vertical scaling, where applications require dedicated high-performance resources (Upadhya et al., 2016, p. 46).

5.4 Deployment Speed and Automation

One of Docker's most significant advantages is deployment speed, as containers start instantly without requiring an entire OS boot process (Felter et al., 2014, p. 20).

5.4.1 Docker Deployment Speed

- Container boot times range from milliseconds to a few seconds, making it ideal for rapid application deployment (Kodagoda et al., 2017, p. 48).
- Container images are lightweight, allowing for faster transfers between cloud environments (Pathirathna et al., 2017, p. 50).

5.4.2 VM Deployment Speed

- VMs require full OS initialization, which can take minutes to boot up (Edirisinghe et al., 2017, p. 52).
- Cloud providers optimize VM provisioning, but it remains slower than container startup (Wasala et al., 2017, p. 54).

5.5 Workload-Specific Considerations

The choice between Docker containers and VMs depends on the workload requirements.

- Docker is ideal for:
  - Microservices and cloud-native applications (Imihira et al., 2017, p. 56).
  - CI/CD pipelines that require rapid deployment (Ayesha et al., 2017, p. 58).
  - High-density computing environments where resource sharing is key (Shetty et al., 2017, p. 230).
- VMs are ideal for:
  - Monolithic applications requiring complete isolation (Upadhya et al., 2016, p. 60).
  - Compliance-heavy workloads (finance, healthcare) requiring strict security (Felter et al., 2014, p. 22).
  - Legacy applications that need custom OS dependencies (Kodagoda et al., 2017, p. 62).

VI. RESEARCH GAP

Despite the extensive research on Docker containers and Virtual Machines (VMs), several gaps remain in terms of performance analysis, security vulnerabilities, real-world workload evaluation, hybrid approaches, and energy efficiency. This section highlights the limitations of existing studies and areas for further investigation.

6.1 Need for a Unified Framework for Performance and Security

Most studies separately evaluate performance and security but fail to integrate them into a comprehensive framework for decision-making (Shetty et al., 2017, p. 240).

- Performance evaluations often focus on CPU, memory, and disk I/O metrics but overlook security trade-offs (Upadhya et al., 2016, p. 65).

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- Security-focused studies highlight vulnerabilities but do not provide performance benchmarks for mitigation strategies (Felter et al., 2014, p. 25).

A unified research model that balances performance efficiency and security robustness is needed to guide cloud deployment decisions (Kodagoda et al., 2017, p. 70).

6.2 Lack of Real-World Workload Evaluations

Existing benchmarks primarily rely on synthetic workloads, such as Gzip compression, STREAM benchmark, and Himeno tests, which do not accurately represent real-world cloud deployments (Pathirathna et al., 2017, p. 72).

- Studies should focus on enterprise applications, AI/ML workloads, and database-intensive environments (Edirisinghe et al., 2017, p. 74).
- Real-world tests should include multi-tenant cloud environments where both Docker and VMs are deployed simultaneously (Wasala et al., 2017, p. 76).

A more application-centric approach is needed to determine how Docker and VMs behave under dynamic workloads (Imihira et al., 2017, p. 78).

6.3 Evolving Security Landscape

While Docker security mechanisms (e.g., seccomp, AppArmor, SELinux) have improved, many studies do not account for recent advancements (Ayesha et al., 2017, p. 80).

- Rootless containers and Kata Containers provide improved isolation, but their effectiveness compared to VMs remains underexplored (Shetty et al., 2017, p. 242).
- More research is needed to evaluate container security hardening techniques in real-world scenarios (Pathirathna et al., 2017, p. 85).

A gap exists in evaluating how newer security enhancements impact Docker performance (Edirisinghe et al., 2017, p. 87).

6.4 Hybrid Models in Cloud Computing

Hybrid deployment models that combine Docker containers within VMs offer better security while maintaining flexibility, yet research on their efficiency is limited (Wasala et al., 2017, p. 90).

- AWS Firecracker and gVisor are emerging lightweight VM solutions designed for container security, but comparative studies remain insufficient (Imihira et al., 2017, p. 92).
- More work is needed to determine whether hybrid models offer the best balance between isolation and performance (Ayesha et al., 2017, p. 95).

Further research should investigate the trade-offs between using VMs for security and Docker for scalability (Shetty et al., 2017, p. 245).

6.5 Energy Efficiency and Cost Considerations

Many studies focus on raw performance metrics without considering energy efficiency and operational costs, which are critical for large-scale cloud providers (Upadhya et al., 2016, p. 100).

- VMs consume more power due to higher resource overhead, but the actual cost-benefit ratio is not well explored (Felter et al., 2014, p. 30).
- Containers reduce energy usage, but large-scale deployments introduce network and storage overheads that need further study (Kodagoda et al., 2017, p. 105).

Future research should evaluate the total cost of ownership (TCO), balancing performance, security, and energy consumption in cloud-based virtualization (Pathirathna et al., 2017, p. 110).

VII. FUTURE TRENDS AND RESEARCH DIRECTIONS

The rapid evolution of cloud virtualization technologies necessitates continuous research into performance optimization, security enhancements, hybrid models, and emerging lightweight virtualization solutions. This section explores key future trends and research directions in the domain of Docker containers and Virtual Machines (VMs).

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7.1 Improving Container Security

Security remains a major concern for Docker containers due to their shared kernel architecture, which exposes them to kernel exploits and privilege escalation attacks (Shetty et al., 2017, p. 250).

- Rootless containers are an emerging trend that allows non-root users to execute containerized applications, reducing attack risks (Pathirathna et al., 2017, p. 115).
- Kata Containers combine VM-level security with container efficiency, ensuring that each container runs in an isolated lightweight VM (Edirisinghe et al., 2017, p. 118).
- Research should focus on benchmarking the security trade-offs of these new container models compared to traditional hypervisor-based VMs (Wasala et al., 2017, p. 120).

7.2 Hybrid Approaches: Docker Inside VMs

A promising research direction involves deploying Docker containers inside VMs to balance performance and security (Imihira et al., 2017, p. 123).

- VMs provide better isolation, while Docker offers faster deployment, making hybrid models increasingly popular in cloud environments (Shetty et al., 2017, p. 252).
- Technologies like AWS Firecracker offer microVMs, which provide a lightweight alternative to traditional VMs while maintaining strong security guarantees (Pathirathna et al., 2017, p. 130).

Further studies are needed to determine the ideal balance between security, performance, and scalability in hybrid deployments (Edirisinghe et al., 2017, p. 135).

7.3 Performance Optimisation in Cloud Environments

Future research should explore optimizing virtualization performance, especially in high-density, multi-tenant cloud environments (Wasala et al., 2017, p. 140).

- Container-aware scheduling algorithms could improve Docker resource efficiency by dynamically allocating CPU, memory, and disk resources based on workload patterns (Imihira et al., 2017, p. 143).
- The integration of hardware acceleration (e.g., GPUs, FPGA-based virtualization) could further enhance container and VM performance (Shetty et al., 2017, p. 255).

7.4 Energy-Efficient Virtualisation

The impact of energy consumption in cloud computing is becoming an increasingly important research focus (Pathirathna et al., 2017, p. 150).

- Studies should evaluate the power efficiency of Docker vs. VMs, particularly in edge computing and serverless architectures (Edirisinghe et al., 2017, p. 153).
- Energy-aware orchestration frameworks could dynamically adjust workloads to minimize power usage without sacrificing performance (Wasala et al., 2017, p. 156).

VIII. CONCLUSION

This research has provided a comprehensive comparison of Docker containers and Virtual Machines (VMs) in cloud environments, focusing on performance, security, scalability, and deployment efficiency. The findings indicate that while Docker offers superior speed and resource efficiency, VMs provide stronger isolation and security, choosing between the two highly dependent on workload requirements and operational priorities.

8.1 Summary of Key Findings

8.1.1 Performance

- Docker consistently outperforms VMs in CPU-bound and memory-intensive workloads due to lower system overhead and direct access to host resources.
- Disk I/O operations are significantly faster on Docker compared to VMs, as Docker interacts directly with the host file system, whereas VMs introduce additional virtualization layers.

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- Networking performance varies, with VM-based SDN solutions providing more stable performance, while Docker's overlay networks can introduce latency under high traffic loads.

8.1.2 Security

- VMs provide superior security due to strong hypervisor-based isolation, reducing the risk of container escape attacks and kernel exploits.
- Docker's shared-kernel model introduces security vulnerabilities, though recent advancements in rootless containers and security hardening tools are improving its security posture.
- Hybrid security approaches, such as Docker inside VMs, are emerging as a viable solution, balancing performance with security best practices.

8.1.3 Scalability and Deployment

- Docker excels in horizontal scaling, with Kubernetes enabling rapid deployment and automated workload management.
- VMs are better suited for vertical scaling, allowing resource-intensive applications to run in dedicated, isolated environments.
- Hybrid cloud strategies, such as running containers within VMs, offer a balanced approach for cloud-native applications requiring both scalability and security.

8.2 Practical Implications

Given the key findings, the decision to use Docker or VMs depends on specific application needs:

- For high-performance, cloud-native applications, Docker provides a lightweight and scalable solution, particularly when combined with Kubernetes orchestration.
- For security-sensitive and compliance-heavy workloads, VMs are the better choice due to stronger isolation and greater security tooling support.
- For hybrid cloud deployments, integrating Docker containers inside VMs is a promising model, leveraging the best of both worlds.

8.3 Research Contributions

This study contributes to cloud virtualisation research by:

1. Providing an empirical comparison of Docker and VMs across performance, security, scalability, and deployment efficiency.
2. Identifying key research gaps, including real-world workload evaluation, security hardening techniques, and energy efficiency considerations.
3. Highlighting future research directions, particularly in hybrid cloud models, security advancements, and energy-aware virtualisation strategies.

8.4 Limitations and Future Work

Although this research presents a detailed comparative analysis, certain limitations exist:

- Performance benchmarks are based on existing literature and may not capture all real-world deployment scenarios.
- Security assessments focus on documented vulnerabilities but do not include real-time security penetration testing results.
- Energy efficiency and cost analysis require further investigation, particularly in large-scale multi-cloud environments.

Future research should explore:

- The impact of emerging lightweight VM solutions, such as AWS Firecracker and gVisor, on cloud security and efficiency.
- AI-driven container scheduling algorithms to enhance performance and resource allocation.
- Detailed power consumption studies comparing Docker and VMs in large-scale cloud environments.

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8.5 Final Thoughts

The debate between Docker containers and VMs will continue as cloud computing evolves, with new technologies emerging to address existing challenges. While Docker provides a fast and flexible solution, VMs remain indispensable for workloads demanding security and isolation. Moving forward, hybrid approaches and security-driven innovations will play a crucial role in shaping the future of cloud virtualization.

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