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Security-Embedded Quality Assurance: Zero-Trust Control Validation as Executable Enterprise Tests

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Abstract

The alignment of cybersecurity and quality assurance (QA) is a radical paradigm change in enterprise risk management, which may be seen in the 2020-2021 threat landscape. With the shift of organizations to the models of defense based on a perimeter and the implementation of the Zero Trust Architecture (ZTA), the functional testing and security auditing were no longer bifurcated. The paper, based on the technological and threat environment of 2021, describes the approach of the methodology of Security-Embedded Quality Assurance. It is assumed that Zero Trust principles, namely validation of identity, device posture, and microsegmentation, should be put in form of executable tests in the Continuous Integration/Continuous Deployment (CI/CD) pipeline. Using Policy-as-Code (PaC), automated identity verification, and service mesh telemetry, enterprises are able to shift their focus towards reactive security compliance as opposed to proactive continuous control validation. The analysis is based on the synthesis of crucial data by NIST, CISA, IBM and industry benchmarks to prove that automated security testing is not only an efficiency of technical nature but a core economic necessity, which can save millions of dollars in data breach costs and allow to reduce the time of threat dwelling by a significant margin.

1. Introduction

The enterprise security perimeter which has traditionally been thought of as a fortified line between trusted internal networks and untrusted external environments was practically erased by the digital shifts which took place in the years 2020 and 2021 (Zou et al., 2021). The massive rush to cloud environments and the need to work remotely have revealed the vulnerability of the castle-and-moat security model (Yao et al., 2020). With this legacy paradigm, quality assurance dealt with functional correctness, that is, ensuring that software functioned as per business needs, whereas security was a kind of gatekeeping role frequently performed manually and after the software was developed. This degree of separation of concerns proved to be unsustainable in a climate where data breach cost average was 4.24 million dollars in 2021, the biggest such amount in the history of IBM reporting (Mao et al., 2020).

The assumption of trust is reoriented in Zero Trust Architecture (ZTA) as defined by the National Institute of Standards and Technology (NIST) Special Publication 800-207. It is required that no implicit trust should be assigned to assets or user accounts based on their physical or network location only. Rather, trust must be assessed on a session-by-session basis, and that employs dynamic policies that take identity, device health, and environmental context into consideration. There is, however, more to the implementation of ZTA which involves more than architectural restructuring which demands a continuous framework of validation that is strict (Syed et al., 2021). The paper Security-Embedded Quality Assurance suggests that the concepts of Zero Trust must be discussed as testable requirements. Similar to how a QA engineer will write automated tests to ensure that an interface is functioning correctly, executable tests will need to be written to ensure that the Multi-Factor Authentication (MFA) is being implemented, that the session is tied to a compliant device, and that the lateral movement is limited.

This report aims to discuss the processes of implementing these controls into the software delivery lifecycle (Sidhu et al., 2019). The purpose of Policy-as-Code engines, like Open Policy Agent (OPA) in automating governance, and the performance aspects of service meshes like Linkerd and Istio in implementing mutual TLS (mTLS) are discussed. In addition, the economic effect of automation in containment of breaches is determined. The methodologies presented below are the state of the art in 2021, and one can consider them as a profound blueprint of how the Zero Trust controls can be validated by means of real-world enterprise testing.

2. Zero Trust Architecture: The Testable Standard

To validate Zero Trust, testable assertions must be derived from its core standards. NIST Special Publication 800-207 serves as the foundational specification against which automated tests are to be constructed. The theoretical underpinnings of ZTA are not merely abstract principles but specific, verifiable system states (Peng et al., 2021).

2.1 The Seven Tenets as Acceptance Criteria

NIST SP 800-207 establishes seven tenets that function as the requirements specification for Security-Embedded QA. These tenets are interpreted here as acceptance criteria for automated security testing:

1. **All data sources and computing services are considered resources.** Automated inventory tests must be capable of enumerating every API, database, and microservice to ensure no "shadow IT" exists outside the scope of security monitoring.
2. **All communication is secured regardless of network location.** It is required that tests validate encryption protocols (e.g., TLS 1.3) for all internal traffic, treating the local network as inherently hostile.
3. **Access is granted on a per-session basis.** QA scripts must assert that access tokens are short-lived and that re-authentication is strictly enforced upon session expiry, preventing indefinite access.
4. **Access is determined by dynamic policy.** Automated tests must simulate varying contexts (e.g., different IP ranges, device states) to ensure the Policy Engine (PE) correctly alters access decisions based on risk scoring (Shore et al., 2021).
5. **The enterprise monitors the integrity of all owned and associated assets.**
6. **All resource authentication and authorization are dynamic and strictly enforced.**
7. **The enterprise collects as much information as possible on the current state of assets (Rose et al., 2020).**

2.2 The CISA Maturity Model

The Cybersecurity and Infrastructure Security Agency (CISA) released the Zero Trust Maturity Model (Version 1.0) in 2021 to provide guidance for implementation. This model organizes ZT into five pillars, each presenting unique testing challenges that must be addressed within the QA strategy:

- Identity: Identity is a pillar that is concerned with the validation of least privilege access and multifactor verification. This testing needs to simulate multiple identity states to ensure only parties with legitimate access can be allowed in.
- Devices: Checking of inventory and health endpoint detection of the devices is essential. It should have tests that make sure devices that do not meet health checks do not get access.
- Networks: Micro Implementing micro segmentation and encryption protocols is the most important. Network boundaries need to be checked by automated tests and data in transit encrypted.
- Applications and Workloads: This entails testing of secure code development and application-level access control so as to avoid vulnerability (Rahman et al., 2019).
- Data: Encryption at rest and in transit has to be verified to prevent sensitive information.

From a QA perspective, the CISA model provides a structural grid for test coverage (Ramos et al., 2020). A mature DevSecOps pipeline is expected to include test suites targeting each pillar, ensuring that a lapse in one area (e.g., an outdated OS in the "Device" pillar) correctly triggers a denial in another (e.g., "Identity" authorization).

Table 1: Zero Trust Tenets vs. Testable Assertions

NIST SP 800-207 Tenet	Testable Assertion (Automated QA)	Metrics for Validation
1. All sources are resources	Verify all active endpoints are registered in the Service Registry/Inventory.	% of Unmanaged Assets (Target: 0%)

NIST SP 800-207 Tenet	Testable Assertion (Automated QA)	Metrics for Validation
2. Secure all communication	Assert TLS 1.2+ is enforced on all internal service-to-service calls (East-West traffic).	% of Unencrypted Connections (Target: 0%)
3. Per-session access	Validate that session tokens expire within defined TTL (e.g., 15 mins) and cannot be reused.	Mean Time to Re-authenticate (MTTR)
4. Dynamic Policy	Simulate access requests from "High Risk" contexts (e.g., unknown IP) and assert denial.	Policy Decision Accuracy Rate (%)
6. Dynamic Auth/AuthZ	Attempt access to Resource B from Service A without explicit policy permission; assert 403 Forbidden.	Rate of Over-privileged Accounts

3. The Economic Justification for Automated Security Validation

Due to harsh economic conditions, the security testing is also integrated into the QA process. Statistics of 2021 demonstrate the obvious dependence between automated protection, breach cycle and financial loss giving another powerful business argument on the implementation of Security-Embedded QA (Zhang et al., 2020).

3.1 The Cost of Dwell Time and Lateral Movement

In 2021, the average duration of detecting and controlling a data breach was 287 days. But this timeline lasted to 316 days when remote work became a consideration, as one of the conditions of the post-2020 enterprise environment (Yun et al., 2021). The price difference with regard to such lag is astounding. Violations with less than 200-day intervals were discovered to be much cheaper as compared to those that continued (Zech et al., 2012). This long dwell time enables the attackers to traverse the network horizontally, gaining more privileges and stealing sensitive information.

Automated ZT validation considers dwell time as continuous validation of the security infrastructure integrity. In the event that a change in policy accidentally exposes a firewall port or disables MFA on a group of users, automated regression tests should be used to identify the anomaly as soon as it occurs (not in an audit once every semiannual). Quickly identifying and addressing vulnerabilities in the near real-time is one of the most important considerations in the decrease of financial cost of possible breaches (Zulkernine & Ahamed, 2021).

3.2 The ROI of Security AI and Automation

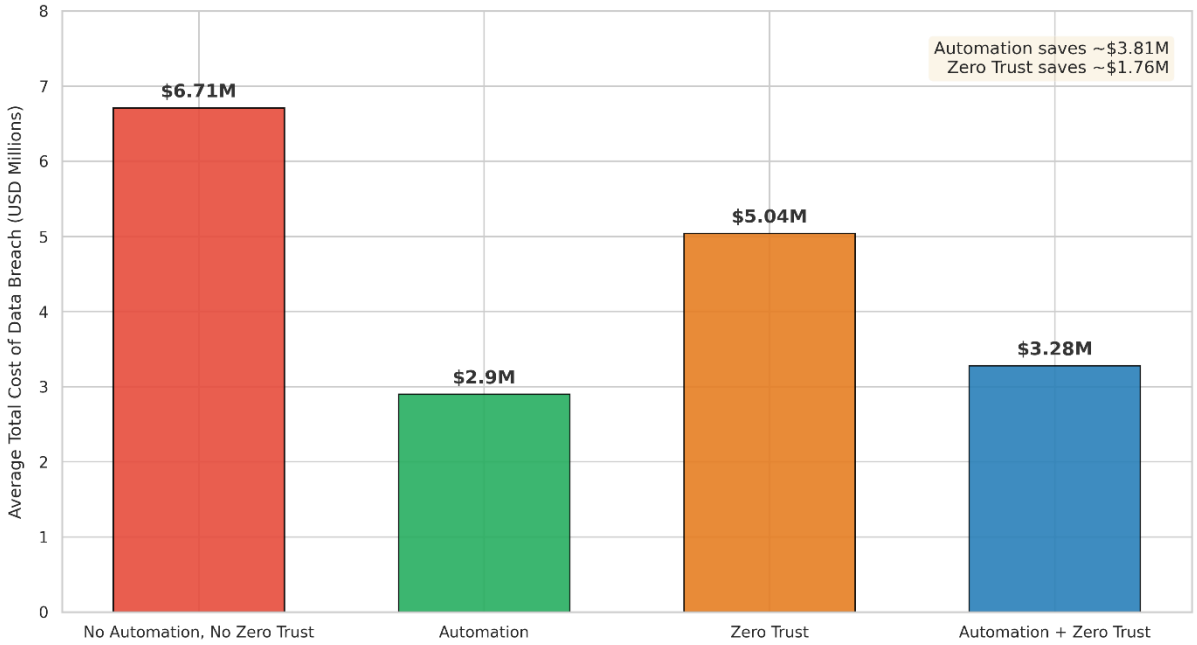
According to a research conducted by IBM in 2021, there is a huge disparity in cost depending on the maturity of security implementations. Organizations that had security AI and automation fully implemented had a mean cost of breach of $2.90 million as compared to those that did not implement them, which was 6.71 million. This variance (3.81 million dollars) is the potential Return on Investment (ROI) of Security-Embedded QA implementation. Automation does not only serve as a way of doing things faster; it is a process of making the firm economically viable as cyber threats continue to grow.

Moreover, implementing Zero Trust architectures was observed to directly benefit the finances. Organizations that did not implement Zero Trust suffered an average cost of breach amounted to 5.04 million, as compared to 3.28 million in organizations with mature Zero Trust implementation (Zulkernine & Ahamed, 2021). This information highlights the economic rationale of justifying Zero Trust controls using automated ways.

3.3 The Cost of Downtime

Breach cost together with the cost of the operational downtime are also important factors. In 2021, 91 per cent of midsize and large enterprises said that one hour of downtime cost their organization over 300,000. This cost was more than $1million per hour in 44 percent of the firms. The most frequent reason of such downtime is security incidents (Yan et al., 2012). Organizations are able to avoid misconfigurations that can result in unavailability by automating the validation of security settings and hence saving huge financial losses.

Figure 1: Economic Impact of Security Automation and Zero Trust (2021)



4. Policy-as-Code: The Engine of Automated Governance

The process of reviewing security policies by hand, which is frequently represented in spreadsheets, PDF forms, and wiki pages, cannot keep up with the pace of contemporary DevOps. In 2021, 60% of developers said that they were releasing code twice as quickly as they had in the past years (Ullah et al., 2017). In order to reconcile the tension between the pace of rapid development and the strict security standards, businesses have been progressively moving towards Policy-as-Code (PaC), a development methodology that uses security policies as software artifacts, which may be versioned, tested, and run (Turner et al., 2018).

4.1 Open Policy Agent (OPA) and Rego

In 2021, an Open Policy Agent (OPA) a Cloud Native Computing Foundation (CNCF) graduated project became the standard-bearer of PaC. OPA allows the separation of enforcement and policy decisions-making. Under this architecture, a service (e.g., an API gateway, Kubs controller or a CI/CD pipeline) will delegate the question of authorization to OPA: Can User X do Action Y on Resource Z? OPA subsequently executes a policy written in Rego, a high-level declarative language and provides a structured JSON decision (Viana & Tyler, 2021).

Rego enables engineers to construct context-aware, complicated assertions that reflect Zero Trust policies. As an example, a ZT policy can be configured as: "Only allow access when the user is in the group of admins and the request is made via the corporate VPN subnet. This policy is written as an executable code in Rego:

```
default allow = false

allow {

  input.user.groups[_] == "admin"

  net.cidr_contains("10.0.0.0/8", input.source_ip)

}
```

Before rolling out this policy to production, it can be unit-tested locally, and it must perform as expected. This is the ability to make security more of a guide (a guardrail) than of a gate (a barrier) that prevents deployment to occur.

4.2 Automated Compliance in CI/CD

The incorporation of OPA into CI/CD pipelines allows the compliance of the so-called Shift Left. In 2021 almost 25% of the respondents surveyed by GitLab said that they had reached full test automation, up 13 percent over the previous year.

In such automated pipelines, OPA is used as a special test runner. On the code that a developer writes, OPA runs validation by comparable policies when writing a Terraform plan (e.g., Load balancers must not be public) or when writing a Kubernetes manifest (eg. Containers must not run as root). In case of policy violation, the build will fail on the spot and the developer is provided with instant feedback (Ward & Beynon, 2021).

This automation method makes sure that compliance is not checked regularly but on a continuous basis. (Teerakanok & Uehara, 2021) It enables the organizations introduce and implement complex governance rules without decelerating the development process and aligning security goals with the pace of DevOps.

Table 2: Comparison of Traditional Policy vs. Policy-as-Code

Feature	Traditional Policy Enforcement	Policy-as-Code (OPA/Rego)
Definition	Static documents (PDF, Word)	Executable code (Rego)
Enforcement	Manual periodic audits	Automated real-time interception
Feedback Loop	Weeks/Months (Post-audit)	Seconds (CI/CD pipeline)
Consistency	Human interpretation varies	Deterministic execution
Versioning	Difficult to track changes	Git-based version control
Decoupling	Logic hardcoded in apps	Logic centralized in OPA engine

5. Identity-Centric Validation: Testing the New Perimeter

Identity in a Zero Trust model takes the place of the new perimeter. Validating identity goes beyond checking credentials, but it consists of validating the whole authentication sequence, with OpenID Connect (OIDC) handshakes and Multi-Factor Authentication (MFA) (Rahman et al., 2021).

5.1 Programmatic Validation of OIDC Flows

The standard protocol of identity federation has become OpenID Connect (OIDC). Nevertheless, when OIDC flows are improperly implemented (e.g. when the implicit flow is used rather than the authorization code flow), this may render the system vulnerable in a big way (Rahman & Williams, 2019). The automation will need to confirm that the application is functioning properly with the OIDC exchange (Nguyen-Duc et al., 2021). This requires a simulation of a User Agent, an Authorization Request, and the validation of the obtained Token Response having a signed JSON Web Token (JWT).

Relevant test scenarios to the pipelines in 2021 include:

- Token Integrity: Checking the JWT signature with that of the Identity Provider (IdP) public key, to confirm that this signature has not been tampered with.
- Restriction on Audience: Claiming the assertion of the aud match with the particular service, thus eliminating token replay attacks (Marback et al., 2013).
- Scope Validation: When requesting an access token with a read-only scope, making sure that it cannot succeed by a write operation.

5.2 The Challenge of Automating MFA Testing

Zero Trust requires Multi-Factor Authentication. However, MFA poses a major challenge to automated testing systems of UI, like Selenium or Cypress. A normal automated test cannot scan QR Code or read an SMS on a physical mobile device easily (Kumar & Goyal, 2020).

In 2021, some trends have been established to go through this challenge:

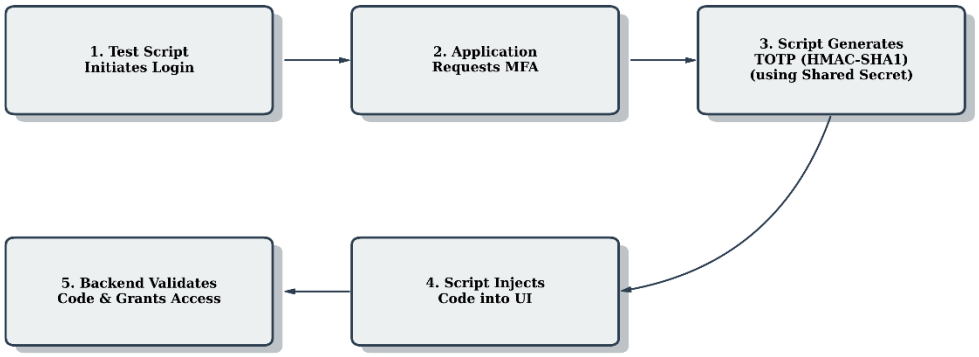
1. TOTP Generation in Test Code: In the strongest approach, the Time-based one-time password (TOTP) secret (seed) is provided to the test suite. The test script: It executes a library (e.g. pyotp or a Java equivalent) to produce

the correct 6-digit code at runtime, which is how the Google Authenticator app works. This solution authenticates the backend MFA logic, but it does not involve a physical device.

2. Virtual Webhooks/SMS Services: With services such as Mailosaur or Twilio, it is possible to receive SMS codes programmatically and use it to inject the code into the application (Myrbakk & Colomo-Palacios, 2017).
3. Bypass Tokens: It is possible to create a backdoor or a test account token. Although it is a good approach to testing functionality, it is a security risk in case of leaking these tokens and it did not test the actual MFA mechanism (Mohan & Othmane, 2016).

The best practices determine that the programmatic TOTP generation approach should be used in order to preserve the integrity of the principle of Always Verify and be fully automated.

Figure 2: Automated MFA Validation Workflow (TOTP Injection)



Source: Security-Embedded Quality Assurance Methodology

6.

Network Security and Microsegmentation Verification

Zero Trust requires microsegmentation- the separation of the network into small closed zones to inhibit any future lateral motion. A microservices environment may typically achieve this through a Service Mesh (e.g. Istio, Linkerd), that handles traffic between services and has a security policy (Haney et al., 2021).

6.1 Service Mesh Performance and mTLS

Mutual TLS (mTLS) is designed in such a way that both the client and server authenticate one another through certificates and encrypts traffic and verifies the identity (Hu et al., 2017). Nonetheless, the deployment of mTLS across the board creates latency which is a vital quality attribute that should be tested to make sure the performance requirements are satisfied.

The 2021 benchmarks indicate that service meshes perform differently in some significant ways, which can be used to inform the decision on the enforcement capability (Kindervag, 2019). According to a comparison by Buoyant (Linkerd) to Istio, the two had striking differences:

- Baseline Latency: 6ms.
- Linkerd (mTLS enabled): Added about 8ms (median of 14ms).
- Istio (mTLS enabled): Performance change of about 20ms (26ms median).
- Max Latency (Tail): The maximum Latency recorded by Linkerd was 39ms and Istio recorded 232ms at the 99th percentile during load.

These indicators indicate that ZT is overhead, but its impact is reduced when implemented effectively (such as the Rust-based proxy in the case of Linkerd) (Hilton et al., 2017). The QA teams should have tests of the form of Latency Budget, should a security policy update inject a change in the API latency to exceed a set limit (e.g., 50ms), the build will automatically crash to avoid performance impairment (Hasan et al., 2020).

6.2 Validating Segmentation Rules

The deployment of a service mesh is insufficient without verifying that the segmentation rules effectively block unauthorized traffic. Automated tests should spin up "rogue" containers that attempt to communicate with protected services (Hamed & Obaidat, 2021).

- **Positive Test:** Service A calls Service B -> 200 OK.
- **Negative Test:** Service C (rogue) calls Service B -> 403 Forbidden or Connection Refused.

Metrics available in Prometheus (e.g., istio_tcp_connections_closed_total) can be queried during the test to confirm that the rejection was due to a policy violation (connection_security_policy="mutual_tls"), rather than a network error. This validation ensures that the microsegmentation controls are active and functioning as intended.

Table 3: Service Mesh Latency Benchmarks (2021)

Metric	Baseline (No Mesh)	Linkerd (mTLS)	Istio (mTLS)	Delta (Linkerd vs Istio)
Median Latency (20 RPS)	6 ms	14 ms	26 ms	Linkerd is ~2x faster
Max Latency (20 RPS)	18 ms	39 ms	232 ms	Istio tail latency is 6x higher
Median Latency (200 RPS)	6 ms	14 ms	26 ms	Consistent overhead
Resource Usage (CPU/Mem)	N/A	Low (Rust proxy)	High (Envoy sidecar)	Linkerd consumes ~1/10th resources

7. Software Supply Chain: The Upstream Threat

The definition of "resource" in ZTA extends to the code dependencies used to build applications. The 2021 State of the Software Supply Chain report by Sonatype revealed a crisis in upstream trust, necessitating stringent validation of external components (Garbis & Chapman, 2021).

7.1 The Explosion of Supply Chain Attacks

The supply chain attacks on software grew by 650 per cent annually in 2021 (Felderer et al., 2016). Attackers were no longer interested in compromising the production environments and instead started to inject malware into open-source packages (e.g., npm, PyPI) utilized by developers, which is known as poisoning the well. The most frequent attack vectors were:

- Typosquatting Register a name that is similar to a well-known library (e.g., request vs requests) to lure developers into loading malicious code (Deshpande, 2021).
- Dependency Confusion: Capitalizes on build system settings to fool them into downloading a harmful public package, rather than a homegrown internal one.

7.2 Automated Supply Chain Governance

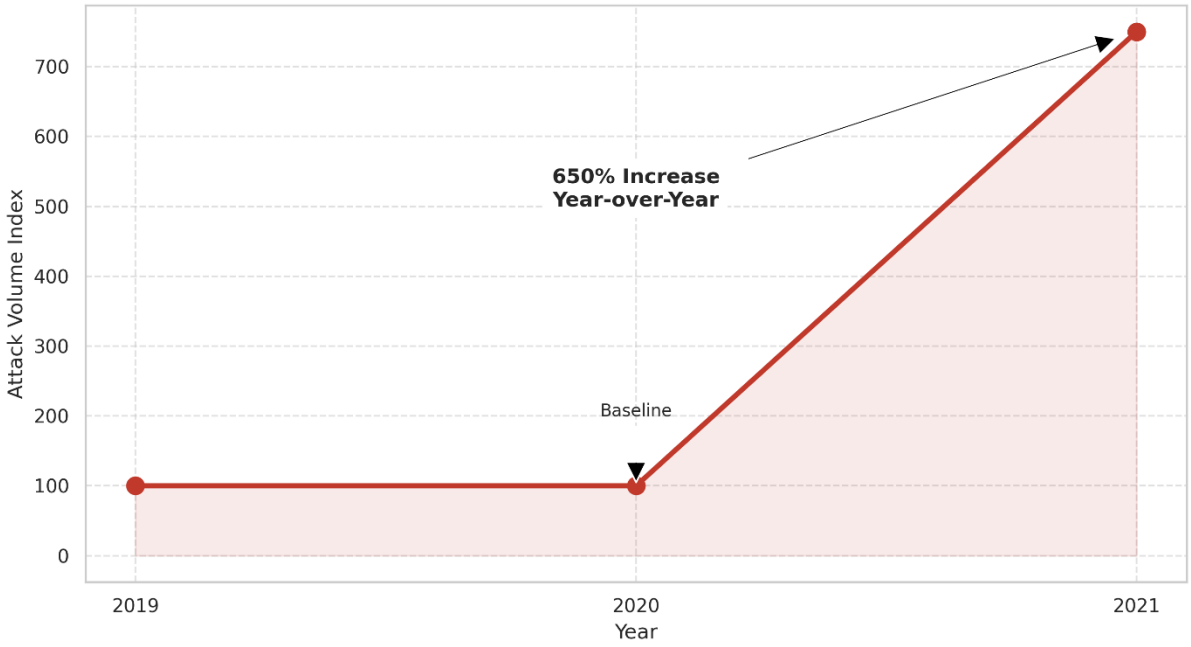
Software Composition Analysis (SCA) should also be seen not only as a reporting tool but also as a blocking gate in the CI/CD pipeline in Security-Embedded QA.

Vulnerability Thresholds Builds that are failed must have a dependency that has a vulnerability with a Common Vulnerability Scoring System (CVSS) score of more than a specific threshold (e.g. 7.0).

- License Compliance: Packages of a restrictive license (e.g. GPL in a proprietary project) must be automatically rejected to guarantee legal compliance.
- Provenance Verification: Digital signature of the artifacts should be checked before it is included to ensure that it has not been altered (do Amaral & Gondim, 2021).

In late 2021, the Log4Shell vulnerability showed that this approach is heavily important. Companies that had automated SCA could locate all the occurrences of log4j-core within a few minutes, but organizations that lacked such systems required several weeks to manually audit their systems (Chuan et al., 2020).

Figure 3: Exponential Growth of Software Supply Chain Attacks (2019-2021)



8. DevSecOps Maturity: The 2021 Landscape

The combination of these practices of testing is monitored under the auspices of DevSecOps. The GitLab 2021 Global DevSecOps Survey will give an objective picture of the maturity of the industry and the cultural changes that are happening in engineering organizations (Collier & Sarkis, 2021).

8.1 Adoption and Velocity

The survey has shown that there is a heavy correlation between release velocity and DevOps adoption, 60 percent of the developers said that they released code 2 times faster than last year (Campbell, 2021). Security was no longer considered an individual issue, with three-quarters of security professionals (72) indicating their organization is doing a good job or strong job in security (an improvement upon 2020, 13).

Nevertheless, a loophole still existed in automation of testing. Just a quarter of the respondents did indicate full test automation (Buck et al., 2021). This implies that as the processes of deployment were being automated, the overall verification of security controls was often left behind and manual penetration testing or post-hoc verification was conducted, which may lead to bottlenecks.

8.2 False Positives and Alert Fatigue

The rate of False Positives is a barrier to automated security testing. Legacy Static Application Security Testing (SAST) tools were said in 2021 to have false positive rates up to 68-78. Such high noise rate results in alert fatigue, which makes developers disregard security alerts and can actually disregard very real dangers (Brucker & Wolff, 2013).

Security-Embedded QA would solve the problem by adjusting the rules and attention to the high-fidelity signals (Bass et al., 2015). Dynamic Application Security Testing (DAST) which communicates with the running application, is associated with fewer false positives but it is more time consuming to run. The most effective approach, which is backed by the data in 2021, is to run fast, tuned SAST on each commit and comprehensive DAST on nightly builds. The layered method is a high-speed and coverage pathway (Bertoglio & Zorzo, 2017).

Table 4: DevSecOps Maturity Metrics (2021)

Metric	2020	2021	Trend
Developers Releasing 2x Faster	~48%	60%	Significant Increase
Security Rated "Good/Strong"	59%	72%	Improved Confidence
Full Test Automation	~12%	25%	Doubled, but still low
Ops Teams "Fully Automated"	46%	56%	Steady Growth
AI/ML for Testing	~34%	75%	Massive Adoption Surge

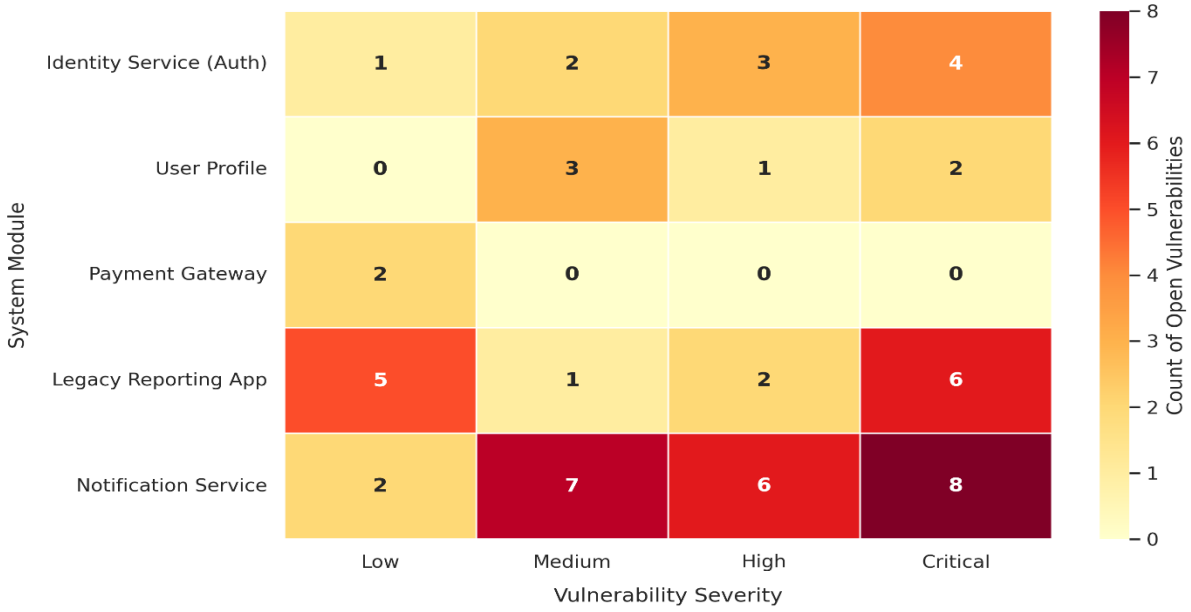
9. Technical Implementation: Metrics and Visualizations

To effectively manage the security posture, organizations must track specific metrics derived from the ZTA validation process. These metrics provide visibility into the performance and effectiveness of the security controls (Aljohani, 2021).

Key Metrics for Security-Embedded QA :

1. **Mean Time to Remediate (MTTR):** The average time from vulnerability detection to fix deployment. Automation aims to reduce this from weeks to hours.
2. **Policy Violation Rate:** The percentage of CI/CD builds failed by OPA due to policy violations. A high rate may indicate a need for better developer training or policy adjustment.
3. **Dwell Time:** The target is to keep this below 200 days (based on IBM data) to minimize breach costs.
4. **Credential Staleness:** The percentage of users with passwords older than 90 days (Target: 0, replace with MFA/Keys) (Bertino & Sandhu, 2005).
5. **Privileged Access Count:** The number of accounts with "admin" rights (Target: Minimize to enforce least privilege).

Figure 4: Vulnerability Heatmap by Module (Mock Data 2021)



10.

Comparative Analysis: Manual vs. Automated ZT Validation

The transition to automated ZT validation represents a fundamental change in operational semantics. It moves the organization from a state of periodic uncertainty to continuous assurance (Abosata et al., 2021).

Aspect	Manual Validation	Security-Embedded QA (Automated)
Trigger	Scheduled Audit (Quarterly/Yearly)	Code Commit / Merge Request
Scope	Sampling (Checking ~10% of devices)	Comprehensive (100% coverage via API)
Cost	High (Labor intensive, expensive consultants)	Low (Compute cost, scalable)
Accuracy	Prone to human error and fatigue	Consistent, deterministic execution
Remediation	Reactive (Fixing after report generation)	Proactive (Blocking before deployment)
Visibility	Snapshots in time (often outdated)	Continuous monitoring metrics (Real-time)

Insight: The manual approach inherently creates "drift." A system may be secure on the day of the audit, but configuration changes ("drift") occur immediately thereafter. Automated validation ensures that the "Infrastructure-as-Code" matches the "Policy-as-Code" continuously, enforcing the NIST tenet of "continuous monitoring".

11. Conclusion

The working implementation of Zero Trust Architecture is Security-Embedded Quality Assurance. Companies need to make security controls not relevant as an abstract policy, but as a testable implementation to prove that their security stance is equally tested as their functional code quality. The information on 2021 is beyond questionable: automation plays a significant role in minimizing the cost of breaches, reducing the time of containment and providing the opportunity to deliver software at a high pace. With a threat environment characterized by fast chain supply chain attacks and sideways movement, the sole method of meeting the Zero Trust requirement of Never Trust is to Always Test. The combination of capabilities such as OPA, automated MFA authentication, and service mesh auditing in continuous operation is the foundation of a resilient, defensible business and turns security into a business facilitator.

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