

Automated Reasoning for Vulnerability Management by Design

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Abstract. For securing systems, it is essential to manage their vulnerability posture and design appropriate security controls. Vulnerability management allows to proactively address vulnerabilities by incorporating pertinent security controls into systems’ designs. Current vulnerability management approaches do not support systematic reasoning about the vulnerability postures of systems’ designs. To effectively manage vulnerabilities and design security controls, we propose a formally grounded automated reasoning mechanism. We integrate the mechanism into an open-source security design tool and demonstrate its application through an illustrative example driven by real-world challenges. The automated reasoning mechanism allows system designers to identify vulnerabilities that are applicable to a specific system design, explicitly specify vulnerability mitigation options, declare selected controls, and thus systematically manage vulnerability postures.

Keywords: Vulnerability assessment · Threat modelling · Secure development processes · Security by design.

1 Introduction

Vulnerabilities in systems can be exploited by malicious actors, and are the primary, enabling factor of cyber security attacks [11]. Vulnerability management is therefore a critical aspect of secure system development and operation. Establishing the vulnerability posture of systems involves identifying and associating vulnerabilities with system components, and identifying the potential mitigation of these vulnerabilities by using security controls. Maintaining the vulnerability posture involves regularly updating the pertinent vulnerabilities and mitigation, to align with design decisions and the dynamic threat landscape (e.g., newly disclosed vulnerabilities affecting the system). Establishing and maintaining vulnerability postures allow the involved stakeholders (e.g., designers, risk managers, and executives) to proactively identify, understand and mitigate potential risks, consequently improving the trustworthiness of systems [8, 12, 15, 25].

In general, vulnerability management can relate to vulnerabilities found in the implementation of specific system constituents, which we relate to as *implementation vulnerabilities*; as well as to conceptual classes of vulnerabilities (i.e.,

types of vulnerabilities), which we relate to as *mechanism vulnerabilities*. Mitigating vulnerabilities at the mechanism level, rather than individually mitigating implementation vulnerabilities, is a desirable security-by-design approach to vulnerability management, because it addresses the root causes of potential security issues and prevents a wide range of existing as well as potential vulnerabilities and threats [1, 4].

The standard security taxonomy provided by MITRE – a global leader in systems engineering and cyber security – refers to mechanism vulnerabilities at various levels of abstraction as *weaknesses*, and to implementation vulnerabilities simply as *vulnerabilities*. The Common Weakness Enumeration (CWE)³ is a hierarchical organisation of weaknesses, while Common Vulnerabilities and Exposures (CVE)⁴ lists implementation vulnerabilities. Implementation vulnerabilities can manifest weaknesses [3, 7]. In this paper, we use *vulnerability* as a unified term to indicate either a mechanism issue or an implementation issue, unless otherwise specified.

Traditional vulnerability management approaches focus mainly on implementation vulnerabilities that are identified and addressed after system development. This reactive approach typically addresses individual implementation vulnerabilities but fails to address their underlying mechanisms – mechanisms that may give rise to future implementation vulnerabilities. As a result, similar implementation vulnerabilities may remain unaddressed, leaving the system exposed to future attacks, sometime exploiting the same underlying mechanisms [20]. This requires to regularly check for new threats and design mitigation to address them [2, 9].

Most approaches either focus narrowly on specific vulnerabilities or lack the scalability and rigor required to systematically integrate vulnerability management into system design processes [17–19]. In a comprehensive review of cyber security vulnerabilities and related concepts, Aslan et al. acknowledge the difficulty of “*applying domain knowledge for automated analysis*” and list it as a major challenge alongside other related challenges, such as the time-consuming design of “*a secure system*”, the detection and prevention of unknown attacks, the protection of multiple components (as a system) and the increasing number of software vulnerabilities [2]. Consequently, organisations struggle to adopt security-by-design principles, limiting their ability to ensure a robust, policy-driven security posture from the outset and proactively mitigate risks. A systematic literature review on security risks and practices calls for better ways of securing systems during development and, specifically, in its early stages [9].

In recent years, security by design has received increasing attention [18]. This is due to the premise that the earlier the security information is integrated into the system development lifecycle, the lower the overall debugging and maintenance costs incurred at later phases [13]. In previous work, we analyse current security-by-design approaches and their characteristics [14, 24]. One of the challenges that remain is the lack of ability to rigorously reason about vulnerabilities

³ <https://cwe.mitre.org/>, Accessed: 3/4/2025

⁴ <https://www.cve.org/>, Accessed: 3/4/2025

at varying levels of abstraction during the design of a system. This challenge is also highlighted by other researchers [20, 26].

To address this challenge, there is a need for a formally specified reasoning mechanism that can support the association of vulnerabilities with specific system designs and reason about their mitigation, which includes the incorporation of relevant security controls into the designs. Such a mechanism should integrate seamlessly with existing design tools, enabling stakeholders to incorporate security considerations as part of the development process rather than as an afterthought.

In this paper, we present our work to develop a formally specified automated reasoning mechanism for vulnerability management by design and implement it as an extension of an open-source security modelling tool. We also illustrate how the mechanism is used to reason about the vulnerability posture of a system design. This illustration relies on real-world vulnerability data.

2 Related Work

Numerous studies have addressed vulnerability management. We overview some related work, highlighting how our approach complements existing methods and uniquely addresses the gap in scalable automated reasoning for vulnerability management.

Some approaches suggest addressing the increasing number of reported vulnerabilities and the limited organisational capacity of remediation by prioritisation. A recent survey overviews dozens of approaches that attempt to prioritise vulnerabilities based on their exploitability [5]. Like many of the survey approaches, Nowak et al. attempt to use the Common Vulnerability Scoring System (CVSS) to prioritise vulnerabilities for remediation, also taking into consideration the possible impact of their exploitation [16]. Such attempts often involve the use of machine learning, which has limitations such as classification errors and need of representative data [2]. Our work does not aim to prioritise vulnerabilities. Instead, we aim to identify vulnerabilities that are pertinent to a specific system design and reason about this in a way which allows to filter out the vulnerabilities that are already mitigated by existing security controls.

Formal methods offer rigorous ways to reason about design characteristics, including security. Sengupta et al. propose a formal methodology limited to detecting managerial vulnerabilities in enterprise information systems, without addressing technical system vulnerabilities [22]. Fithen et al. model vulnerabilities formally, using propositional logic [6]. Their formalisation is limited to specific product types (associated with *Microsoft Windows*) and to implementation vulnerabilities, with patching being the only demonstrated security control and without addressing the temporal evolution of the security landscape [2, 23]. Huff and Li propose a formal approach to model software vulnerability risk in the context of the network environment and firewall configuration [7]. Focused on operations, the approach does not trivially translate into system design contexts, where system constituents are considered within their designated operating envi-

ronment. To the best of our knowledge, there is no formally specified mechanism that allows reasoning to scale about the vulnerability posture of systems, while considering vulnerabilities at different levels of abstraction and their potential mitigation.

Other approaches lack formal foundations. For example, the approach proposed by Longueira-Romero et al. assesses known vulnerabilities in industrial components using directed graphs, without any formalisation of their mitigation [10]. Almorsy et al. use the declarative language OCL to automate limited aspects of vulnerability analysis, without providing formal definitions [1].

Rouland et al. propose a model-driven formal approach to specifying mechanism vulnerabilities and controls with respect to software architecture [21]. The implemented vulnerabilities library is limited, and the approach does not take into consideration implementation vulnerabilities and, accordingly, does not integrate with common vulnerability management practices (e.g., addressing CVEs via patching). This can be seen as complementary to our work, as it allows to formally define mechanism vulnerabilities, while our more conceptual approach aims to curate such information within the context of existing security design practices and body of knowledge and with respect to high-level system design.

TRADES Tool [23] is an open-source systems security design tool. It is underpinned by a semi-formal modelling methodology and relies heavily on a domain metamodel. We have previously extended TRADES Tool with vulnerability management concepts [24]. However, the lack of formal foundations for addressing vulnerability management by design – including the hierarchical organisation and mitigation of vulnerabilities – remains a significant gap. In this paper, we present our work to develop a formally specified automated reasoning mechanism for vulnerability management by design and implement it as an extension of TRADES Tool.

3 Formally Specified Automated Reasoning for Vulnerability Management

We provide a formally specified, automated reasoning mechanism to analyse the vulnerability posture of systems designs. The contribution of this mechanism is two-fold. First, it associates potential vulnerabilities with system components based on pre-specified associations between vulnerabilities and component types. Second, it assesses the vulnerability posture of the design by determining whether the security controls associated with the components are sufficient to mitigate the associated vulnerabilities. The latter is performed according to pre-specified rules that provide guidance for the mitigation of vulnerabilities – in the context of specific component types – by suggesting pertinent controls.

We employ the following finite sets to formalise concepts related to vulnerability management:

- C – the components $c \in C$ available in a system design or threat model
- T – the component types $t \in T$ available
- V – the known vulnerabilities $v \in V$ available
- S – the security controls $s \in S$ available
- R – the security rules $r \in R$ available

To obtain a formal vulnerability management model, we would define the following mappings: $\text{VULNS} : T \rightarrow \mathcal{P}(V)$ maps a component type to the vulnerabilities that affect it; $\text{TYPES} : C \rightarrow \mathcal{P}(T)$, maps a component to the component types it manifests; $\text{CONTROLS} : C \rightarrow \mathcal{P}(S)$, maps a component to the controls associated with it; $\text{AVULNS} : V \rightarrow \mathcal{P}(V)$, maps a vulnerability to vulnerabilities of higher abstraction that it manifests, in a unidirectional, acyclic manner; $\text{RVULNS} : R \rightarrow \mathcal{P}(V)$, maps a rule to the vulnerabilities to which it applies; $\text{RTYPES} : R \rightarrow \mathcal{P}(T)$, maps a rule to the component types to which it applies; $\text{RCONTROLS} : R \rightarrow \mathcal{P}(S)$, maps a rule to the security controls it suggests as mitigation.

In our framework, these sets and mappings can be manually defined and/or automatically generated, without loss of generality or limitation. The result is a body of formally codified knowledge about the system design and security at a particular point in time, which can then be used as the basis for reasoning about the vulnerability posture of the system. Evolution of the design – for example adding components or augmenting the mitigations in place – can be done by augmenting the relevant mappings. Likewise, new vulnerabilities or rules can be added by augmenting the relevant sets and mappings. The reasoning can then be performed by an automated reasoning mechanism, as further explained.

As part of our vulnerability management reasoning mechanism, we wish to derive an indication whether a specific component is vulnerable. First, the reasoning mechanism can collect all the vulnerabilities that apply to a component $c \in C$ based on the component's types:

$$\text{CVULNS}(c) = \bigcup_{t \in \text{TYPES}(c)} \text{VULNS}(t)$$

The mechanism can then check whether each vulnerability so obtained is mitigated by a collection of security controls that is deemed appropriate by some security rule. For a given vulnerability v of a component c , a rule is pertinent if one of its types is also a type possessed by c and applies to v . Proper mitigation for the vulnerability is considered as a situation in which all the security controls s identified by the rule are associated with the component. Formally:

$$\text{MitigatedV}(v, c) \equiv \exists r \in R. \begin{cases} \exists t \in \text{RTYPES}(r). t \in \text{TYPES}(c) \wedge \\ v \in \text{RVULNS}(r) \wedge \\ \forall s \in \text{RCONTROLS}(r). s \in \text{CONTROLS}(c) \end{cases}$$

MitigatedV defines whether a vulnerability is directly mitigated by a relevant control. But a vulnerability can also be mitigated indirectly, by mitigating all the higher level abstractions it manifests. Formally, this is expressed by

$$\text{Mitigated}(v, c) \equiv \begin{cases} \text{MitigatedV}(v, c) \vee \\ (\text{AVULNS}(v) \neq \emptyset \wedge \forall v' \in \text{AVULNS}(v). \text{Mitigated}(v', c)) \end{cases}$$

where the well-foundedness of this recursive formulation is established by the fact that the abstraction relation on vulnerabilities is a finite partial order.

We can now define a predicate that allows the reasoning mechanism to indicate whether a component has a vulnerability that remains unaddressed by the associated controls:

$$\text{Vulnerable}(c) \equiv \exists v \in \text{CVULNS}(c). \neg \text{Mitigated}(v, c)$$

Finally, the automated reasoning mechanism can make sure that the design model satisfies the following property, indicating that no unmitigated vulnerabilities exist in any of the components in the design model:

Property 1. $\forall c \in C. \neg \text{Vulnerable}(c).$

4 Implementation

Fig. 1 shows an excerpt from the *metamodel* of the TRADES Tool, into which the above vulnerability management concepts and automated reasoning mechanism are integrated. The metamodel has five classes that correspond to the five sets introduced above: C , T , S , V and R (Fig 1 (b)). For example, **Rule** corresponds to the set R and **Control** corresponds to the set S . The labeled arrows represent the family of mappings introduced above, with the label giving the name of the mapping in TRADES Tool. For example, **componentTypes** from **Component** to **ComponentType** represents the mapping $\text{TYPES} : C \rightarrow \mathcal{P}(T)$.

In TRADES Tool, the **Analysis** concept ((Fig 1 (a))), is the root element of a design model and can store instances of the other concepts/classes. The reasoning mechanism implementation adds derived elements, annotated in blue and with a slash prefix. These include: the **cVA** relation between **Component** and **Vulnerability**, corresponding to the formalism's CVULNS mapping; and the derived attributes **vulnerable** for the **Component** and **property_DesignAddressesVulnerabilities** for the **Analysis**, corresponding to the Vulnerable predicate and *Property 1*, respectively. Operations are also added to the **Component**, implementing the *MitigatedV* and *Mitigated* predicates.

5 Illustrative example

We describe an illustrative example application using the formally-specified automated reasoning mechanism for vulnerability management and its TRADES

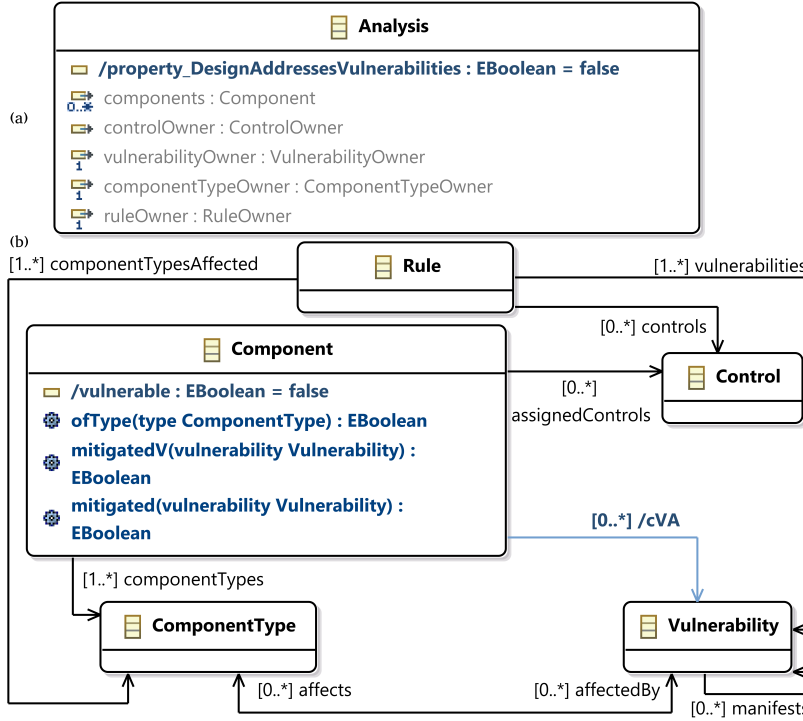


Fig. 1. TRADES Tool metamodel excerpt, showcasing integration of the formally-specified vulnerability analysis mechanism.

Tool implementation. The TRADES Tool extension is available from the TRADES Tool Github repository⁵. The example application TRADES model is also available online⁶.

Consider the following case of assessing the vulnerability posture of a computer system being developed for the internal use of an organisation. According to the preliminary design, the system comprises two software components: a UNIX-like operating system instance, and an organisational application instance. The set of types for the system’s components accordingly includes two types: “UNIX-like operating system” and “internally developed application”.

For the preliminary design, we – as security engineers – identify the vulnerability *Improper Restriction of Operations within the Bounds of a Memory Buffer (CWE-119)* as being of interest. A recommended mitigation for such vulnerabilities is to *use memory-safe programming languages* [3]⁷. Accordingly, we design a security rule, called “rule1”, to address this vulnerability in internally-developed

⁵ <https://github.com/UKRI-DSbD/TRADES>

⁶ <https://github.com/UKRI-DSbD/TRADES/tree/VulManEx/VulManEx>

⁷ Also: <https://cwe.mitre.org/data/definitions/119.html>, Accessed: 3/4/2025

applications, mandating the recommended security control. The formalisation of this design situation defines the following sets:

$$\begin{aligned}
 C &= \{\text{OperatingSystem}, \text{Application}\} \\
 T &= \{\text{UNIX_like_operating_system}, \text{internally_developed_application}\} \\
 V &= \{\text{CWE-119}\} \\
 S &= \{\text{use_memory_safe_languages}\} \\
 R &= \{\text{rule1}\}
 \end{aligned}$$

and these mappings:

$$\begin{aligned}
 \text{VULNS}(\text{internally_developed_application}) &= \{\text{CWE-119}\} \\
 \text{TYPES}(\text{OperatingSystem}) &= \{\text{UNIX_like_operating_system}\} \\
 \text{TYPES}(\text{Application}) &= \{\text{internally_developed_application}\} \\
 \text{RVULNS}(\text{rule1}) &= \{\text{CWE-119}\} \\
 \text{RTYPES}(\text{rule1}) &= \{\text{internally_developed_application}\} \\
 \text{RCONTROLS}(\text{rule1}) &= \{\text{use_memory_safe_languages}\}
 \end{aligned}$$

Fig. 2 shows the various model elements and highlights rule1 in TRADES Tool. We note that TRADES Tool extension that we developed allows to import the entire CWE catalogue of mechanism vulnerabilities and their hierarchical organisation into our design workspace. Once this is done, the catalogue can be used as a resource for vulnerabilities.

At this point in the development life cycle, no controls have been assigned to any component. If we exercise the automated reasoning mechanism, *Property 1* is violated, with $\text{Vulnerable}(\text{Application})$ being true, with a counterexample being $\neg \text{Mitigated}(\text{CWE-119}, \text{Application})$. Fig. 3 shows the initial Vulnerable status of the Application component (at the very bottom), alongside other mappings, including the unmitigated vulnerabilities mapping to CWE-119, which is automatically set by the automated reasoning mechanism as a counterexample.

To deal with the vulnerable component, we can use the knowledge codified in rule1 to assign a security control as a requirement to the Application component, setting $\text{CONTROLS}(\text{Application})$ to be $\{\text{use_memory_safe_languages}\}$. If we now re-apply the reasoning mechanism, *Property 1* is satisfied, i.e., all of the specified components are not vulnerable. Fig. 4 shows the assignment of the $\{\text{use_memory_safe_languages}\}$ control to the Application component, resulting in the component being assessed as not vulnerable (based on rule1).

As our system design evolves, we identify the specific operating system we wish to use – FreeBSD version 14. Common Platform Enumeration (CPE)⁸ is a structured naming scheme for information technology systems, software, and packages. CPE is useful in associating vulnerabilities with affected software. Accordingly, we introduce a new component type, with the CPE of FreeBSD version 14: `cpe:2.3:o:freebsd:freebsd:14.0:-:*:*:*:*:*`. This is shown in Fig. 5. We can now query the NIST’s National Vulnerability Database (NVD) to retrieve implementation vulnerabilities associated with the newly incorporate component type.

⁸ <https://cpe.mitre.org/>

For conciseness and readability, and to reduce cognitive load on the reader, we query the NVD only for vulnerabilities that manifest the aforementioned CWE-119, which results in two CVE records: CVE-2011-2895 and CVE-2020-10565 (Fig. 6). These vulnerabilities are then imported into our design space, along with their associations – as detailed in the NVD database – with mechanism vulnerabilities and with the queried component type (Fig. 7).

Fig. 8 shows the consequences of setting the type mapping of the `OperatingSystem` component to include the new FreeBSD 14.0 component type. Automatically, the reasoning mechanism deduces that the component is vulnerable, and lists the unmitigated vulnerabilities (the two CVEs that were imported into our design space).

The vendor advisory for CVE-2020-10565⁹ is to apply a specific patch. We capture this using *rule2*. Similarly, the NIST NVD record for CVE-2011-2895 provides links to another patch, to solve this issue. We capture this using *rule3*. Each of these newly added rules refers to newly identified security controls in the form of specific patches. Fig. 9 shows that our design space now includes two new rules and two new controls, and the details of *rule3* as an example.

We can capture a design decision to incorporate the two patches – for example, while preparing a new deployment of our system – into the system design model by associating the relevant security controls with the `OperatingSystem` component. Fig. 10 shows the immediate results of the automated reasoning mechanism following such association: the `OperatingSystem` component is no longer vulnerable.

As new implementation vulnerabilities emerge, new patches should be identified as security controls and new rules should address each specific vulnerability. Alternatively, we can address vulnerabilities by design, i.e., by eliminating the class of vulnerabilities, pending pertinent security controls. One such mitigation is to use a capability based addressing hardware (such as CHERI-Morello [3]). We introduce this new security control into the knowledge base within our design environment, and specify a new rule – *rule4* – to guide system designers in addressing CWE-119 in FreeBSD instances (Fig. 11). We can then assign the new control to our `OperatingSystem`, instead of the previous patches. Fig. 12 shows this assignment as well as the assessment – by the automated reasoning mechanism – that the component is not vulnerable. This explicitly shows that the mechanism considers the mitigation of the CWE-119 mechanism vulnerability also as mitigation to the implementation vulnerabilities that manifest CWE-119: the potentially applicable vulnerabilities listed under the computed cVA mapping – which is the implementation of the CVULNS(c) collection (as indicated in the previous section) – do not appear under the Unmitigated Vulnerabilities, indicating that they are mitigated in the current system design.

⁹ <https://svnweb.freebsd.org/ports?view=revision&revision=525916>, Accessed: 3/4/2025

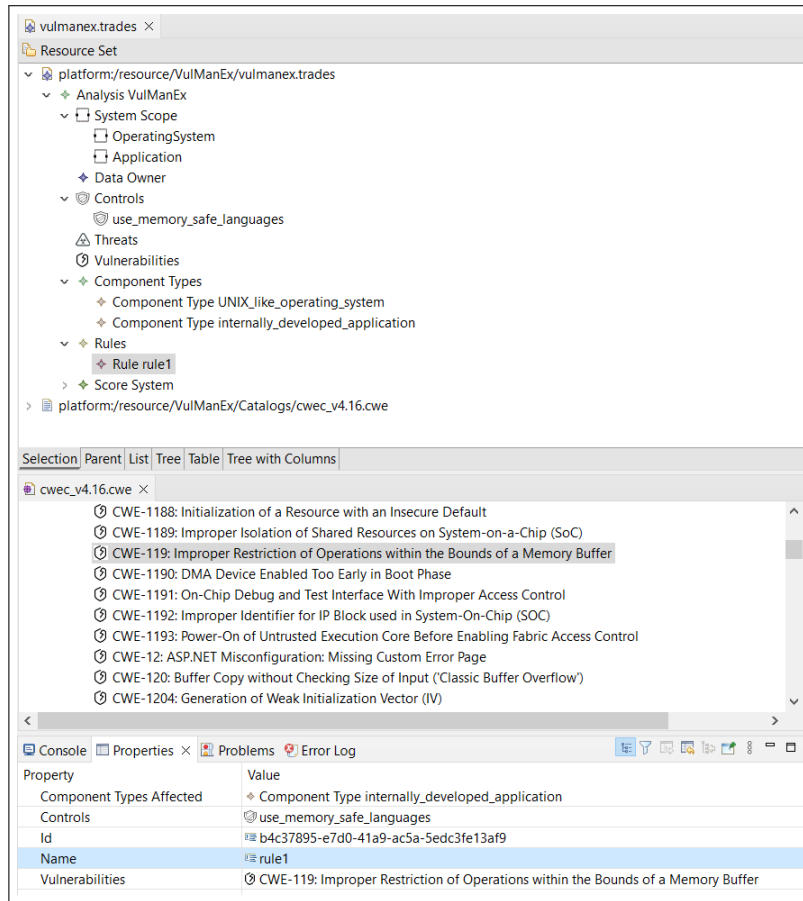


Fig. 2. The illustrative example in TRADES Tool: the Resource Set panel shows the model elements grouped by their concepts, the middle panel shows an excerpt from the imported CWE catalogue, and the Properties panel shows the attributes and mappings of rule1.

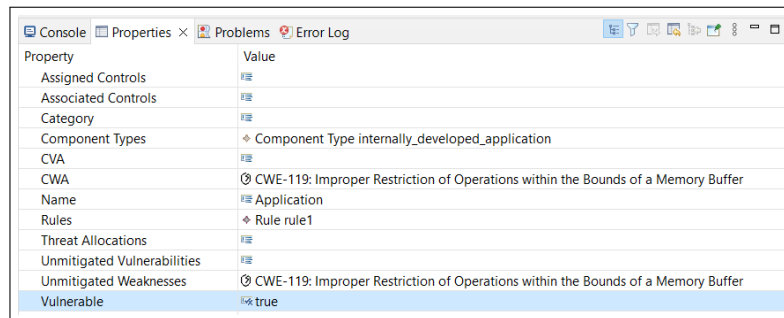


Fig. 3. The Application component assessed as Vulnerable.

Property	Value
Assigned Controls	use_memory_safe_languages
Associated Controls	use_memory_safe_languages
Category	
Component Types	Component Type internally_developed_application
CVA	
CWA	CWE-119: Improper Restriction of Operations within the Bounds of a Memory Buffer
Name	Application
Rules	Rule rule1
Threat Allocations	
Unmitigated Vulnerabilities	
Unmitigated Weaknesses	
Vulnerable	false

Fig. 4. The Application component assessed as not Vulnerable due to the assigned control.

Resource Set

- platform/resource/VulManEx/vulmanex.trades
 - Analysis VulManEx
 - System Scope
 - OperatingSystem
 - Application
 - Data Owner
 - Controls
 - use_memory_safe_languages
 - Threats
 - Vulnerabilities
 - Component Types
 - Component Type UNIX_like_operating_system
 - Component Type internally_developed_application
 - Component Type cpe:2.3:freebsd:freebsd:14.0:-:****

Selection Parent List Tree Table Tree with Columns

Console Properties Problems Error Log

Property	Value
Affected By	
Id	6f9577c4-49a9-4a70-9fd4-8c2a66d42561
Manifests	Component Type UNIX_like_operating_system
Name	cpe:2.3:freebsd:freebsd:14.0:-:****
Subject To Threats	

Fig. 5. A new CPE-based component type is incorporated into our design space.

Select a CPE name to search for its vulnerabilities.

Enter the first few characters of a CPE to filter the below list:

CPEs found:

- internally_developed_application
- cpe:2.3:freebsd:freebsd:14.0:-:****
- UNIX_like_operating_system

Fetch

Enter optional NVD API parameters below:

&isVulnerable&cwelid=CWE-119

Download progress:

Select CVEs from below:

- CVE-2011-2895
- CVE-2020-10565

This product uses data from the NVD API but is not endorsed or certified by the NVD.

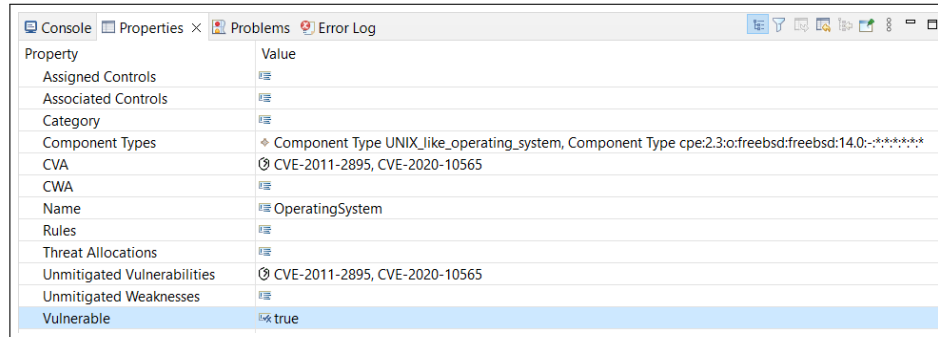
< Back Next > Finish Cancel

Fig. 6. Querying NVD for CWE-119 related vulnerabilities in FreeBSD 14.

CVE-2011-2895		
General	Property	Value
Default	Affects	Component Type cpe:2.3:freebsd:freebsd:14.0:-:****
	Id	795e7bdc-e7c1-4e06-966e-163957995c25
	Manifests	CWE-119: Improper Restriction of Operations within the Bounds of a Mem...
	Name	CVE-2011-2895
	Vulnerability Type	CVE

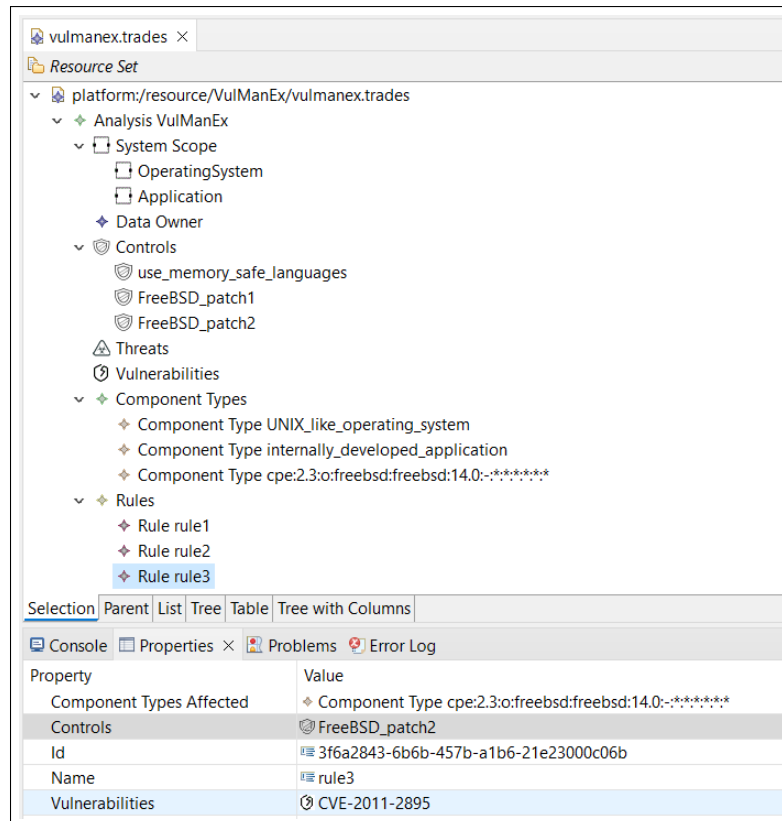
CVE-2020-10565		
General	Property	Value
Default	Affects	Component Type cpe:2.3:freebsd:freebsd:14.0:-:****
	Id	259843b5-e70f-4b62-8bec-a8d0ee7d8874
	Manifests	CWE-119: Improper Restriction of Operations within the Bounds of a Mem...
	Name	CVE-2020-10565
	Vulnerability Type	CVE

Fig. 7. Imported implementation vulnerabilities (CVEs) and their association with mechanism vulnerabilities (CWEs) and component types.



Property	Value
Assigned Controls	
Associated Controls	
Category	
Component Types	Component Type UNIX_like_operating_system, Component Type cpe:2.3:o:freebsd:freebsd:14.0:-:*:*:*:*
CVA	CVE-2011-2895, CVE-2020-10565
CWA	
Name	OperatingSystem
Rules	
Threat Allocations	
Unmitigated Vulnerabilities	CVE-2011-2895, CVE-2020-10565
Unmitigated Weaknesses	
Vulnerable	true

Fig. 8. The OperatingSystem component's type mapping is set to include the new FreeBSD component type. The automated reasoning mechanism assesses the component as Vulnerable and lists unmitigated vulnerabilities.



Property	Value
Component Types Affected	Component Type cpe:2.3:o:freebsd:freebsd:14.0:-:*:*:*:*
Controls	FreeBSD_patch2
Id	3f6a2843-6b6b-457b-a1b6-21e23000c06b
Name	rule3
Vulnerabilities	CVE-2011-2895

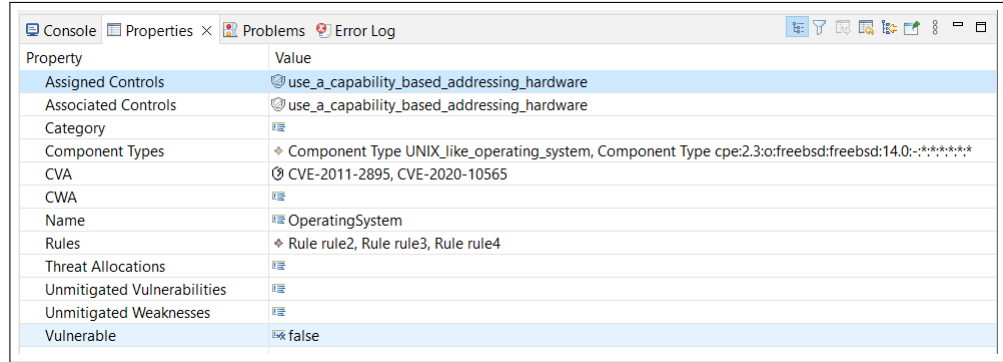
Fig. 9. The system design model now includes two new controls representing available FreeBSD patches as well as two new rules to specify the use of each patch as a mitigation for a specific implementation vulnerability.

Property	Value
Assigned Controls	FreeBSD_patch2, FreeBSD_patch1
Associated Controls	FreeBSD_patch2, FreeBSD_patch1
Category	
Component Types	Component Type UNIX_iike_operating_system, Component Type cpe:2.3:o:freebsd:freebsd:14.0:-:*:*:*:*
CVA	CVE-2011-2895, CVE-2020-10565
CWA	
Name	OperatingSystem
Rules	Rule rule2, Rule rule3
Threat Allocations	
Unmitigated Vulnerabilities	
Unmitigated Weaknesses	
Vulnerable	false

Fig. 10. Once pertinent patches are assigned to the OperatingSystem component, the automated reasoning mechanism assesses that the component is no longer vulnerable.

Property	Value
Component Types Affected	Component Type cpe:2.3:o:freebsd:freebsd:14.0:-:*:*:*:*
Controls	use_a_capability_based_addressing_hardware
Id	553cb4d8-20b5-4c11-80ee-ad420b2b3b2d
Name	rule4
Vulnerabilities	CWE-119: Improper Restriction of Operations within the Bounds of a Memory Buffer

Fig. 11. A new design rule prescribes the use of capability based addressing hardware as mitigation for the CWE-119 mechanism vulnerability in the context of FreeBSD.



Property	Value
Assigned Controls	use_a_capability_based_addressing_hardware
Associated Controls	use_a_capability_based_addressing_hardware
Category	
Component Types	Component Type UNIX_like_operating_system, Component Type cpe:2.3:o:freebsd:freebsd:14.0:-:*:*:*:*
CVA	CVE-2011-2895, CVE-2020-10565
CWA	
Name	OperatingSystem
Rules	Rule rule2, Rule rule3, Rule rule4
Threat Allocations	
Unmitigated Vulnerabilities	
Unmitigated Weaknesses	
Vulnerable	false

Fig. 12. A new alternative design of the system includes an OperatingSystem that uses a capability based addressing hardware. Accordingly, the automated reasoning mechanism assesses that the FreeBSD OperatingSystem is not vulnerable to the collection of vulnerabilities (CVA).

6 Discussion

Accounting for vulnerabilities in the design of systems requires careful and rigorous consideration. In this paper, we have introduced formal foundations to reason about the vulnerability posture of a system, and have demonstrated a simple yet representative application. While our illustrative example is intentionally simple for clarity, it remains representative of design-related vulnerability management for two reasons: (1) our tool’s knowledge base is populated with real-world vulnerability data, retrieved from the CWE and NVD databases; (2) the reasoning mechanism operates at the design level, based on design decisions (e.g., choosing a programming language for an internally developed application, selecting an operating system or an hardware platform, deploying a new version of a system with patches installed) as opposed to implementation details (e.g., specific code addressing a buffer beyond its boundaries). Accordingly, the example makes a valid, general case for adopting the automated reasoning mechanism for vulnerability management.

The suggested vulnerability management by design formalism is rooted in well-established vulnerability management concepts, most notably the concepts of *component*, *component type*, *vulnerability* (in various levels of abstraction), and *control*. Consequently, the formalism is integrative. We have presented an integration of the formalism into an open-source system security design tool. While the integration is already fully functional, providing automated reasoning capabilities, we are further integrating the reasoning procedure and results into the diagrammatic representations and improving other user experience aspects of the tool. Similarly, the formalism can be incorporated into other design and process management tools.

We are working towards adding additional design-related reasoning based on formal properties and establishing their value in design contexts. For example, another property can mandate the existence of sufficient rules for addressing

known vulnerabilities. A violation of such a property can trigger a security engineer to formulate additional rules, thereby enriching the knowledge base that is available within the modelling environment in support of more resilient designs. We are also considering separation between implementation vulnerabilities and mechanism vulnerabilities, to provide better quantitative assessment of mitigation strategies and their coverage of existing and future vulnerabilities.

While our formally grounded automated reasoning mechanism is scalable, we are well aware that manually specifying the models of the systems can be time consuming. For exercising the formalism and the automated reasoning capabilities at scale, further research can attempt to automate the generation of the models. A possible approach could be to use Software Bill of Materials records – indicating the software components of products – to populate the formal model. Once the formal model’s definitions are in place, the automated reasoning can be applied without additional effort, as our TRADES Tool implementation demonstrates.

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