Carnegie Mellon University
Software Engineering Institute

THREAT MODELING: EVALUATION AND RECOMMENDATIONS

Nataliya Shevchenko, Brent R. Frye, Carol Woody, PhD

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Introduction

Addressing cybersecurity for a complex system, especially for a cyber-physical system-of-systems (CPSoS), requires a strategic view of and planning for the whole lifecycle of the system. For the purpose of this paper, "system-of-systems" is defined as a system, components of which operate and are managed independently [46]. Thus, components of a system-of-system (systems by themselves) should be able to function fully and independently even when the system-of-systems is disassembled. Also, they typically are acquired separately and integrated later. Components of a system-of-systems may have physical, cyber, or mixed natures. For simplicity, we will use term "cyber-physical system" instead of "cyber-physical system-of-systems."

The nature of a cyber-physical system (CPS) implies a diversity of potential threats that can compromise its integrity, targeting different aspects ranging from purely cyber-related vulnerabilities to the safety of the system as a whole. The traditional approach used to tackle this matter is to employ one or more threat modeling methods (TMMs) early in the development cycle. Choosing a TMM can be a challenging process by itself. The TMM you choose should be applicable to your system and to the needs of your organization. Therefore, when preparing for the task it makes sense to answer two questions. First, what kind of TMMs exist and what are they? And second, what criteria should a good TMM satisfy? We explored answers to the first question in *Threat Modeling: A Summary of Available Methods* [47]. In this paper, we will address the second question and evaluate TMMs against the chosen criteria.

Evaluation Criteria

Before evaluating the list of potential TMM candidates, let's discuss the criteria that they need to satisfy.

The first criteria is *Strengths and Weaknesses.* Although there are a number of threat modeling methods in the field, there is no one perfect method. Each method was developed with different points of view in mind and each addresses different priorities. Some methods are focused on assets, some are focused on attackers, and some are focused on risks. Thus, each method has strengths and weaknesses relating to which types of threats they are best at discovering, which threats they can miss (false negatives) or mistakenly identify (false positives), and how thorough they are. Each method has its own level of maturity and time to implement. Each deals with its own mitigation strategies. These aspects determine a method's usefulness in a given situation.

The second criteria is *Adoptability.* Implementing any comprehensive methodology in an organization will impose some level of burden on everyone involved, so choosing an easy-to-use solution can be important. Add to this a learning curve for the implementers of the methodology and associated changes to already existing processes and you can end up with a situation that may make the overall cost of adopting the method prohibitive. Availability of (or absence of) good documentation and support can be critical for successfully adapting a method.

The third criteria is *Tailorability.* No two organizations have identical development processes, no matter how similar they are. Therefore, a good TMM candidate should be flexible enough to be tailored to the type of system, the organization's priorities, and the systems development lifecycle (SDLC) without compromising the quality of the method. This should include whether the candidate method may be integrated into a development process, and, based on growing usage, specifically into the Agile development process. Methods applied to CPS must be scalable and able to meet the needs of very large and distributed systems.

The fourth criteria is *Applicability to CPS.* Since this white paper concentrates on cyber-physical systems (CPS), our evaluation should address TMM aspects that are specifically related to CPS. One of the main characteristics of CPS is complexity. Methods must be able to be applied recursively and account for the relationships among sub-systems. They must also address hardware-software dependencies and safety-security interdependencies.

The fifth and final criteria is *Automation,* which specifies the availability of automation for the method and supporting tools and whether this automation is useful. Many cyber-physical systems belong to critical infrastructure (both publicly and privately owned) or to government-developed weapon systems. To an organization that requires secrecy, portability of the tools to a stand-alone mode is another important feature.

In summary, we have identified the following list of criteria for evaluating TMM candidates

1. Strengths and Weaknesses
    a. maturity and usage
    b. focus/perspective
    c. time to implement
    d. effectiveness
    e. mitigation strategies
2. Adoptability
    a. easy to use
    b. easy to learn
    c. documentation and support
3. Tailorability
    a. integration with SDLC
    b. compatibility with agile development process
    c. scalability
4. Applicability to CPS
    a. coverage of safety-security interdependency

    b. integration of hardware and software threats
5. Automation
    a. availability of tools
    b. integration options for tools into an SDLC
    c. portability of tools

Evaluation

In this section, we will evaluate the following TMMs

1. STRIDE
2. PASTA
3. LINDDUN
4. CVSS
5. Attack Trees
6. Persona Non Grata (PnG)
7. Security Cards
8. hTMM
9. Quantitive TMM
10. Trike
11. VAST Modeling
12. OCTAVE

For our evaluation, we will use the definitions and findings from *Threat Modeling: A Summary of Available Methods* [47].

Strengths and weaknesses

Almost all of the methods in question are designed to detect potential threats; the exception is CVSS, which is a scoring method. The number and types of threats vary considerably, as does the quality and consistency of the methods. There is no comprehensive study involving all of these methods. We can only speculate how effective and efficient they are based on a few sources that list studies that used them [12, 15, 28] and a number of sources that used these methods for their case studies [14, 15, 20, 28, 40].

The STRIDE method has a moderately low rate of false positives and a moderately high rate of false negatives [28]. Persona Non Grata produces few false positives and has high consistency but tends to detect only a certain subset of threat types [15]. Security Cards can help identify almost all of the threat types but produces a high number of false positives; it is better suited to addressing non-standard situations [15]. The study on hTMM [24] gave inconclusive results.

Since STRIDE, PASTA, LINDDUN, Trike, VAST Modeling and OCTAVE provide well-structured and guided frameworks, they can potentially lead to the discovery of more threats. This presents some

disadvantages. In particular, STRIDE and LINDDUN suffer from so-called "threat explosion", when the number of threats can grow rapidly [12, 28]. Quantitive TMM combines Attack Trees, STRIDE, and CVSS, which allows it to mitigate potential threat explosion from STRIDE by applying the other two methods. The effectiveness of Attack Trees depends on the understanding of both the system and security concerns. It requires a high level of cybersecurity expertise from analysts [2].

One study introduced a formal method of timed automata in addition to applying the Attack Trees method for modeling socio-technical attacks [1]. Timed automata is a formal method for modeling and analyzing the behavior of computer systems. It uses language and state machine-like diagrams to describe the possible states of the system. Timed automata was implemented as a tool—UPPAAL, an integrated environment for modeling, validating, and verifying real-time systems [48]. The study used these two methods on cyber-physical system, and showed how to generate and validate possible attacks on a system. Even though this method combination was applied only in an academic setting, it has a potential for safety-critical cases.

Table 1 displays a summary of other relevant attributes. *Maturity* is assessed based on how well each method is defined, how often it has been used in case studies, how often it has been combined with other methods, and whether it will be maintained by the owner or community. *Focus/Perspective* lists the point of view from which the method was designed. *Time/Effort* provides some idea as to how time-consuming and laborious the method is. *Mitigation* lists whether any mitigation strategies are provided by the method. Finally, *Consistent results* notes whether the method produces consistent results if repeated (depending on the knowledge of those who are applying the method).

	Maturity	Focus/Perspective	Time/Effort	Mitigation	Consistent results
STRIDE	High	Defender	High	Yes	No
PASTA	High	Risk	High	Yes	Not clear
LINDDUN	High	Assets/Data	High	Yes	No
CVSS	High	Scoring	High	No	Yes
Attack Trees	High	Attacker	High	No	Yes
PnG	Medium	Attacker	Medium	No	Yes
Security Cards	Medium	Attacker	Medium	No	No
hTMM	Low	Attacker/Defender	High	No	Yes
Quantitive TMM	Low	Attacker/Defender	High	No	Yes
Trike	Low	Risk	High	Yes	No
VAST	High	Attacker	High	Yes	Yes
OCTAVE	Medium	Risk/Organization	High	Yes	Yes

Table 1. Strengths and weaknesses

Adoptability

One cannot overstate the importance of the adoptability of a method. There are very few, if any, easy TMMs. The successful implementation of a TMM requires a deep understanding of the system and

extensive knowledge of cybersecurity. However, the intuitiveness of the method can ease the effort needed to learn and use it. If the method employs techniques that are already well understood and used in the field (such as architecture diagrams or brainstorming) this can help during the adoption process.

STRIDE, PASTA, LINDDUN, hTMM, Quantitive TMM, Trike, and VAST Modeling use data flow diagrams (DFDs), which are usually a part of the design phase of the system's development cycle. Security Cards and PnG are types of brainstorming, which is also a widely used design technique. STRIDE and LINDDUN (and method combinations that use them) use their names as mnemonics, which naturally guides the process of threat discovery. On the other hand, complicated and vague formulas and instructions (such as those used in CVSS) or excessive or laborious steps within a method (such as those found in PASTA) can negatively impact the adoption of that method.

Table 2 summarize the evaluation of the main attributes that contribute to the adoptability of the method.

	Easy to Use	Easy to Learn	Documentation
STRIDE	Medium	Medium	Very Good
PASTA	No	No	Very Good
LINDDUN	No	Medium	Good
CVSS	No	No	Good
Attack Trees	Yes	Medium	Good
PnG	Yes	Yes	Some
Security Cards	Yes	Yes	Very Good
hTMM	Medium	Medium	Good
Quantitive TMM	No	No	Some
Trike	Medium	Medium	Good for v1
VAST	Medium	Medium	Very Good
OCTAVE	No	No	Good

Table 2. Adoptability

Tailorability

All methods except OCTAVE are designed to be applied at the beginning of the systems development life cycle (SDLC), during the requirements and design phases. This allows them to be integrated into any development lifecycle that contains these phases. Some (e.g., PnG, Trike, and VAST) integrate with the Agile development process better than others. PASTA and Trike explicitly map their activities to the requirements and design stages of SDLC as well as the implementation and test stages. OCTAVE is an evaluation process oriented to the organization rather than a specific system, so it will not integrate well with any development cycle.

Since none of these methods were designed with a specific type of system in mind, all may be applied to any kind of system. Case studies illustrate specific tailoring of STRIDE, PASTA, CVSS, Attack

Trees, hTMM, Quantitive TMM, LINDDUN, and PnG to both cyber system [13, 28, 31] and cyber-physical systems [1, 2, 3, 15, 19, 20].

OCTAVE, PASTA and VAST modeling were designed for large systems. The rest of the methods may be scaled up relatively easily to accommodate large systems or systems-of-systems.

Applicability to CPS

As the literature review *Threat Modeling: A Summary of Available Methods* [47] shows, most of the methods under evaluation were used to model threats for cyber-physical systems: railway communication networks [3], drone systems [15], and the automotive industry for connected cars [20]. However, none were used as the sole modeling method. Combinations of two or more TMMs seemed to perform better. In many cases other techniques were added to the mix, such as the National Institute of Standards and Technology (NIST) guidelines and standards (Special Publications 800-30 [49], 800-82 [50], and 800-53 [51]), Failure Modes and Effects Analysis (FMEA), the Risk Priority Number (RPN), and Threat Agent Risk Assessment (TARA) [3, 8, 20, 39]. The methods most used in these studies were STRIDE and CVSS. Combining methods and adding domain-specific techniques allows for deeper analysis of the system, and, thus, better threat discovery.

Only one study [39] specifically talked about the importance of integrating safety analysis with cybersecurity analysis. It suggested using FMEA in addition to STRIDE, and stated that there is no conflict between these two types of analysis. In fact, combining these methods helps to identify more possible threats as well as specific points of failure. Another study mentioned that Attack Trees was developed as an adaptation of the Fault Trees technique from safety engineering [1].

Specifics of CPS requires focused attention not only on application and system software-related threats, but also on hardware and physical threats. Malware installed on a hardware system or physical tampering with a component can cause cyber or cyber-physical impact and put a system into an undesirable state. Studies show that Attack Trees or frameworks like PASTA, (where building Attack Trees is one of the steps) are capable of identifying physical and hardware threats, including their impact on the system as a whole [1, 3, 19].

All methods that start with modeling the system—for example, with data flow diagrams (STRIDE, PASTA, LINDDUN, hTMM, Quantitive TMM, Trike, and VAST)—can be used recursively with some modifications. In *Software and attack centric integrated threat modeling for quantitative risk assessment* [3], a technique was described to account for the risk propagation between components called attack ports.

Automation

Very few of the methods examined were automated. In fact, most of them exist only as a framework of instructions, questionnaires and checklists. Automated methods include STRIDE (implemented as the Threat Modeling Tool as a part of the Microsoft Secure Development Lifecycle (SDL) [29]), the CVSS online calculator [52] (which cannot be installed as a stand-alone tool), and VAST Modeling—implemented as ThreatModeler [53], which can be installed as an on-premises solution.

The two existing portable tools (Threat Modeling Tool (STRIDE) and ThreatModeler (VAST)) can potentially be integrated into SDLC during the requirements and design stages. For non-automated methods that utilize DFD or other diagrams, system design tools (e.g., Enterprise Architect, Microsoft Visio, Gliffy, NoMagic, and Cameo EA) can be used to create the diagrams. Those design tools can be integrated into SDLC.

	Automation	Portable	Tool Integration with SDLC
STRIDE	Yes	Yes	Yes
PASTA	No	Yes	No
LINDDUN	No	Yes	No
CVSS	Yes	No	No
Attack Trees	No	Yes	No
PnG	No	Yes	No
Security Cards	No	Yes	No
hTMM	No	Yes	No
Quantitive TMM	No	Yes	No
Trike	No	Yes	No
VAST	Yes	Yes	Yes
OCTAVE	No	Yes	No

Table 3: Automation and Portability

Recommendations

Examples of cyber-physical systems-of-systems (CPSoS) include rail transport systems, power plants, and integrated air defense systems. Each of these systems is comprised of large physical, cyber-physical and cyber-only sub-systems with complex dynamics. They are connected via one or more cyber networks and operated by one or more organic operators. The components of those systems are often distributed and are sometimes partially autonomous, with multi-level control and management. They are safety or life critical. Thus, threat modeling for this type of system needs to address the full spectrum of threats: kinetic, physical, cyber-physical, cyber-only, supply chain, and insider threats.

Evaluation of existing TMMs showed that there is no one method that can cover all potential threats. Therefore, a framework that employs a combination of methods and techniques should be used.

- Our recommendation is to use the PASTA modeling method as the basis of this framework.
- In addition to PASTA, we recommend using components of STRIDE and LINDDUN.
- We also recommend using other tactics that address threat aspects that are not covered by these three models.

PASTA provides the most detailed guidance for the process of threat modeling, including resources that can be easily adapted to different kinds of systems. It can be incorporated into existing SDLCs and allows for easy addition or removal of activities from stages as needed. PASTA also mitigates the "threat explosion" weakness of STRIDE and LINDDUN by utilizing risk and impact analysis. The reviewed literature does not explicitly discuss whether PASTA produces a consistent result. However, since PASTA uses Attack Tress and CVSS as its primary threat finding and assessment techniques, we can argue that it will produce relatively consistent results. This flexibility makes this combination a good candidate for a comprehensive TMM framework.

Some modification should be done to this combination of methods to accommodate the scope of the problem. Initially, we recommend implementing PASTA for the whole system using a high-level architecture and treating sub-systems as black boxes. This initial round of analysis will not require you to go through every activity, but it should effectively define all inputs and outputs for each sub-system. Then, PASTA should be implemented recursively for each sub-system —and in turn, each sub-system of the sub-systems. All discoveries from a higher level should be passed to the next level as an input. Expect to encounter quite a few levels of sub-systems, depending upon the complexity of the system.

In addition to the basic PASTA stages, the following activities should be added to address the full spectrum of threats.

Stage 1. Define Objectives

Additional documents:

- safety standards and guidelines from related industries
- data security requirement document
- logistic documents
- identify critical functions and assets

Stage 2. Define Technical Scope

Additional activity:

- identify system critical dependencies from the supply chain, including dependencies from trusted third-party systems
- identify system critical dependencies from the external infrastructure (e.g., sources of power and other resources, protection from physical damage and destruction)

Stage 3. Application Decomposition

Additional activity:

- identify physical boundaries (direct and indirect access) to the system's components
- implement corresponding supply chain techniques

Stage 4. Threat Analysis

Additional documents:

- supply chain threat-related documents
- physical safety and security-related documents

Additional activities:

- build fault trees and/or FMEA for hardware [39]
- apply supply chain analysis
- apply internal threat identification methods
- perform step 2 from STRIDE method for cyber threat finding
- perform steps 2 and 3 from LINDDUN method to identify data privacy and security threats

Stage 5. Vulnerability and Weakness Analysis

Additional activities:

- analyze vulnerabilities in hardware
- analyze vulnerabilities in supply chain including trusted third-party systems
- analyze vulnerabilities in physical protection of assets

Stage 6. Attack Modeling

Additional activities:

- generate attack ports [3]

Stage 7. Risk and Impact Analysis

Additional activities:

- use mitigation strategies from step 5 of the LINDDUN method for data privacy and security threats
- use mitigation strategies from STRIDE method
- calculate risk propagation [3]

The following are a few of the "best practices" that will help with the process of adopting a TMM [14]:

- It is important to recognize that threat modeling works best if applied in early stages of the project—i.e., the requirements and design phase.

- Threat modeling is an ongoing process. It is hard to perfect it on the first run and you cannot refine it indefinitely. You need milestones along the way. It does not stop after your system is delivered. Some steps must be repeated when the system changes.
- In threat modeling, it is dangerous to concentrate exclusively on threats. Modeling users and attackers and controlling impact on requirements and mitigations are just as important.
- Threat modeling is not an innate skill. It is learnable and improves with practice. With each iteration, it become better and deeper.

By combining components of PASTA, STRIDE, and LINDDUN with tactics that address additional aspects of CPSoS, we believe this combination of TMMs will provide better coverage of threats than any one model by itself. Adopting the proposed framework will be a laborious and time-consuming process, but will create a flexible and comprehensive structure for modeling a wide range of threats.

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Contact Us

Software Engineering Institute
4500 Fifth Avenue, Pittsburgh, PA 15213-2612

Phone: 412/268.5800 | 888.201.4479
Web: www.sei.cmu.edu
Email: info@sei.cmu.edu

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