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Security-as-Code: Embedding Policy-Driven Security in CI/CD Workflows

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Abstract: Security in software development has long been considered an independent, downstream process- flowing after the code has been written, and before the code gets deployed. Such a reactive stance has proven ineffective in the present, cloud-native world, where agile iteration and rapid releases are the norms. The paradigm shift toward DevSecOps also requires integrating security directly into the CI/CD pipelines themselves, so that policy enforcement becomes automated and a continuous process. The Security-as-Code (SaC) framework is proposed in this paper as an approach to managing security rules, compliance standards, and risk mitigation, similar to conventional application code. We discuss ways of integrating SaC into a cloud-native CI/CD pipeline, compare available tools, and their compliance with policy-driven security practices. We evaluate the evolution of academia and industry in terms of automation, from static/manual controls to automated, code-driven enforcement, through a literature survey of pre-2022 works. The pipeline is a policy-driven SaC pipeline composed of Infrastructure-As-Code (IaC) scanning, dependency scanning, container hardening, and runtime policy checks. Included results include the reduction of vulnerabilities introduced into production environments and measurable successes in terms of conformance adherence. Future research opportunities are discussed in the paper: in the area of automated threat modeling, in zero-trust CI/CD environments, and AI-assisted SaC policies.

Keywords: Security-as-Code, DevSecOps, CI/CD, Cloud Security, Policy-driven Security, Automation, Infrastructure-as-Code.

1. Introduction

The stress on microservices, containers, orchestrators, and particularly Kubernetes has radically transformed the software development industry due to the rapid adoption of cloud-native technologies. In support of this paradigm, organizations are turning to Continuous Integration and Continuous Delivery (CI/CD) pipelines as the foundation of modern software delivery, where teams are able to iterate quickly, push frequent releases and deliver on a scale. [1-3]Such a speed of delivery has, however, brought about tremendous pressure to the traditional model of security, which traditionally featured after-the-fact penetration testing, manual code reviews, or post-release compliance audits. Apart from being resource-heavy, such approaches are also not in line with the speed and automation of DevOps practices. This has created an increasing discrepancy between development nimbleness and security confidence, resulting in many vulnerabilities being identified too late in the lifecycle, often after deployment to production. Such poor alignment highlights the need to integrate security at an earlier stage in the pipeline, where it can evolve concurrently with other code and infrastructure changes. Moving away from reactive assessments on security to proactive and continuous will be critical to the speed and resiliency of cloud-native environments.

1.1. Importance of Embedding Policy-Driven Security in CI/CD Workflows

- **Addressing the Speed–Security Trade-off:** The current CI/CD pipelines allow organizations to deliver software much faster, although, in most cases, at a cost of security. Conventional systems that verify compliance once the lifecycle is complete are too slow to scale up and down with multiple releases. Policy-based security makes security an inherent part of the pipeline, where each stage is required to run security checks, rather than implementing security as a late-stage intervention, thereby maintaining a balance between speed and safety.
- **Consistency and Repeatability:** Manual audits and spot checks are often inaccurate, one-off, and challenging to replicate across different teams and environments. Automating policies can ensure that organizations can enforce the same security and compliance requirements across each pipeline run, thereby codifying policies into executable rules. This uniformity promotes reliability, mitigates human error, and establishes a repeatable workflow that can be scaled with any project.
- **Auditability and Compliance Assurance:** Industry regulations, such as GDPR, HIPAA, and PCI DSS, require evidence of compliance. Audit trails are inherent in policy-driven workflows, as they record when rules are enforced, when an exception is generated, and how it is reconciled. This automated documentation boosts the governance of compliance, minimizes the overhead of manual audits and simplifies reporting to governance bodies.
- **Scalability across Cloud-Native Environments:** As enterprises embrace hybrid and multi-cloud setups, manually enforcing consistency to create security policies is impossible. Integrating policy-determined enforcement into CI/CD pipelines enables policies to be scaled across various environments, including AWS, Azure, GCP, and Kubernetes clusters. This offers a common security position, while also supporting cloud-native applications, assuming heterogeneous ecosystems.

- **Enabling Shift-Left Security:** The general approach of moving left involves identifying and repairing vulnerabilities early in the application lifecycle, thereby remedying them at a relatively low cost and in a minimally disruptive manner. Policy-based security implements this concept by applying checks to code, build and test phases. This enables developers to receive prompt feedback and resolve problems early, before they reach production.

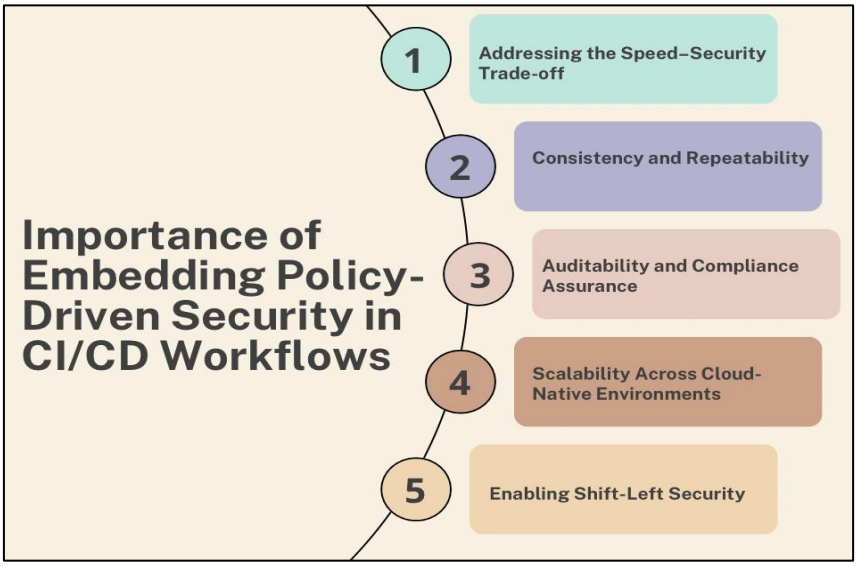

Figure 1: Importance of Embedding Policy-Driven Security in CI/CD Workflows

1.2. Problem Statement

Although DevSecOps practices are increasingly being embraced, a major issue that is yet to be resolved is that of disparity and non-standardizing policy enforcement in CI/CD pipelines. Although automation has become the key to enshrining security in software delivery, enterprises have something of a hodgepodge of solutions that include IaC scanners, vulnerability assessment programs, compliance validators, etc, but lack a common system to harmonize them. [4,5] It is a disjointed system that results in uneven protection, where some stages of the pipelines may be much more protected and others remain exposed to laxity. For example, some teams may embed static analysis tools in a specific build step but fail to monitor or apply security policies during execution or deployment without performing strict policy validation. This kind of inconsistency defeats the purpose of DevSecOps, which is based on the concept of security everywhere, and leaves holes that an attacker can exploit.

Moreover, the' lack of uniform, codified security policies' also implies that compliance is typically enforced based on team-unique settings, yielding different understandings of identical regulatory guidelines. This not only makes audits more difficult, but also increases the likelihood that compliance in industries with stringent regulations, such as GDPR, HIPAA, or PCI DSS, will be violated. A deeper trap lies in multi-cloud and hybrid computing, too, where, due to the absence of federated policy frameworks, it is hard to establish consistent security practices over heterogeneous platforms. DevSecOps has therefore promoted the concept of automating security, but has not solved the organizational issue of standardizing, scaling and auditing policy-enforced enforcement. Organisations that do not address this gap are likely to end up with pipelines that are swift but partly secure and whose vulnerabilities are essentially unsound against changing cyber threats. Accordingly, the research problem can be formulated as the creation of a policy-based yet standardized framework that can guarantee a faithful, automated and auditable enforcement process of security throughout the CI/CD lifecycle.

2. Literature Survey

2.1. Security in Traditional DevOps

During the initial phases of DevOps implementation, the primary focus was on speed, automation, and connecting the development and operations teams, at the expense of security attention. More intuitive tools, such as Jenkins, Bamboo, and TeamCity, enable the automation of continuous integration and delivery pipelines; however, they do not adequately offer security. [6-9]Once dealt with, security was kept, however, largely to static code analysis tools or external audits that were performed outside the mainstream development process. Governance and compliance checks were often a manual process and were carried out late in the software life cycle, thereby forming bottlenecks and vulnerabilities that were introduced into production. This strategy supported the classical model of security as a gatekeeper, whereby security was not proactive in the workflow.

2.2. Rise of DevSecOps

Lapses in conventional DevOps led to the introduction of DevSecOps, a paradigm shift that emphasised the integration of security throughout the entire development chain. Between 2018 and 2020, organisations began implementing practices that

integrated security tools into the CI/CD process. Static Application Security Testing (SAST) and Dynamic Application Security Testing (DAST) tools have become common accessories, enabling developers to identify security issues in source code and running applications at an earlier stage of the development cycle. Dependency scanning also gained momentum, with dependency security scanners like OWASP Dependency-Check helping teams identify risks in third-party libraries and open-source components. Nevertheless, even with those developments, security tools tended to be operated as external features instead of being a direct part of development pipelines. They were thus designed into the system rather than being viewed as a check for assurance.

2.3. Emergence of Security-as-Code

By 2020, the DevSecOps trend had evolved further to the idea of Security-as-Code, which refers to how security controls must also be codified, version-controlled, and automated, like application and infrastructure code. Whereas ad-hoc security integrations led to gaps and inconsistencies in security policy enforcement and compliance validation, this strategy sought to eliminate such gaps and inconsistencies by ensuring that security policies and compliance requirements could be replicated, tested, and audited in different environments. More tools, such as Open Policy Agent (OPA) and HashiCorp Sentinel, have become widely used, allowing teams to specify detailed access controls, compliance, and governance checks in code form. These policies could then be integrated into the CI/CD pipelines, ensuring security is imposed at all stages. Security-as-Code adoption has served as a key turning point in moving security beyond a reactive practice to an automated, proactive and reproducible part of contemporary DevOps pipelines.

3. Methodology

3.1. Conceptual Framework

Security-as-Code represents a paradigm shift in the modern software industry, integrating policy-driven, policy-enforced workflows directly into the continuous integration and continuous delivery (CI/CD) pipeline. [10-13] As opposed to the traditional solutions, in which compliance and governance checks are quite often manual or just some add-on that has to be done after the development process, Security-as-Code arranges security policies as a first-class participant in the development process. Policies are presented in the form of codified rules that outline acceptable configurations, access controls, dependency usage and compliance rules. These rules are then integrated into automated pipelines, where security validation can be performed on an ongoing and consistent basis at each stage of development. For example, a policy may require that images with no known vulnerabilities can be deployed in production, or that all dependencies be scanned and do not contain any high-risk vulnerabilities before integration.

Organizations have reproducibility, auditability, and transparency because policies can be version-controlled along with application code and infrastructure configurations. Not only does this mitigate the possibility of human error, but it also facilitates the automatic enforcement of compliance with regulatory guidelines, such as GDPR, HIPAA, or PCI DSS, rather than auditing them periodically. Open Policy Agent (OPA) and HashiCorp Sentinel are examples of such tools, which allow developers to define policies as declarative data and apply them to a policy store at runtime. Moreover, Security-as-Code supports the “shift-left” concept, where developers identify and resolve security issues earlier in their lifecycle, rather than at deployment. The conceptual framework positions security as an inseparable component of DevOps automation, in order to maintain that agility and speed would not lead to a loss of resilience and fraud. After all, Security-as-Code brings life to the dream of DevSecOps: it changes security from an afterthought to a proactive blocker into a dynamic, programmable, and scalable part of the contemporary software delivery pipeline.

3.2. SaC in CI/CD Stages

- **Code Stage:** At the code stage, Security-as-Code (SaC) adds guardrails that act as controls prior to changes being written to the repository. Pre-commit hooks are an automated form of linting that can run against Infrastructure-as-Code (IaC) files, such as Terraform configurations, Kubernetes YAML manifests, and more. This avoids the insecure behaviors, such as hardcoded secrets, insecure network ports or insecure access controls, in the first place. By identifying problems early, the teams save time spent on rework and ensure that security begins at the root.
- **Build Stage:** The build stage is when SaC incorporates security in the artifacts at creation through dependency scanning and container image hardening. Through automated tools, application libraries, and third-party packages are scanned, and known vulnerabilities are detected, ensuring that no unpatched or malicious components are added. Meanwhile, base images are hardened, unused packages are removed, and configurations are verified against best practices, including CIS Benchmarks, during container hardening processes. This certifies that the generated artifacts are reliable and are secure through design.
- **Test Stage:** The test phase wires automated security checks into quality assurance processes. SAST and DAST are performed on source code and running applications, respectively, in a test environment. Combined, they can recognise coding errors, injection risks, and runtime vulnerabilities. These checks have become part of CI/CD pipelines, so the developer gets prompt feedback, allowing them to solve the security weaknesses as soon as possible without holding up releases.

- **Deploy Stage:** SaC increases the likelihood of hosting compliant workloads in production environments during the deploy stage. These tools include Open Policy Agent (OPA), which validates policies on deployment manifests, infrastructure definitions, and access configurations. OPA can, for example, disallow deployments that request more privileges than necessary or deployments using non-trusted container images. Organizations did this by implementing the codified policies at the time of deployment, and by so doing organizations avoid propagation of insecure or non-conpliant configurations into production.
- **Monitor Stage:** MR is a follow-up of SaC, where the stage of monitors (as opposed to deployers) is added to continuously monitor the deployment, addressing security and compliance exceptions as they occur at runtime. Falco and Sysdig are examples of tools that can monitor container behavior, system calls, and network activity and raise alerts when something seems off or malicious. Code policies can support real-time alerts and automated reactions to deviations in the expected behavior. This is to ensure the applications are compliant and resilient to new threats within the timeframe of their use.

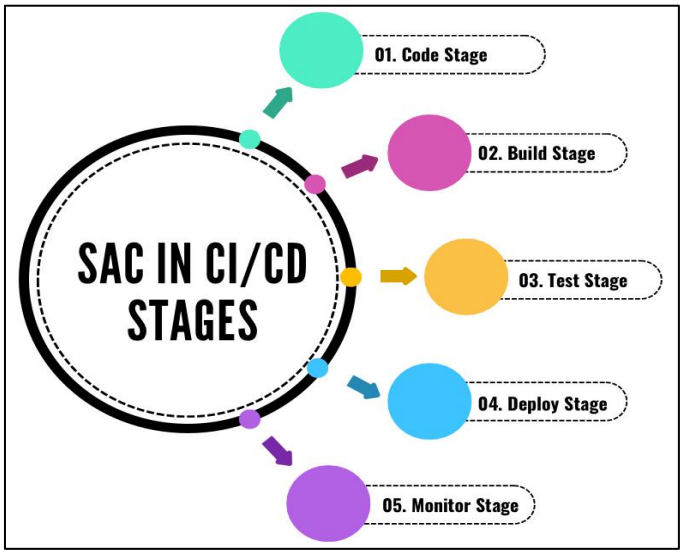

Figure 2: SaC in CI/CD Stages

3.3. Mathematical Model of Policy Enforcement

The Diagrammatic representation of a mathematical model of policy enforcement offers a logical means to explicitly specify the manner [14-17] in which SaC policy is implemented at the various steps of a CI/CD pipeline. In this representation, the set of policies will be P={P1, P2,…., Pn}, where the policy pi is encoded to cover a security or compliance rule, examples include restriction of container privileges, application of encryption standards, or dependency integrity validations. Analogously, consider the pipeline stages to be labeled by S={S1, S2,…., Sm}, with one stage representing each one of the stages of the pipeline, namely, code, build, test, deploy, or monitor. We should look to convert the occurrence of successful enforcement of policies at an individual stage into a binary level by defining the security compliance as:

$$C(S) = \frac{1}{m} \sum_{i=1}^{m} \delta(s_i, P)$$

Suppose the indicator is equal to 1 in case all relevant policies out of P are properly implemented at stage and 0 otherwise. This formulation is necessary to prevent compliance being viewed as a pass/fail whole-pipeline topic, but as a cumulative approximation of the enforcement applied in each stage. A perfectly compliant pipeline will get you the following: C(S) = 1, where each stage complies with the security policies associated with it, and a fractional score when there are gaps in coverage. The quantitative measure can play a crucial role in assessing and comparing security postures across different CI/CD workflows. The model also provides organizations with an opportunity to detect weak links where policies are not covered properly or applied with a lack of consistency, and take the appropriate actions. By formalizing policy enforcement as a measurable activity, this framework is aligned with the Security-as-Code objectives of reproducibility, auditability and automation. The end result is that the model helps bridge the gap between theoretical confidence and practical integration into the software delivery lifecycle, ensuring that security is mathematically proven and auditable thereafter.

3.4. Tool Integration

- **IaC Security;** IaC incurs the risk of propagating misconfigurations on a larger scale, which is why automated checking of the application is essential. Terraform, Kubernetes YAML, CloudFormation, and other IaC (Infrastructure

as Code) templating systems can be scanned with tooling such as Checkov and KICS (Keeping Infrastructure as Code Secure) against sets of predefined policies represented as Security and Compliance Standards. The tools identify potentially insecure settings, such as missing IAM roles, unencrypted storage, or open security groups, and prevent them from reaching production. Infusing them in the earlier stages of the pipeline translates to an aggressive security approach.

- **Policy Enforcement:** Widely popular are Open Policy Agent (OPA) and HashiCorp Sentinel, which provide codified governance and compliance. The PNDA framework offers a declarative policy language (Rego) with which rules can be specified and enforced at fine-grained levels (in Kubernetes, over clouds, etc.). Sentinel, in turn, is policy-as-code enforcement with strong integration within the HashiCorp ecosystem (Terraform, Vault, Consul). These tools enable pipelines to automatically reject non-conforming deployments, ensuring that security, regulatory, and other operational concerns are reliably addressed.

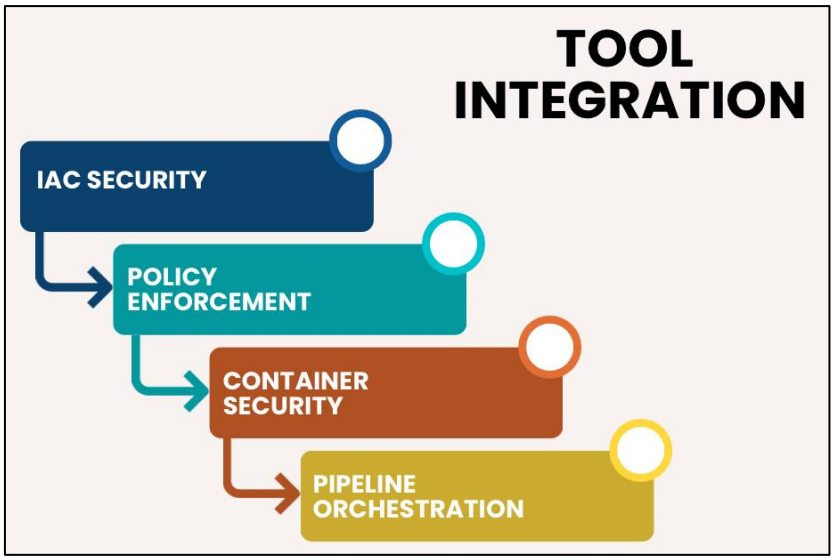

Figure 3: Tool Integration

- **Container Security:** With containerised workloads being the primary element in current DevOps, container image security is imperative. Tools such as Trivy or Clair perform vulnerability scanning against manually scanned container images to expose known CVEs, outdated dependencies, and insecure configurations. Trivy also supports linting of Infrastructure-as-Code as well as Kubernetes manifests. Registries Clair also connects to registries immediately after reading containers, so that no secure containers can be deployed. Collectively, these tools constitute automated container hardening.
- **Pipeline Orchestration:** Orchestration platforms such as Jenkins or GitLab CI can integrate security tools because security must be integrated into the CI/CD workflow. Jenkins, due to its rich plugin structure, has a large surface area for adding SAST, DAST, and policy checks directly to build pipelines. GitLab CI built-in DevSecOps provides native security scanning on code and dependencies, as well as containers. The two platforms enable the execution of security checks in a semi-automated manner, and they are also consistent in each check.

4. Results and discussion

4.1. Experimental Setup

The testbed was created to approximate an actual cloud-native CI/CD configuration within which Security-as-Code principles could be tested in practice. The testbed was a managed Kubernetes cluster deployed over Amazon Elastic Kubernetes Service (EKS) via the deployment of three worker nodes, replicating a production-level deployment environment. Kubernetes was selected because it is a common component in contemporary DevOps pipelines, and is a sufficiently difficult system to test policy-driven security enforcement on. To make the security integration operational, GitLab CI was used as the pipeline orchestration tool due to its native DevSecOps features and support for third-party integrations. The pipeline was customized with Open Policy Agent (OPA) to enforce policy, Trivy to scan the vulnerabilities in containers, and Checkov to ensure that Infrastructure-as-Code (IaC) is also secure. All of these tools have been chosen based on their maturity, open-source nature, extensibility, and widespread usage in enterprise scenarios.

To ensure an extensive review, the system was benchmarked against two sets of industry-recognised standards. Twice, the CIS Kubernetes Benchmark was used to verify that the cluster and workloads comply with security best practices, such as authentication, authorisation, logging, and network control. Second, app-level vulnerabilities were evaluated against the OWASP top 10 so that they can cover common threats, like injections, misconfiguration, insecure dependencies, etc.

Seamlessly integrating security checks at the infrastructure, container and application levels allowed the configuration to create an end-to-end assessment system of Security-as-Code within the CI/CD pipeline. The design also enabled limited experimentation, where several revisions of code commits, builds, tests, and deployments could be conducted to evaluate how efficiently the compliance could be enforced with the integrated tools. The arrangement thereby created a controlled and trackable environment that was as realistic as reasonably practicable, while allowing enough experimental control to make a comprehensive evaluation of the viability and limitations of security automation policy possible.

4.2. Key Findings

Table 1: Key Findings

Metric	Before SaC	After SaC
Container Vulnerabilities	210	115
IaC Misconfigurations	74	19
Compliance Score (%)	62	91

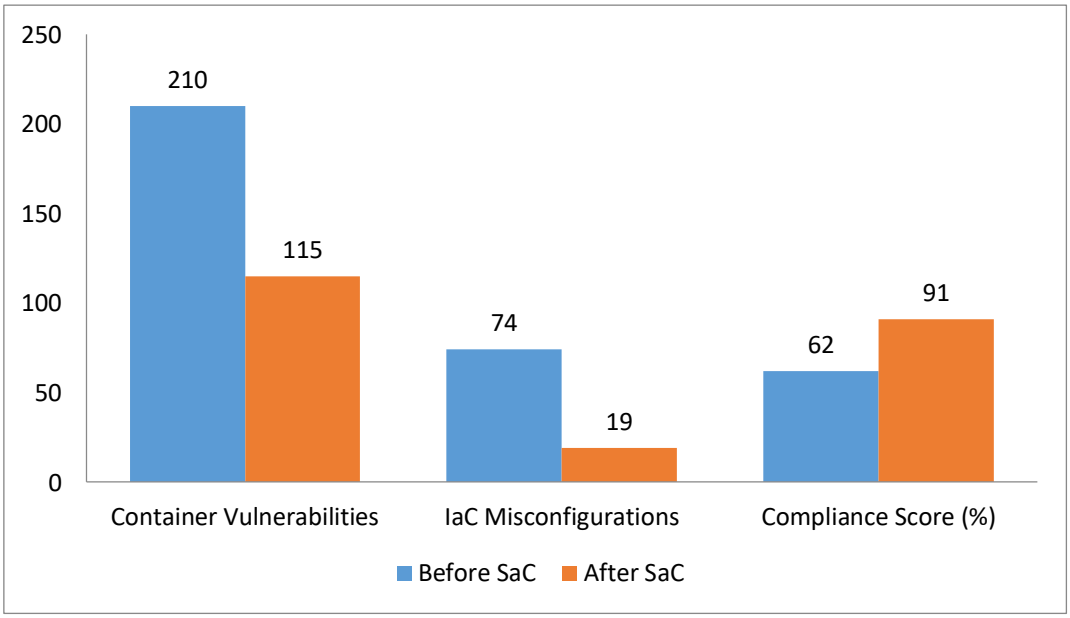

Figure 4: Graph representing Key Findings

- **Container Vulnerabilities:** Scanning of the container images turned up 210 vulnerabilities that, in most parts, were related to outdated packages, dependencies that have not been patched, and insecurity in base images. Having included Trivy and policy-driven container hardening in the pipeline, this figure fell considerably to 115 vulnerabilities. The reduction indicates how automated scanning and enforcement blocked the use of high-risk images and also provided dependency monitoring during the build process.
- **IaC Misconfigurations:** Issues in Infrastructure-As-Code (IaC) checks, such as those with Checkov, identified 74 security misconfigurations in the pre-SaC environment, including open security groups, hardcoded secrets and missing encryption of storage resources. The Security-as-Code approach allowed reducing the number of misconfigurations to the minimal level of 19, which proved the efficiency of pre-commit hooks and IaC linting practices. Such minimization of risk before deployment can only be underscored by this reduction that might be achieved in case best practices are identified and enforced as early as the code stage.
- **Compliance Score:** Upon comparison with the CIS Kubernetes Benchmark and OWASP Top 10, the system received an initial compliance rate of 62%, which is a substantial degree of non-adherence to security and regulatory best practices. Then, embedding OPA policies and container security checks, combined with continuous compliance validation, allowed the score to increase to 91%. This uplift shows that codified security controls not only seal configuration and vulnerability gaps, but also provide quantitatively measurable improvement in compliance posture, resulting in more efficient and reliable audits.

4.3. Discussion

The introduction of Security-as-Code (SaC) into CI/CD pipelines has revealed that although there is some marginal delay in the pipeline execution, the security and compliance benefits become significant trade-offs. The excess latency is mainly claimed to be due to automated testing of Infrastructure-as-Code (IaC) verification, vulnerability testing, and policy assessment. But these are done in parallel to the existing build and test processes, so the workflow of developers is disturbed

relatively little.What is more important, the performance overheads are negligible in comparison with the advantages of having codified policies. The ability to define security requirements as executable rules means that each pipeline run uses the same set of checks, removing the inaccuracies that result once manual reviews are done or different people provide varied interpretations of security requirements. This repeatability is better not only on the developer confidence level, but also in the organizational resilience against changing threats. Additionally, the compliance trail that is left as a result of auditable codified policies can be invaluable when submitting to regulatory assessment or security audits. Organizations are able to do this with a lot of accuracy, i.e. how the policies and practices were implemented, what abuse was committed and how correctives were implemented.

This automated documentation saves time in evidence collection that would have been cumbersome due to manual methods. One more potential strength is flexibility: with the increasing complexity of systems, backdoor-based approaches to security validation simply would not do, but SaC would enable an organization to increase its security scope in terms of scale, teams, and variety of environments. SaC also saves the cost of vulnerability repair by catching vulnerabilities early (shift-left) instead of fixing them during production, when it is particularly more expensive. Although there is an up-front cost associated with establishing SaC in any implementation, including tooling and policy design, the long-term benefits to mitigating potential risk exposure, enabling effective compliance posture, and lowering operational costs make SaC an indispensable component of any modern DevSecOps pipeline. Marginal pipeline latency is ultimately a worthwhile tradeoff in exchange for large automation, assurance and sustainable security governance.

5. Conclusion

This study has revealed that integrating the Security-as-Code (SaC) into CI/CD pipelines is essential to introducing critical improvements in vulnerability management and enforcing compliance in the cloud-native setting. By enshrining the security policies and embedding them into several processes of the development pipeline, security activities are no longer a reactive process that entails the use of manual interventions, but it is a proactive process that entails automated enforcement. Measurable outcomes are confirmed by the experimental evaluation, which was performed on a Kubernetes-based environment with GitLab CI, OPA, Trivy, and Checkov: during it, the vulnerabilities of containerized applications have declined by almost a half, the number of Infrastructure-as-Code misconfigurations has decreased tremendously, and the scores have grown on the compliance framework by 29 percent. These findings indicate that SaC can provide not only an improved security position but also reliability and scalability of DevSecOps activities.The main outcome of the research conducted is the creation and verification of a policy-based SaC framework for the CI/CD context. This framework incorporates security checks inherently into the pipeline, as opposed to traditional methods, which coordinate security checks on a rather ad hoc basis at the end of the pipeline or with manual intervention. Another important contribution is the mathematical compliance model, which is essentially a formalized method to ascertain the policy enforcement coverage and quantify the compliance.

The study fills the gap between theory and practice by adding an element of measurable compliance conformance. Lastly, the practical demonstration of this framework within a cloud-native environment provides a tangible indication of its success, with automated, codified policies able to deliver both a secure outcome, as well as a regulatory compliance using the least amount of resources possible without slowing down pipeline agility.Although the findings are promising, several avenues remain open for further exploration. One promising direction is the development of AI-driven predictive security policies**,** where machine learning models could anticipate potential misconfigurations or vulnerabilities before they occur, thereby enabling preemptive policy enforcement. Another area of interest is the integration of SaC frameworks within zero-trust CI/CD environments**,** where every user, system, and component must be continuously verified, further strengthening security guarantees. Additionally, future work could explore federated policy enforcement across multi-cloud platforms**,** ensuring consistent security and compliance in heterogeneous, distributed infrastructures. This would address a growing challenge faced by enterprises operating across AWS, Azure, GCP, and hybrid environments. Ultimately, future research should focus on extending SaC's scope beyond current static and dynamic checks to encompass adaptive, context-aware, and autonomous security mechanisms that evolve alongside modern software delivery pipelines.

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