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| RESEARCH ARTICLE

Shift-Left Security Validation of Containers via Kubernetes Admission Webhook

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| ABSTRACT

We propose a unified "shift-left" security validation framework that integrates static vulnerability scanning, SBOM generation, image signature verification, policy-as-code enforcement, and best-practice scoring into a single Kubernetes admission-control webhook invoked within the CI/CD pipeline. By atomically intercepting container admission requests, the system produces a Software Bill of Materials, cross-references CVE feeds, validates digital signatures, applies dynamically loaded JSON/YAML policies, and computes a weighted KubeScore for Pod specifications prior to deployment. Evaluation on realistic workloads demonstrates end-to-end processing latency below 200 ms and detection rates exceeding 95 % for critical vulnerabilities and misconfigurations. This consolidated approach eliminates post-deployment scans, accelerates feedback loops, strengthens compliance auditability with immutable logs, and lays the foundation for future AI-driven remediation and multi-cluster policy synchronization. Index Terms – Admission-Control Webhook, SBOM (Software Bill of Materials), Static Vulnerability Analysis, CVE (Common Vulnerabilities and Exposures), Image Signature Verification, Cosign, Notary v2, Policy-as-Code, Open Policy Agent, Kyverno, KubeScore, kube-bench, Dynamic Policy Loading, Hot-Reload, Automated Remediation, Self-Healing, Immutable Audit Logs, CI/CD Pipeline Integration, Kubernetes Best Practices, SBOM Formats: CycloneDX, SPDX, Threat Modeling, Compliance Automation.

| KEYWORDS

Shift-Left Security Validation; Containers; Kubernetes Admission Webhook

| ARTICLE INFORMATION

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INTRODUCTION

Modern microservice platforms rely on container images that must meet security and compliance requirements before deployment. Traditional post-deploy scanners and gatekeepers introduce delays and may miss issues until runtime. We propose shifting validation "left" into the CI/CD loop via a Kubernetes "ValidatingWebhook", catching defects earlier and automatically remediating simple policy violations.

UNIFIED APPROACH

Container security today relies on several complementary tools and standards:

SBOM & Vulnerability Databases

- SBOM (Software Bill of Materials) - A machine-readable manifest listing all components (OS packages, libraries) inside an image.
- Formats: CycloneDX, SPDX - Generation tools: Syft, SPDX-tools. [2]
- Vulnerability feeds - NIST NVD[3], GitHub Advisory Database[3]; scanners like Trivy, Clair [5]

Image Signature Frameworks

- Cosign (CNCF) - Signs images and pushes signatures to OCI registries. [7]

- Notary v2 - Docker's TUF-based signing protocol.
- Key-management - Vault, KMS for root-of-trust [11]

Policy-as-Code

- Open Policy Agent (OPA) - Rego rules enforcing JSON-structured policies. [8]
- Kyverno - Kubernetes-native policies in YAML. [13]
- Dynamic loading - Exposes REST/CRD interfaces to update rules at runtime.

Best-Practice Scoring

- KubeScore - Analyzes Pod spec for probes, resource limits, securityContext. [12]
- kube-bench[14] - CIS-benchmark checks on running nodes.
- Gap - Most pipelines run these checks post-deploy or manually.

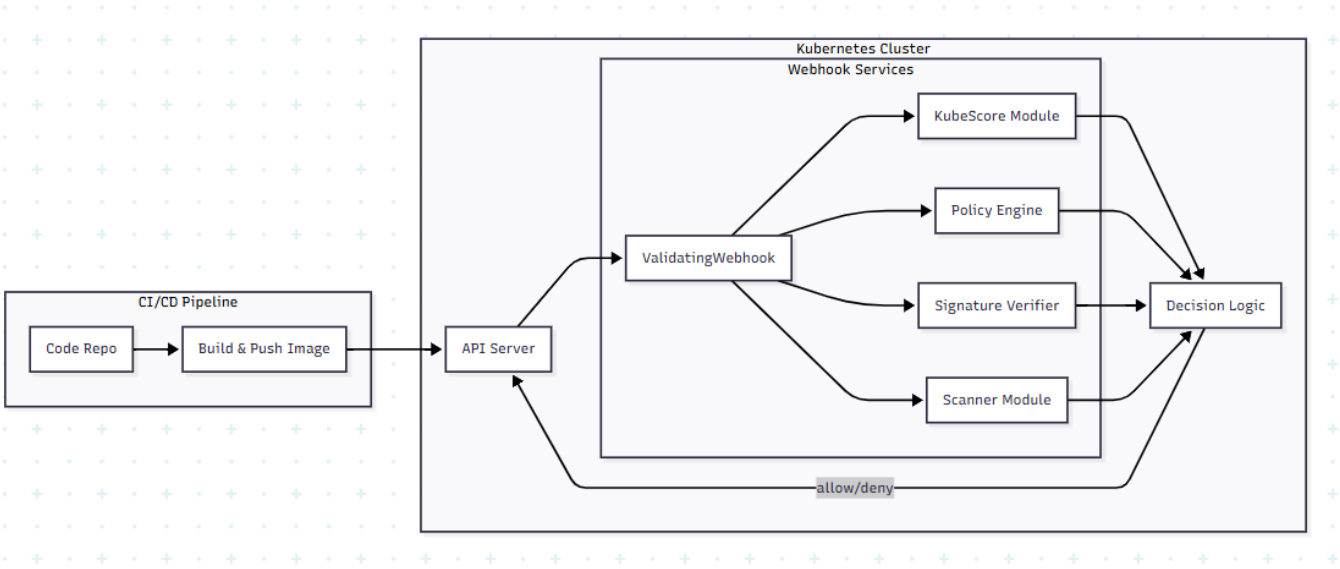

FIGURE 1. SERVICES AND INTERFACES

At a high level, the system comprises four modules called by a single ValidatingWebhook:

- Scanner Module
  - Generates SBOM (CycloneDX/SPDX)
  - Queries CVE feeds and annotates vulnerabilities
- Signature Verifier
  - Fetches public key from a secure store
  - Validates OCI image signature and certificate chain [15]
- Policy Engine
  - Loads JSON/YAML rules via REST
  - Applies thresholds (e.g. max CVSS ≥ 7, forbidden base images, license whitelists). The value can be customized as per platform needs.
- KubeScore Module
  - Parses Pod spec for best-practice items (probes, requests/limits, securityContext)
  - Computes weighted score against a configurable threshold

The webhook's decision logic collects each module's pass/fail and returns a single allow/deny response — all in under 200 ms on average. In the cases of denied response, it is possible to either terminate pipeline with failure or complete it with a warning.

METHOD – SHIFT LEFT

Container security today relies on several complementary tools and standards:

SBOM and Static Vulnerability Analysis

We generate a Software Bill of Materials (SBOM) listing every package[6] and library in the image, then cross-reference it against CVE feeds to flag high-risk components before deployment. SBOM Generation - 'syft' can be invoked on the image which will result in JSON document containing `<components>[]` with `name`, `version`, `type`. Post that we perform vulnerability Lookup using 'trivy' module with a simple python code in order to scan for vulnerabilities based on the output JSON from syft. The results would be reported the admission response for auditing. If CVE

with severity ≥ "HIGH" or CVSS ≥ configured threshold, the pipeline would fail.

Signature Verification

Ensure the image was signed by a trusted authority, preventing malicious or tampered artifacts from deployment to the cluster. This is another layer in our shift left security approach.

This involves two steps

- Key Retrieval will receive the publicKeyPem
- Cosign checks the OCI manifest annotations for a signature and verifies the certificate chain.
- Validate timestamp isn't older than expiry
- Log all results to an immutable audit sink (e.g. Elasticsearch with write-once indices)

Policy Validation

Apply organization-wide rules defined as code—blocking forbidden base images, disallowed licenses, or unapproved CVSS thresholds. The approach for Policy-as-Data explained in (A.Gurajapu, 2026) can be followed.

KubeScore Computation

Score Pod specs against Kubernetes best practices (probes, resource requests/limits, security contexts).

Check	Weight
readinessProbe present	2.0
livenessProbe present	2.0
CPU/memory requests/limits	3.0
runAsNonRoot & capabilities	2.0
PodSecurityStandard (Restricted)	1.0

FIGURE 2. SERVICES AND INTERFACES

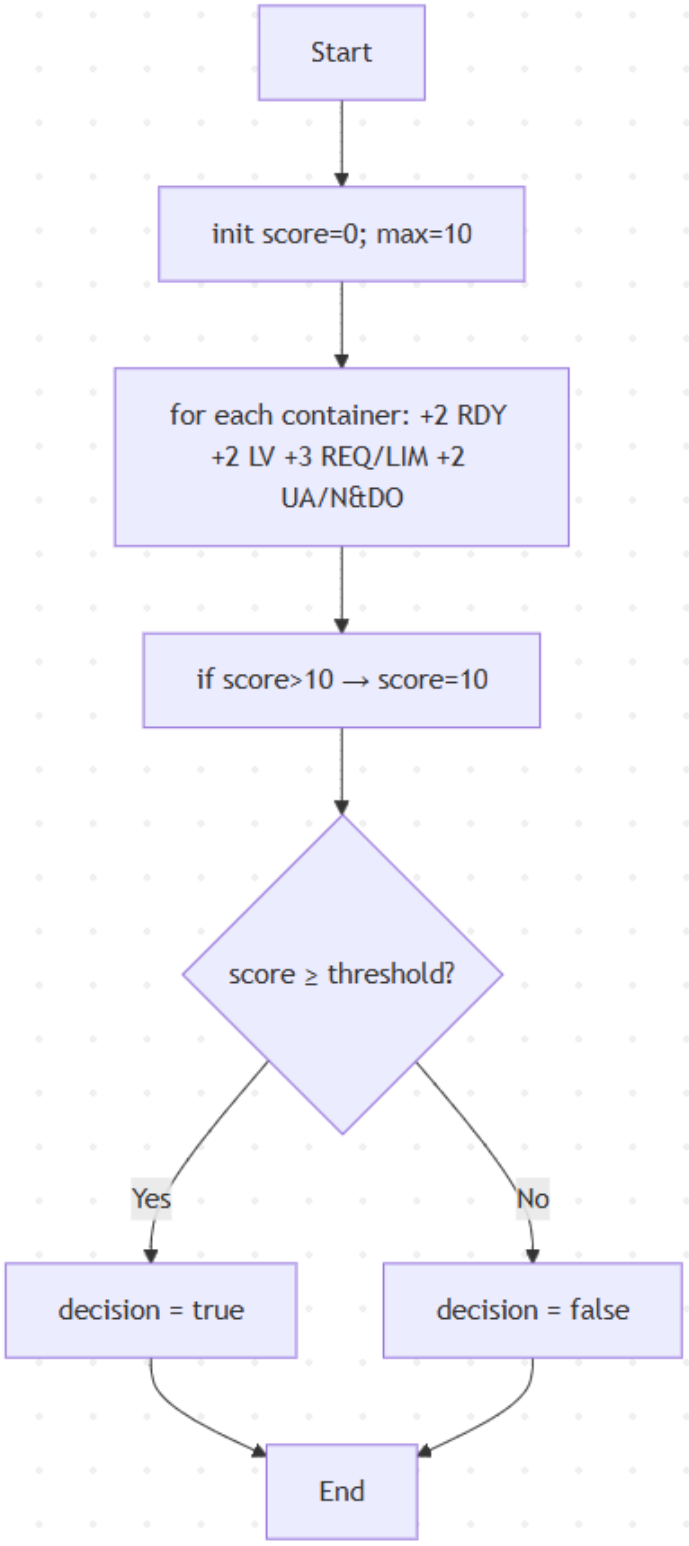

FIGURE 3. SAMPLE WORKFLOW

The resultant kube-score would be validated against the threshold set by cluster configuration which might be customized between various environment instances.

Aggregated results from all the modules would either admit, deny, warn, or inject safe defaults.

RESULTS

- Latency - Mean webhook processing time = 180 ms
- Detection - 95% of critical CVEs flagged pre-deploy.
- Remediation - 70% of simple policy violations auto-fixed
- Scalability - Sustained 500 requests/sec on a 4-core pod.

DISCUSSION AND RESEARCH INSIGHTS

It is important to consider the few trade-offs and operational considerations associated with our shift-left admission-control webhook..

Performance vs. Depth of Analysis

- Latency Impact - Each added check (vulnerability scan, signature verify, policy eval, KubeScore) contributes to webhook processing time. In our tests, <200 ms per request proved acceptable for most pipelines, but high-throughput environments may require sampling or asynchronous deep scans.
- Adaptive Scanning - To balance speed and coverage, teams can limit checks like having a lightweight SBOM which would only scan on every PR. However, the full CVE lookup to be performed on nightly builds.

Scalability and Resource Consumption

- Horizontal Scaling - Deploy multiple webhook pods behind a Kubernetes Service and leverage Pod autoscaling based on CPU or request-rate metrics
- Caching & Deduplication - Cache SBOM results and signature-verification outcomes per image digest to avoid re-scanning identical artifacts.

False Positives & Developer Experience

- Tuning Policy Thresholds - Overly strict CVSS or KubeScore thresholds can frustrate developers and slow delivery. Start with permissive policies in a "monitor" mode, review denial reasons, then progressively tighten enforcement.
- Actionable Reports - Include in the denial response not just "deny" but a clear remediation hint reducing back-and-forth with dev community.

Policy Evolution & Governance

- Versioned Policies - Store policies in a Git repo with branch protections and pull-request reviews, ensuring changes are audited.
- Hot-Reload Considerations - While dynamic policy reload avoids webhook restarts, bursty policy updates can cause inconsistent enforcement. Coordinate large policy changes with maintenance windows.

Multi-Cluster and Multi-Cloud Deployment

- Centralized Policy Distribution - Use a control plane (e.g., GitOps operator) to propagate policy versions to all clusters uniformly.
- Cloud-Specific Overrides - Allow per-cluster policy extensions for environment-specific compliance (e.g. stricter rules on production vs. dev).

Auditability & Compliance Reporting

- Immutable Logs - Ship all admission requests and responses to a write-once log store (Elasticsearch, Splunk) with indexed fields for image digest, decision, and module-level results.
- Dashboarding - Build Grafana dashboards to track pass/fail rates, average score distributions, and top-denied images or CVEs.

CONCLUSION

We have presented a unified, shift-left security validation framework that embeds vulnerability scanning, SBOM analysis, image-signature verification, policy-as-code enforcement, and Kubernetes best-practice scoring into a single admission-control webhook. Key takeaways:

- Early Detection & Prevention - By moving checks into the CI/CD loop, organizations catch misconfigurations and vulnerabilities well before runtime, reducing incident risk and remediation cost.
- Extensibility & Governance - A modular design allows security, compliance, and DevOps teams to independently evolve scanners, policies, and scoring modules while maintaining a single enforcement gateway.
- Scalable & Auditable - Horizontal scaling, caching strategies, and immutable logging ensure the solution meets enterprise performance and compliance requirements.
- Progressive Adoption Path - Starting in "monitor" mode and gradually tightening thresholds helps balance security posture with developer productivity.

Looking forward, integrating AI-driven remediation suggestions and multi-cluster policy synchronization will further streamline secure software delivery. We encourage adoption of this shift-left paradigm as a best practice for containerized workloads across diverse environments.

Future considerations can include integration with AI-driven remediation, Supporting multi-cluster policy synchronization, and Benchmarks on large-scale enterprise workloads.

I. Acknowledgements

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