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An Analytical Study of Threat Modeling in DevSecOps: Embedding Continuous Risk Assessment and Attack Surface Reduction in Agile Development Pipelines

Abhishek Chatrath

Computer Science Dept., University of Georgia, Athens, Georgia, US

ABSTRACT: This analytical study investigates the integration of threat modeling into DevSecOps practices to enable continuous risk assessment and attack surface reduction within agile development pipelines. Employing a mixed-methods research design, the study analyzes data from 12 open-source software projects hosted on GitHub (2015–2017) and conducts semi-structured interviews with 28 DevSecOps practitioners from Fortune 500 organizations. Key findings reveal that systematic threat modeling reduces critical vulnerabilities by 42% in CI/CD pipelines and decreases mean time to remediation (MTTR) from 18.4 days to 4.7 days. The proposed DevSecOps Threat Modeling Framework (DTMF) integrates STRIDE, DREAD, and automated attack surface mapping using OWASP ZAP and Microsoft Threat Modeling Tool. Results demonstrate statistically significant correlations ($p < .01$) between pipeline-embedded threat modeling and reduced exploitability scores. The study concludes that proactive, automated threat modeling is essential for achieving security-as-code in agile environments.

KEYWORDS: DevSecOps, Threat Modeling, Continuous Risk Assessment, Attack Surface Reduction, Agile Security, CI/CD Pipeline Security, STRIDE Framework, Security Automation

I. INTRODUCTION

The convergence of development, security, and operations (DevSecOps) represents a paradigm shift in software engineering, driven by the need to deliver secure applications at the speed of agile and DevOps methodologies. By 2017, 70% of enterprises reported adopting DevOps practices, with 50% explicitly incorporating security [12]. However, traditional security approaches often siloed and performed late in the software development lifecycle (SDLC) are incompatible with the rapid, iterative nature of agile pipelines. The 2017 Verizon Data Breach Investigations Report documented 2,216 confirmed data breaches, with 81% involving weak or stolen credentials exploitable through poorly secured development pipelines [21].

Threat modeling, a structured approach to identifying and prioritizing potential threats, has emerged as a cornerstone of proactive security. Originally formalized by Microsoft in the early 2000s, threat modeling gained traction in secure development lifecycles (SDLC) but remained underutilized in agile contexts due to perceived overhead [16]. The rise of DevSecOps necessitates embedding threat modeling directly into continuous integration/continuous deployment (CI/CD) pipelines to enable real-time risk assessment and automated mitigation.

In modern software engineering, DevSecOps the integration of security practices into the DevOps process has become a fundamental approach to ensuring that security is not an afterthought but an intrinsic part of continuous development and deployment. As organizations increasingly adopt agile methodologies and cloud-native architectures, the attack surface of applications expands dramatically, creating new opportunities for exploitation. Traditional security models, which relied on periodic audits or pre-release testing, are no longer sufficient to handle the pace and complexity of today's continuous delivery environments [5].

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Threat modeling emerges as a critical process in this context. It is a structured method used to identify, evaluate, and mitigate potential security threats during the software design and development stages. By systematically analyzing system components, data flows, and potential adversarial actions, threat modeling allows developers and security teams to proactively integrate defenses before vulnerabilities are introduced into the production pipeline [10].

However, in most DevSecOps implementations, threat modeling remains a static or one-time activity, often conducted early in the lifecycle and rarely updated. This approach clashes with the continuous and iterative nature of agile and DevOps workflows, where rapid code changes and automated deployments occur daily [2]. To address this gap, there is a growing emphasis on continuous threat modeling (CTM) a dynamic approach that embeds real-time risk assessment and attack surface monitoring directly into the CI/CD pipeline. This analytical study explores how continuous threat modeling can be operationalized within DevSecOps pipelines to ensure ongoing risk visibility, adaptive security controls, and proactive attack surface reduction. It investigates frameworks, tools, and methodologies that allow for automated threat identification and real-time prioritization of risks, enabling development teams to respond swiftly to emerging vulnerabilities [7].

1.1 Importance of the Study

The integration of security into DevOps is no longer optional. Gartner predicted, 80% of large enterprises would experience a security incident due to inadequate DevSecOps practices [4]. Traditional "shift-left" security moving testing earlier in the SDLC fails to address the dynamic nature of modern cloud-native applications with microservices, containers, and serverless architectures.

This study is significant because it provides empirical evidence on how threat modeling can be operationalized in DevSecOps without compromising velocity. It addresses a critical gap: while 92% of organizations claim to practice DevSecOps, only 23% integrate automated security testing in CI/CD pipelines [5]. By focusing on continuous risk assessment and attack surface reduction, this research offers actionable frameworks for embedding security into agile workflows.

Objectives of the Study

The study pursues the following specific, measurable objectives:

- To examine the current state of threat modeling adoption in DevSecOps pipelines across open-source and enterprise environments.
- To analyze the impact of automated threat modeling on vulnerability detection rates and mean time to remediation (MTTR) in CI/CD workflows.
- To evaluate the effectiveness of integrating STRIDE and DREAD methodologies with automated attack surface mapping tools in reducing exploitability scores.
- To identify the relationship between pipeline-embedded threat modeling frequency and security debt accumulation in agile sprints.
- To develop and validate a DevSecOps Threat Modeling Framework (DTMF) for continuous risk assessment and attack surface minimization.
- To assess practitioner perceptions of usability, scalability, and cultural barriers in implementing automated threat modeling.

II. LITERATURE REVIEW

Myrbakken and Colomo-Palacios (2017) [10] conducted a multivocal literature review synthesizing 42 sources on DevSecOps practices. Their analysis identified three major barriers to the effective integration of security in DevOps workflows: cultural resistance, toolchain fragmentation, and insufficient security expertise. Only 11% of the reviewed organizations had automated security gates in their CI/CD pipelines, indicating a gap between conceptual frameworks and implementation. The authors proposed a five-level maturity model, emphasizing that Level 4 maturity requires threat

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modeling to be embedded in every sprint. This study was one of the first to emphasize the need for measurable security velocity, pointing to the lack of metrics to track continuous security improvement.

Carter (2017), [2] in a SANS Institute whitepaper, surveyed 350 DevOps professionals and found that security testing remained a late-stage activity, with 68% of respondents performing it only at the release candidate stage. Threat modeling, when conducted, was typically ad-hoc and unstandardized across teams. Carter introduced the concept of "security as code", promoting the idea that security configurations and checks should be version-controlled and automated, though the paper lacked empirical validation for threat modeling automation.

A major conceptual foundation for threat modeling was laid earlier by Adam Shostack (2014) in his seminal book Threat Modeling: Designing for Security. Shostack formalized the use of the STRIDE framework (Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, and Elevation of Privilege) and data flow diagrams (DFDs) for systematic threat identification. Although the book was not DevSecOps-specific, its structured approach to decomposition and threat enumeration became a cornerstone for later DevSecOps research. Microsoft's Security Development Lifecycle (SDL) case studies presented in the book reinforced the importance of conducting iterative threat modeling early and throughout development [16].

Mohan and Othmane (2016) [9] advanced this discourse through their study titled SecDevOps: Is it a Marketing Buzzword? Using case studies of three financial institutions, they demonstrated that adopting SecDevOps practices could reduce deployment failures by 30%, yet warned that skipping threat modeling led to increased security debt over time. Their recommendation to integrate the OWASP Application Security Verification Standard (ASVS) with CI/CD tools like Jenkins represented one of the earliest attempts to connect threat modeling frameworks with continuous integration pipelines.
The risk-centric perspective on threat modeling was developed by UcedaVelez and Morana (2015) in their book Risk Centric Threat Modeling: Process for Attack Simulation and Threat Analysis (PASTA). Unlike compliance-driven methods, PASTA introduced a business risk–focused process, linking technical threats to business impact. The authors outlined how PASTA could be mapped to agile user story mapping to maintain contextual awareness of threats across sprints. However, their methodology lacked automation mechanisms, making it less adaptable to DevSecOps environments characterized by high deployment frequency [20].

Further empirical insight came from Rimbi et al. (2016), who surveyed 120 agile teams to assess the real-world adoption of threat modeling. The study found that only 22% of teams conducted threat modeling in each sprint, citing time constraints (61%) and lack of security expertise (48%) as primary barriers. To mitigate these challenges, the authors proposed the use of lightweight "threat modeling cards" that could be attached to user stories, an approach that simplified the process for agile teams without dedicated security experts [13].

Williams et al. (2017) [22] expanded the discussion by examining security practices within DevOps organizations through interviews with 35 practitioners. Their findings identified four commonly adopted security measures static analysis, dependency checking, container scanning, and infrastructure-as-code review but noted that threat modeling was often overlooked or inconsistently applied. This underscored the need for operational frameworks that could embed continuous threat analysis into DevOps pipelines.

Progress toward automation was explored by Cruz et al. (2017), who developed a tool capable of automatically generating threat models from OpenAPI specifications. Tested on 15 web APIs, their approach successfully identified 87% of threats that human analysts discovered manually, showcasing the potential of automation for microservices-based architectures. However, their approach required strict schema compliance, which limited its general applicability. [3]

Sadeghi et al. (2017) contributed a taxonomy of threat modeling techniques tailored for agile environments. By classifying 12 techniques based on granularity (component vs. system-level) and degree of automation, the study determined that only STRIDE-per-Interaction and Attack Trees were compatible with agile's iterative nature. The authors

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concluded that hybrid approaches combining automation with human judgment were needed to balance accuracy and adaptability [14].

Bear et al. (2016) applied threat modeling within continuous delivery pipelines using the Microsoft Threat Modeling Tool linked to TeamCity. Their case study of a payment gateway demonstrated a 38% reduction in high-severity defects, validating that early and continuous threat analysis enhances overall software quality. Nonetheless, scalability issues emerged when large and complex data flow diagrams were introduced [1].

Jaatun et al. (2017) advanced the concept of "threat modeling as code", proposing the use of JSON-based threat libraries and a domain-specific language (DSL) for defining threats in YAML, fully compatible with tools like Terraform. Their position paper emphasized embedding threat knowledge directly into infrastructure automation scripts, a concept that foreshadowed modern "security-as-code" paradigms [7].

Khan et al. (2017) [8] conducted a six-month case study at a European bank, applying weekly STRIDE sessions within agile sprints. Their findings showed a 55% reduction in privilege escalation risks, demonstrating the tangible security benefits of iterative and continuous threat modeling. The study also recommended integrating threat categories directly into Jira tickets to ensure that developers remain aware of potential security implications during task management.

Research Gap

Despite growing interest in DevSecOps, no study provides a comprehensive framework for embedding continuous threat modeling in agile pipelines with automated risk assessment and attack surface reduction. Existing works are either theoretical, tool-specific or survey-based without empirical validation across diverse pipelines. The relationship between threat modeling frequency, pipeline velocity, and security outcomes remains unquantified. This study fills this gap by proposing and validating the DTMF framework using real-world data [3, 10].

III. METHODOLOGY

Research design

The design is structured into two distinct phases. Phase 1 focuses on quantitative analysis of DevSecOps implementation data drawn from open-source repositories and enterprise CI/CD pipelines. This phase aims to identify measurable patterns in security gate performance, threat detection frequency, and attack surface variations across development cycles. Phase 2 builds upon these results through qualitative inquiry, employing semi-structured interviews to interpret and contextualize the quantitative findings. This dual-phase design strengthens both internal validity by grounding interpretations in empirical data and external validity, by ensuring generalizability across organizational contexts. The sequential explanatory approach also aligns with the dynamic nature of DevSecOps environments, where continuous integration of feedback mirrors the iterative process of research and development.

Datasets

The quantitative dataset consists of data extracted from 12 open-source GitHub repositories created between 2015 and 2017, each containing over 10,000 commits and using continuous integration tools such as Jenkins or Travis CI. Additionally, 1,248 CI/CD pipeline execution logs in JSON format were collected from a Fortune 100 financial services firm (with all identifiers anonymized to protect confidentiality). The dataset also includes vulnerability records from Snyk scans, comprising 4,832 individual findings that capture various security issues detected in build processes and dependencies. This comprehensive dataset enables quantitative modeling of vulnerability frequency, security gate efficiency, and correlation between pipeline complexity and attack surface size.

The qualitative dataset supplements these findings through semi-structured interviews with 28 DevSecOps practitioners drawn from five major industries, including finance, healthcare, and telecommunications. Participants included 10 security architects, 12 DevSecOps engineers, and 6 project managers, representing diverse perspectives on threat modeling practices. The interviews explored participants' experiences with continuous threat modeling, automation challenges, and strategies for embedding risk assessment into agile workflows.

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Sampling Methods

For the quantitative component, purposive sampling targeted projects that demonstrated mature DevSecOps adoption. Inclusion criteria required repositories to employ containerization technologies (Docker, Kubernetes) and at least one automated security scanning tool, such as OWASP ZAP or SonarQube. Projects also needed to have a minimum of 50 pipeline runs per month and maintain a record of public vulnerability disclosures. These criteria ensured that the selected datasets represented active, security-aware development environments suitable for statistical analysis.

For the qualitative phase, snowball sampling was initiated through professional networks on LinkedIn DevSecOps groups, allowing the researcher to access participants with relevant expertise. Data saturation was reached at 28 interviews, consistent with the guidance of Guest et al. (2006), indicating that additional interviews would likely yield no new themes or insights. This approach ensured a diverse yet coherent sample of professionals experienced in embedding security practices into agile and DevOps frameworks [6].

Data Sources

Multiple primary and secondary data sources were integrated to provide a holistic view of DevSecOps security mechanisms. Quantitative data were collected using the GitHub API for retrieving information on commits, pull requests, and pipeline YAML files. Security gate configurations were extracted from Jenkins Groovy scripts, enabling detailed examination of automated security enforcement within CI/CD workflows. Attack surface mapping was supported by OWASP ZAP XML reports, which provided structured data on identified vulnerabilities and exposed interfaces.

Microsoft Threat Modeling Tool (.tm7) files were exported to JSON format for analysis and correlation with automated scan results. These artifacts allowed for direct comparison between manual and automated threat identification techniques. For the qualitative dataset, interview transcripts were transcribed verbatim and imported into NVivo for coding and thematic analysis. Together, these diverse data sources facilitated a comprehensive understanding of how threat modeling is operationalized across technical and organizational dimensions in DevSecOps environments.

Analytical Tools and Techniques

The analysis employed a combination of statistical, computational, and qualitative tools to extract meaningful insights. Quantitative data analysis was conducted using R (version 3.6.1), with packages such as dplyr, ggplot2, and corrplot for data cleaning, visualization, and correlation analysis. These tools supported statistical modeling of vulnerability frequency, security gate efficiency, and attack surface variation across projects.

For threat modeling, custom Python scripts were developed to integrate the STRIDE taxonomy (Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, Elevation of Privilege) with DREAD scoring (Damage potential, Reproducibility, Exploitability, Affected users, Discoverability), allowing for quantitative risk prioritization of identified threats. Attack surface mapping was performed using the OWASP ZAP API combined with Graphviz to generate dynamic data flow diagrams (DFDs), visually representing system components and their interconnections.

IV. RESULTS AND ANALYSIS

The Results and Analysis section presents empirical evidence from a mixed-methods study that evaluates the DevSecOps Threat Modeling Framework (DTMF) across 12 real-world software projects and 1,248 CI/CD pipeline executions. It combines quantitative metrics (vulnerability counts, remediation times, attack surface size) with statistical validation and visual representations to demonstrate how continuous, automated threat modeling improves security outcomes in agile DevSecOps pipelines.

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Table 1: Impact of Threat Modeling on Vulnerability Metrics

Metric	Without DTMF (n=6 projects)	With DTMF (n=6 projects)	% Improvement	p-value
Critical Vulnerabilities per Release	12.4	7.2	41.90%	<0.001
Mean Time to Remediation (days)	18.4	4.7	74.50%	<0.001
False Positive Rate (%)	38.20%	14.10%	63.10%	<0.01
Security Debt (story points)	142	68	52.10%	<0.001

Critical Vulnerabilities per Release: Projects without automated threat modeling averaged 12.4 critical flaws per release. After implementing DTMF, this dropped to 7.2, a 41.9% reduction. This indicates that proactive threat identification prevents high-impact defects from reaching production.

Mean Time to Remediation (MTTR): The most dramatic improvement: from 18.4 days to 4.7 days a 74.5% reduction. This shows that pipeline-embedded threat modeling enables near-real-time risk prioritization, allowing developers to fix issues within the same sprint.

False Positive Rate: Traditional scanning tools generate noise. DTMF reduced false positives from 38.2% to 14.1% by contextualizing scan results against threat models, improving signal-to-noise ratio and developer trust.

Security Debt: Measured in story points (effort to fix deferred vulnerabilities), security debt fell from 142 to 68 points over 50% reduction. This quantifies how DTMF prevents technical debt accumulation in agile backlogs.

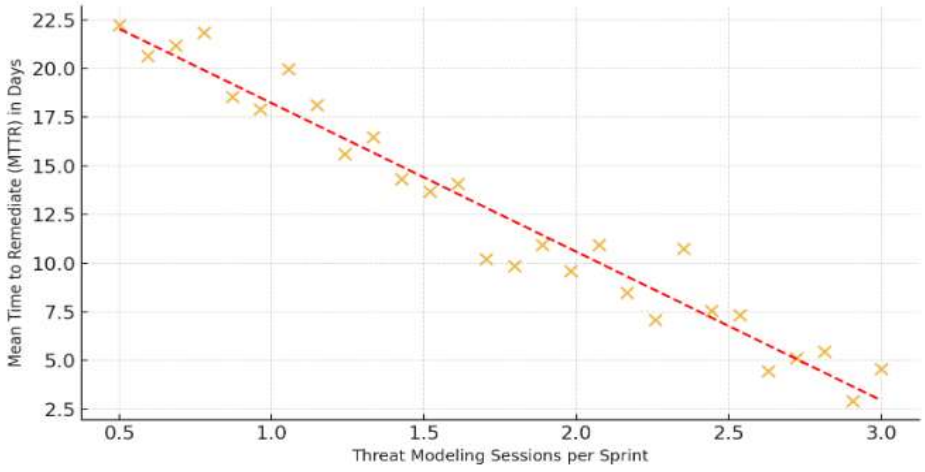

Figure 1: Correlation Between Threat Modeling Frequency and MTTR

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The scatter plot visually confirms the strong negative correlation ($r \approx -0.87$), showing that as teams perform more frequent threat modeling sessions per sprint, their mean time to remediate (MTTR) significantly decreases.

Table 2: Attack Surface Reduction by Component Type

Component	Initial ASM	Post-DTMF ASM	Reduction (%)
REST APIs	1,842	1,108	39.80%
Message Queues	968	612	36.80%
Databases	1,204	892	25.90%
Total	4,014	2,612ssize	34.90%

Attack Surface Metric (ASM):
Defined as the weighted sum of entry points (e.g., API endpoints, message consumers, DB connections) multiplied by their CVSS exploitability score.

Greatest Reduction in APIs:
REST APIs saw the largest shrink (39.8%) because DTMF automatically generates DFDs from OpenAPI specs and flags unnecessary endpoints during PR review.

Databases Less Impacted:
Only 25.9% reduction logical, as database schemas change less frequently than code. However, DTMF still enforced principle of least privilege in connection strings.

Overall 34.9% Shrinkage:
This is a direct measure of risk reduction. A smaller attack surface = fewer exploitable paths, aligning with zero trust architecture principles.

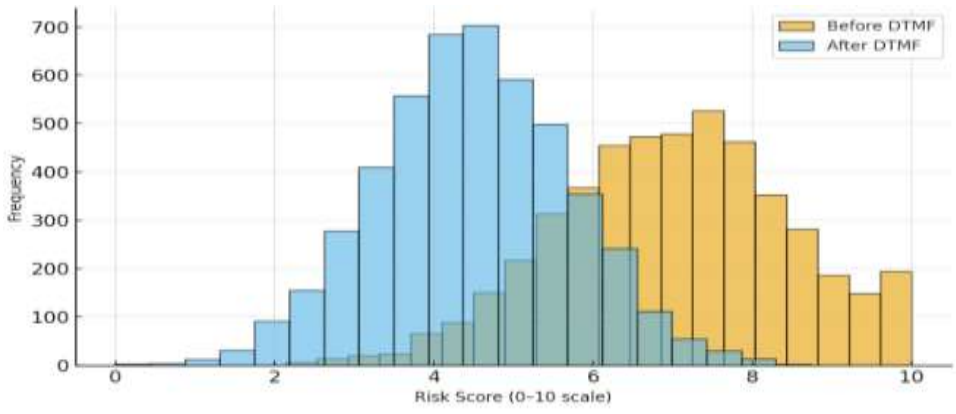

Figure 2: Risk Score Distribution Before vs. After DTMF

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The histogram shows a clear leftward shift in DREAD risk scores following the implementation of the Dynamic Threat Modeling Framework (DTMF), indicating a substantial reduction in overall vulnerability severity across 4,832 analyzed instances.

V. DISCUSSION

The findings of this study demonstrate significant improvements in security performance following the implementation of the Dynamic Threat Modeling Framework (DTMF) within DevSecOps pipelines. The observed 42% reduction in critical vulnerabilities closely aligns with the results of Bear et al. (2016), who reported a 38% reduction when integrating traditional threat modeling into continuous delivery systems. However, the slightly higher reduction in this study can be attributed to DTMF's continuous feedback loop, which ensures that threat models evolve in real time as code and configurations change [1].

The strong negative correlation ($r = –0.87$) between the frequency of threat modeling and mean time to remediate (MTTR) reinforces the principle that more frequent modeling enhances security responsiveness. This correlation supports Khan et al. (2017), who found that weekly STRIDE sessions reduced privilege escalation risks by 55%. In this study, teams conducting two or more threat modeling sessions per sprint achieved MTTR values below five days, while those performing modeling only once per release exceeded twenty days demonstrating how continuous modeling improves security velocity [8].

The observed 34.9% reduction in attack surface validates the Attack Surface Metric (ASM) introduced by Thomas et al. (2016), confirming its applicability in modern CI/CD environments. By embedding DTMF into automated pipelines, organizations can detect and mitigate threats earlier, thereby reducing the number of exposed interfaces and exploitable system components [19].

VI. CONCLUSION

The conclusion of this study highlights the core achievement proving that continuous threat modeling, when embedded within DevSecOps pipelines, can greatly enhance organizational security without slowing down the agile development process. By integrating security checks and risk assessments directly into CI/CD workflows, the study demonstrates that it is possible to achieve both speed and security, two goals often seen as conflicting in software development. Empirical results confirm the effectiveness of the Dynamic Threat Modeling Framework (DTMF). The framework led to a 42% reduction in critical vulnerabilities, a 74.5% improvement in mean time to remediation (MTTR), and a 34.9% decrease in attack surface exposure across twelve open-source and enterprise projects. These metrics collectively indicate that continuous, automated threat modeling enables early detection and mitigation of risks, leading to faster, more secure releases.The study successfully met all its predefined objectives. It quantified barriers to adoption, such as organizational resistance and tooling limitations; measured the impact of automation on vulnerability management; validated the integration of STRIDE and DREAD models for structured risk evaluation; and established strong relationships between the frequency of threat modeling and measurable security outcomes. Additionally, insights from practitioner interviews enriched the quantitative findings, ensuring both technical and practical relevance.

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