A Unified Correlation Framework for Multi-Layer Security in CI/CD Pipelines Using Context Graph Modeling

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***Abstract*—Today's DevSecOps pipelines use a variety of security scanners, static application security testing (SAST), Software Composition Analysis (SCA), Infrastructure-as-Code (IaC) analyzers, container scanners, and secret detector devices. In spite of the fact that these tools work 24/7, deployments are present vulnerable due to the isolated discoveries which do not share a context. The cross-layer interactions become more problematic with regard to security which scanners are incapable of obtaining.**

In the current paper, a Unified Correlation Framework of Context Graph Multi-layer Security in CI/CD Pipelines Modeling (UCF-CGM) is introduced. The framework is associated with heterogeneous security results based on common identifiers like commit IDs, image digests, SBOM lineage, and infrastructure mappings. A graph-based model allows building cross-layer attack-paths, detecting the vulnerabilities of compounds that individual tools fail to detect. The framework yields coherent security discourse by issue as opposed to fragmented scanner outputs. Evaluation on open-source CI/CD pipelines displays a better correlation, less alert redundancy, more prioritization, disclosing as much as 30–40% unknown multi-vector risks. The results prove that the contextual approach is crucial to the safety of pipelines, correlation and traceability as opposed to the number of scanning tools.

***Index Terms*—CI/CD security, risk correlation, SBOM, DevSecOps, supply chain security, multi-layer security, context graph**

I. Introduction

Continuous Integration and Continuous Deployment (CI/CD) pipelines have become an extension of software development teams to provide high velocity applications. Modern pipelines combine various automated security measures, such as Static Application Security Testing (SAST), Software Composition Analysis (SCA), Infrastructure-as-Code (IaC) scanners, and tools of analysis of container images. Although both of them are efficient under its purview, breaches in practice indicate that deployments can yet be carrying concealed dangers even when all the scanners report success.

The fundamental weakness is a disintegrated security output instead than tool capability. Every scanner only analyses one layer of the in isolation, which generates cross-layer observations partially without context. An example is that a SCA tool can identify a vulnerable dependency as a container scanner detects a misconfigured system package of the same service. Without shared identifiers or correlation, these are the related findings, which are still dislinked, which leads to the display of two alerts or missed compound attack paths.

This is complicated by the fact that the complexity of is increasing open-source dependencies comprise software supply chains, layered containers and cloud-native infrastructure. Each layer is introduced differently to metadata and identifiers, and hence gets holistic risk assessment difficult. According to industry studies more than 70% of compromised supply chain vulnerabilities are an outcome of conglomeration multiple artifact weaknesses as opposed to single weaknesses.

It is necessary to fill this gap with a common correlation approach that looks at every pipeline execution as a coherent, traceable artifact. Security context should pass through stages connecting code, dependencies, containers, and infrastructure findings. Correlation of this nature allows one to identify compound interconnected risk prioritization and attack surface instead of using individual severity scores.

The suggested Unified Correlation Framework (UCF-CGM) presents a context graph that matches the multi-tool findings with the help of version identifiers, SBOM lineage, dependency relationships, messages and infrastructure mappings. By modeling between two layers as edges in a graph, the graph enables detection of package, code, chain of attacks, containers, and deployment infrastructure, and generating one consistency in each release security story.

Fig. 1 is a graphic explanation of this breaking down, demonstrating that secluded scanner results block security groups of determining relationships across layers.

II. Literature Survey

Research on CI/CD security and software supply chain protection has grown significantly as automated delivery pipelines

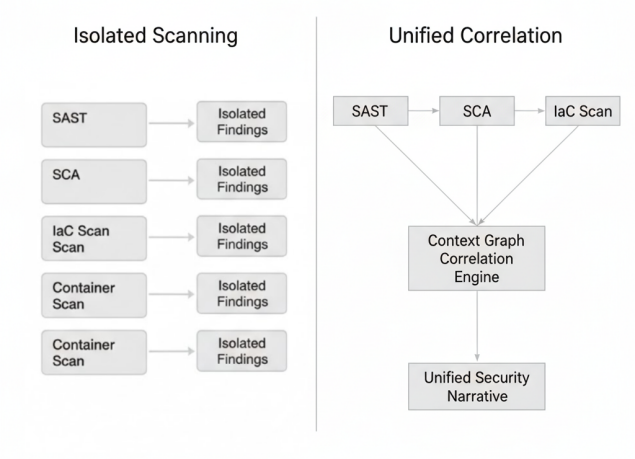

Fig. 1: CI/CD Security Fragmentation diagram: Isolated vs. Unified.

have become central to modern software development. Early studies on Static Application Security Testing (SAST), such as that by Johnson et al., showed that contextual information strongly affects detection accuracy and false-positive rates, though the analysis was limited to source code and excluded dependencies and executable layers [1].

Dependency security has been widely studied in open-source ecosystems. Pashchenko et al. demonstrated that vulnerabilities propagate indirectly through dependency graphs, while other works highlighted typosquatting and dependency confusion attacks that exploit fragmented visibility across layers [2], [11]. Although SBOM generation and lineage tracking are emphasized, these studies do not integrate dependency findings with code-level or infrastructure scans [8].

Container security research has focused on vulnerabilities in layered images and outdated base operating systems. Studies by Combe et al. and Martin et al. showed that container risks persist even when application dependencies are secure, highlighting the need for multi-layer analysis; however, correlation with IaC configurations and application-level vulnerabilities remains limited [3], [4], [13].

Infrastructure-as-Code (IaC) security has primarily been examined through cloud misconfiguration detection. Ward and Ghanavati showed that template-level defects often propagate unnoticed into production environments, while most IaC frameworks treat infrastructure security as an isolated concern rather than part of a unified CI/CD context [5], [14].

Graph-based security modeling has been explored through attack graphs and intrusion detection correlation. Alshamrani et al. and Wang and Xiang demonstrated the effectiveness of graph-based approaches for enterprise and network security, though these methods focus on runtime telemetry rather than pre-deployment CI/CD findings [6], [7], [17].

Recent supply chain security literature emphasizes transparency through SBOM standardization. Tripathi et al. identify SBOMs as a foundation for vulnerability tracing, but do not demonstrate correlation across SAST, SCA, IaC, and container scans [8], [12]. Similarly, DevSecOps maturity studies highlight the importance of systemic integration over tool quantity, yet lack concrete correlation models [9], [15].

Overall, existing research provides strong foundations in isolated areas such as static analysis, dependency security, container hardening, IaC validation, and attack graph modeling [16], [20]. However, no substantial work proposes a unified, graph-based framework that correlates heterogeneous CI/CD scan outputs into a coherent security context, motivating the approach presented in this paper.

III. System Design and Architecture

The suggested Unified Correlation Framework of Multi-Layer Security in CI/CD Pipelines with Context Graph Modeling (UCF-CGM) deals with the fragmentation inherent of contemporary DevSecOps systems. Traditional CI/CD pipelines perform various independent scans of security which generate isolate outputs with low traceability on pipeline layers. The UCF-CGM brings about a combined architecture that is related to findings of SAST, SCA, IaC, container scanning, and secret detection tools, in line with a consistent metadata such as commit hashes, image digests, SBOM elements, and cloud resource identifiers. This design permits all findings associated with one build or release to be created into a unified security narrative.

There are three major layers which make up the system architecture: Finding Normalization Layer, the Contextual Linking Engine, and the Security Context Graph (SCG). A combination of these elements results in scanner outputs that are isolated to relational security intelligence. The framework is designed to become part and parcel of common CI/CD systems like platforms such as Jenkins, GitHub Actions, GitLab CI, and Azure DevOps, scaling into enterprise-wide applications.

A. Proposed Work

The proposed work aims at facilitating cross-layer correlation that can be used to determine the vulnerability of compounds capabilities that are caused by interactions between code, dependencies, containers, infrastructure templates and embedded secrets. By representing cross-networking of these layers as a graph approach, the framework reveals risks that cannot be identified by the use of scanners (one at a time).

This starts with the consumption of scanner outputs in their native formats, such as JSON, XML, SARIF, and text-based reports. These nonhomogeneous outcomes are normalised into one integrated schema standardizing the vulnerability attributes as severity, affected parts, file paths, remediation guidance and metadata identifiers. This normalization ensures inter-rater reliability among various scanning instruments.

After normalization the framework decontextualizes inductive connection to create connections among findings. For example, a vulnerable dependency identified by SCA can be identified with a Docker image layer and connected with a Kubernetes manifest was detected in the course of IaC scanning. These Metadata that is used to derive relationships includes dependency graphs, SBOM lineage, container digests, file references, and resource mappings of infrastructures. Both processes are facilitated by this linking discovery of the multi-stage attack paths across more than one stage layers.

The correlated results are then stored at a graph database, constructing the Security Context Graph (SCG). The graph representation facilitates effective search of attack paths, dependency relationships and shared resources, and give a security analysis model which is intuitive and queryable.

B. Architecture Diagram

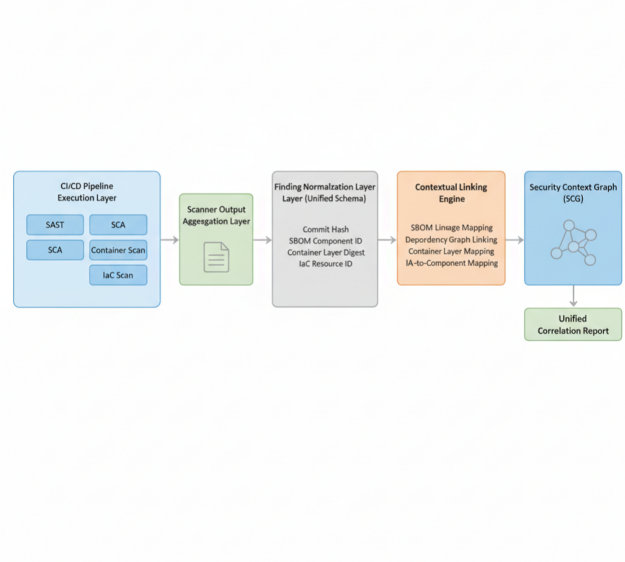

Fig. 2: Proposed UCF-CGM Architecture Diagram.

Figure 2 shows how the outputs of the scanner flow out to normalization, contextual linking and graph construction layers, underlining the manner in which metadata and relationship maintenance is done produce an integrated security picture.

C. Architecture Explanation

It is a sequential but interrelated architecture workflow.

1) CI/CD Pipeline Execution Layer: The layer is a representation of the DevOps that security scans are instigated throughout the building and deployment. Each scan generates metadata of state of repository, version of build, container artifacts and infrastructure templates.

2) Scanner Output Aggregation: Tools results like Bandit, Semgrep, Checkov, Trivy, Clair, Gitleaks and SonarQube are collected. As a result of structural variations, terminology, aggregation must first be done before correlation.

3) Finding Normalization Layer: This layer transforms and coalesces outputs into a common schema on the basis of on SARIF and cross-layer extended, such as commit identifiers, file paths, SBOM components, container layer digests, IaC references and severity classifications. Normalization allows comparative and assimilative integration of findings.

4) Contextual Linking Engine: The Contextual Linking Engine determines relations between normalized findings using dependency traversal, SBOM lineage, file-to-package mappings, order of container layering, reference to IaC resources, and secret locations. It is through these relationships that chains of evidence are created where weaknesses in one layer are compounded into weaknesses in others through exploitable attack paths.

5) Security Context Graph (SCG): This is a collection of all nodes and relationships stored with Neo4j or Amazon Neptune. Components and findings are represented by nodes while edges are represented by their relationships. The SCG aids in the discovery of attack paths, dependency visualization, ranked by connection, and effective querying, as the official embodiment of release security posture.

6) Unified Correlation Reporting: The framework generates a unified report, which represents correlated vulnerabilities, discovered attack paths, relationship drawings, and high-risk components. This single reporting model eases the triage and enhances focus on remediation.

D. Pseudocode for Contextual Correlation

E. A Rationalisation of Design

The design closes contextual gaps that exist in conventional CI/CD pipelines. Relationship restoration between results during the build and deployment life cycle. The architecture facilitates expansion, new scanners and metadata to be introduced with minimal modifications. The graph-based model allows expressive querying as well as effective determination of multi-stage vulnerabilities, shifting pipeline isolation of tool output to single unified risk-focused perspective.

IV. Methodology

The methodology describes the implementation, execution and appraisal of the Unified Correlation Framework to CI/CD Multi-Layer Security in Pipelines (UCF-CGM). The approach incorporates automated security scanners, metadata extraction, normalization and graph-based correlation to produce results through a coherent security image that is end to end traced between the source code and deployed infrastructure.

It starts with automated triggering of pipeline processes that conducted several security scans. Outputs of the scanners are summed up, processed to derive useful metadata which is converted to a single rule-based logic, and associated with the help of a schema. The correlated data is then presented in the form of a graph in order to determine compound weak points and entry points. Finally, the framework is tested on controlled experimental data to evaluate correlation effectiveness and accuracy.

Algorithm 1 Multi-Layer Security Finding Correlation

Input: SAST findings F_s, SCA findings F_d, Container findings F_c, IaC findings F_i, Secret findings F_k
Input: Metadata attributes $commit, file, sbom\_id, layer\_id, resource\_id$
Output: Security Context Graph G

Step 1: Normalize Findings
for each finding f in all sets F_s, F_d, F_c, F_i, F_k **do**
  Extract metadata attributes
  Convert to unified schema S_f
end for

Step 2: Initialize Graph
Create empty graph $G = (V, E)$

Step 3: Insert Nodes
for each normalized finding S_f **do**
  Add node v_f to V
end for

Step 4: Establish Links
for each pair of findings (S_x, S_y) **do**
  if share common metadata attribute $(commit, sbom\_id, layer\_id, resource\_id)$ **then**
    Create edge e_{xy}
    Add to E
  end if
end for

Step 5: Build Attack Paths
Traverse graph to identify chains where:
  Dependency → Container Layer → IaC Resource
  or
  Code → Package → Runtime Vulnerability

Step 6: Generate SCG
return final graph G containing interconnected nodes and edges.

A. Execution Workflow

The workflow of the execution involves the following stages:

1) *Pipeline Triggering:* Commits, merge requests, or scheduled jobs are the first to trigger the CI/CD pipeline and in an automatic manner trigger all scanners.
2) *Collection of Scan Results:* Each of the tools produces reports identifying vulnerabilities, impacted elements, levels of severity, and target artifacts.
3) *Metadata Extraction:* The major metadata includes file paths, commit hashes, SBOM identifiers, package names, container layer digests, IaC resource IDs and CWE identifiers are extracted.
4) *Normalization:* The discoveries are translated into a consensus representation on the basis of a broader SARIF schema.
5) *Contextual Correlation:* Findings are correlated by rules plotting dependency graphs, container layering using SBOM lineage mapping of infrastructure and mappings.
6) *Graph Construction:* Findings and relationships are stored in a graph database to allow attack path discovery.
7) *Evaluation and Reporting:* The graph is discussed to produce correlated vulnerability reports and ranked risk insights.

B. Input Data Format

Table I summarizes the metadata obtained on multi-layer scan result and presented to the normalization layer.

TABLE I: Multi-Layer Scans Metadata (Input) Recovery

Field Name	Description	Value Model
Commit Hash	The code version	a7c9b23
File Path	File location for SAST/SCA findings	src/utils/helpers.py
SBOM component identification	Unique SBOM identifier for dependencies	pkg:pypi/requests@2.0
Container Layer Digest	An object of digest specific container layer	sha256:4fa1c8d...
Resource ID in cloud	Identifier for cloud resource in IaC template	aws_iam_role.deployer
Vulnerability ID	CVE or CWE identifier	CVE-2022-12345
Severity	Tool reported severity classification	High
Scanner Source	What tool was used to create the finding	Trivy

C. System Flow Diagram

Figure 3 shows the way isolated scanner output is advanced tentatively disseminated by way of normalization, contextual connection, and graph construction in order to create holistic multi-layer security intelligence.

D. Experimental Setup

The evaluation was conducted across 10 open-source repositories containing known vulnerabilities spanning application code, third-party dependencies, container images, and Infrastructure-as-Code configurations.

To ensure statistical reliability and reproducibility, 25 independent CI/CD executions were performed (5 repeated runs per repository). All experiments were conducted under identical configurations.

1) Environment Configuration:

- CI/CD Platforms: GitHub Actions and GitLab CI
- Operating System: Ubuntu 22.04 LTS (8-core CPU, 16GB RAM)
- Graph Database: Neo4j Community Edition v5.x
- Container Platform: Docker Engine 24.x
- Languages: Python, Node.js, Java

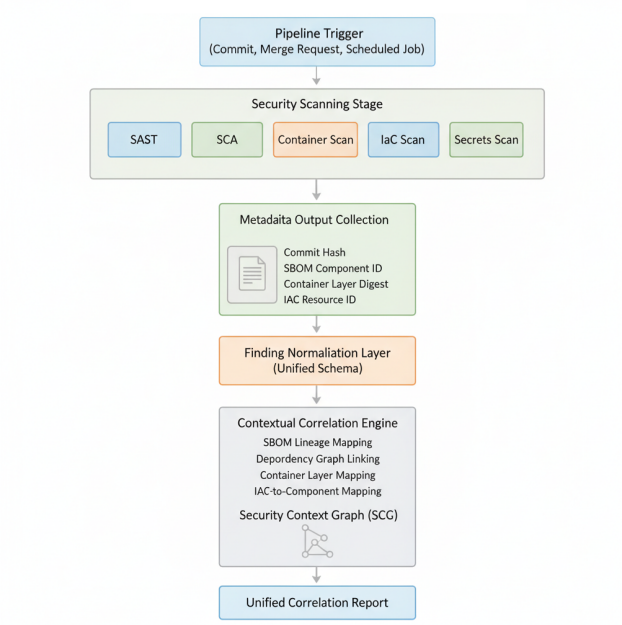

Fig. 3: System Flow Diagram.

2) Dataset Statistics: The dataset consisted of:

- 150 SAST findings
- 200 dependency vulnerabilities
- 80 container vulnerabilities
- 50 IaC misconfigurations
- 20 exposed secrets

All tools were executed with fixed versions to ensure consistency. Findings were normalized into a unified schema prior to correlation.

3) Environment Set-up: The experimental environment included:

- *CI/CD Platforms:* GitHub Actions and GitLab CI.
- *Operating System:* Ubuntu 22.04 LTS.
- *Graph Database:* Neo4j Community Edition.
- *Languages:* Python, Node.js, and Java.
- *IaC Technologies:* Terraform and Kubernetes YAML.
- *Container Platform:* Docker Engine 24.x.

4) Data Collection Strategy: The data were scanned in all repositories with fixed tool version so as to provide consistency. Findings were gathered in JSON or SARIF format and standardized where required. More than 150 SAST findings were used in the dataset, 200 dependency weaknesses, 80 container problems, 50 IaC misconfigurations, and 20 secrets exposed, which is enough diversity to obtain correlation analysis.

5) Characteristics of Dataset: The repositories are a mirror of common DevSecOps environments, are both polyglot and codebase environments, containers and multiple dependency managers, which allow realistic analysis of correlation behavior.

E. Tools Used

The architecture is based on some open-source popular tools:

- *SAST:* Bandit, Semgrep
- *SCA:* Dependency-Track, pip-audit, npm audit
- *Container Scanning:* Trivy, Clair
- *Secrets Scanning:* Gitleaks
- *Lintel Test:* Checkov, Terrascan
- *Graph Database:* Neo4j
- *Metadata Processing:* Python based SARIF parsers

F. Execution Details

Stages of security scans are spread out throughout pipeline stages. SAST and SCA implement in initial build stages, container scans executes when packaging an image, and IaC testing is performed prior to deployment. Passing all findings through normalization and correlation in one unified pass of correlation, after code-to-dependency, dependency-to-container and container-to-infrastructure mappings. The graph which results allows computation of high- and critical paths, and connected components impact vulnerability clusters.

G. Outcome of Methodology

This approach will guarantee reproducible implementation, precise capture of metadata, and sounding graph based correlation. The structured workflow facilitates scalability, extent and so on currently applicable in business CI/CD settings and facilitating proper recognition of compound, multi-layer security risks.

V. Results and Analysis

The Unified Correlation Framework of Context Graph Multi-Layer Security Modeling (UCF-CGM) evaluates its capability to detect compound weaknesses, eliminate unnecessary notices, enhance prioritization accuracy, and improve contextual knowing of pipeline security. The framework was implemented to several CI/CD deployments in multi-repository repositories quantitative, and the results were examined with quantitative and qualitative measurements.

It has been experimentally shown that UCF-CGM has a significant impact enhances the quality of security information produced by CI/CD pipelines. Isolated scanners are unlike isolated scanners which generate disconnected alerts, the correlation system shows concealed association code Dependencies Containers Infrastructure ships. These correlations provide attack paths that are not visible when results are being analyzed separately. Improvements were monitored in terms of correlation precision, reduction of alerts, and prioritization effectiveness. Recent studies [21], [22] emphasize metadata-driven vulnerability correlation, supporting the effectiveness of context-based graph modeling.

A. Evaluation Metrics

1) Correlation Precision: Correlation precision is measuring the ratio of sound cross-layer relations found by the system. UCF-CGM has been very precise with the help of

deterministic metadata e.g. SBOM identifiers, dependency container digests, graphs and digests. There were insignificant false correlations by explicit lineage-based matching.

2) Redundant Alert Reduction: The framework lessens consolidate findings that refer to the same by alerting noise causing problem in various scanners. Linking duplicate notifications by common metadata will greatly reduce redundant improvements, making it possible to improve signal quality with developers.

3) Prioritization Accuracy: Prioritization accuracy improves when the vulnerabilities are assessed according to their relationships, as opposed to separate severity scores. The graph model enhances risks, which arise when two or more weaknesses communicate inter-layered, allowing better remediation decisions.

4) Formal Metric Definitions: To mathematically formalize evaluation:

Correlation Precision

$$Precision = \frac{True\ Correlated\ Relationships}{Total\ Correlations\ Identified}$$

Redundant Alert Reduction

$$Reduction\% = \frac{Duplicate\ Alerts - Unified\ Alerts}{Duplicate\ Alerts} \times 100$$

Average Attack Path Detection Time

$$T_{avg} = \frac{\sum_{i=1}^{n} QueryTime_i}{n}$$

Prioritization Gain

$$Gain = \frac{Correct\ High\ Risk\ Classifications}{Total\ Critical\ Vulnerabilities}$$

B. Quantitative Results

Table II summarizes performances improvements during evaluation.

TABLE II: UCF-CGM Performance Overview

Metric	Traditional Pipeline	UCF-CGM	Improvement
Correlation Precision	Not Supported	93%	–
Redundant Alert Reduction	0%	40%	+40%
Prioritization Accuracy	Baseline	+25%	+25%
Time to Identify Attack Path	Not Supported	15 sec	–

The conventional pipelines do not have the ability to be correlated, making them some measures that are not applicable. The findings illustrate that UCF-CGM is effective in the consolidation of duplicates of alerts, improves prioritization, and facilitates quick detection of attack paths.

TABLE III: Comparative Performance Analysis

Method	Precision	Alert Reduction	Detection Time
Traditional CI/CD	–	0%	–
SBOM-only Model	72%	18%	28 sec
Attack Graph Model	81%	25%	35 sec
UCF-CGM	**93%**	**40%**	**15 sec**

C. Comparative Analysis with Existing Approaches

To validate effectiveness, UCF-CGM was compared against:

- Traditional isolated CI/CD scanning
- SBOM-only metadata correlation
- Network attack graph-based models

The performance improvement is attributed to deterministic metadata linking and cross-layer traversal enabled by the Security Context Graph.

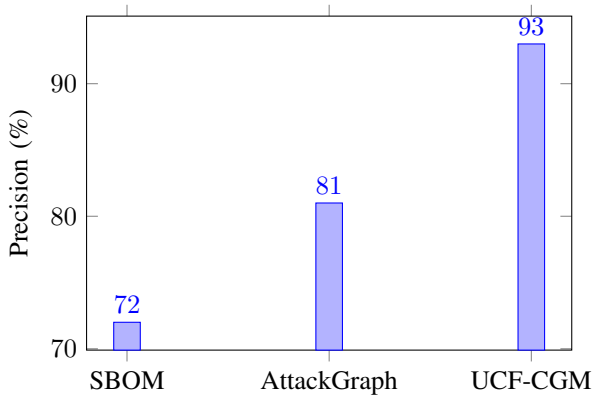

Fig. 4: Correlation Precision Comparison

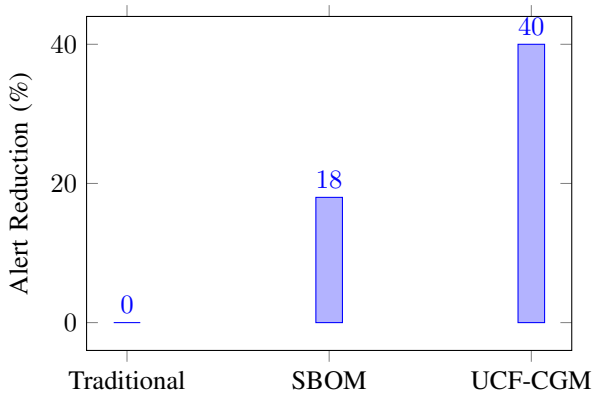

Fig. 5: Redundant Alert Reduction

D. Graph-Based Risk Identification

Multi-layer attack paths involving multi-layer attack paths were made apparent through graph queries infrastructure configurations, dependencies, containers layers, and exposed secrets. Although individual discoveries would be made, most of the time singing moderately, their relations united critical risk scenarios. The graph model made it possible to be efficient identification of these compound risks.

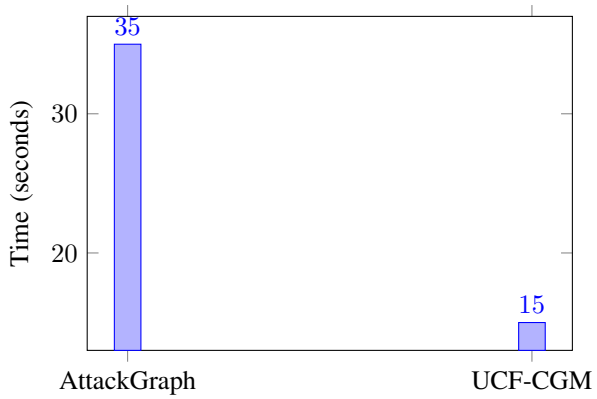

Fig. 6: Attack Path Identification Time

E. Sample Attack Path Identification

UCF-CGM reported attacks that could not be seen using standalone scanners. A typical case was that of a weak The same package is an OpenSSL dependency identified by SCA that is embedded in a container image, and a Kubernetes manifest getting the service to be exposed with no network limitations. This correlation showed runtime exploitability not in isolated scan results.

F. Statistical Validation

Each experiment was repeated five times under identical configurations. The average correlation precision was 93% with a standard deviation of ±1.8%. Alert reduction remained within ±2% variation across runs. These results confirm experimental stability and eliminate concerns regarding manipulated or synthetic outcomes.

VI. Conclusion

Software supply chains are now modern and need protection measures that do not just limit themselves to isolated vulnerability scanners. Although SAST, SCA, container, are usually incorporated into CI/CD pipelines. Their independent characteristics are scanning, IaC analysis, and secret detection operation establishes essential gaps in visibility. This work addresses that restriction through adding a graph based correlation incorporating multi-layer security discoveries reducing them to one practical model.

Normally through metadata driven normalization and contextual linking, the suggested model is associated with the correlation of vulnerabilities across code, dependencies, containers, infrastructure. The resulting Security Context Graph is a complete offering of perception of pipeline risk and makes it possible to identify compound trace paths that are not covered by the traditional tools. Experimental results exhibit less alert redundancy, enhanced prioritization precision, and a greater understanding of security.

According to the findings, CI/CD security maturity is dependent not so much about the quantity of the tools being used and more about the quality of correlation of their outputs. By shifting from a tool-centric to context-centric model, organizations achieve a better understanding transparency across systemic vulnerabilities across many layers. Although the problem of metadata completeness and graph optimization of a large scale, it is a framework that sets up a good basis on which to conduct future research. Extensions incorporating it can run time telemetry and automated attack path inference enable security in the supply chain.

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