CoReTM: An Approach Enabling Cross-Functional Collaborative Threat Modeling

Jan von der Assen, Muriel F. Franco, Christian Killer, Eder J. Scheid, Burkhard Stiller
Communication Systems Group CSG, Department of Informatics IfI, University of Zürich UZH
Binzmühlestrasse 14, CH–8050 Zürich, Switzerland
E-mail: [vonderassen, franco, scheid, killer, stiller]@ifi.uzh.ch

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***Abstract*—Threat Modeling is a structured process to identify critical assets in an organization and the threats posed by adversarial agents. The goal of applying such a process is to achieve a shared understanding of the inherent risks and potential countermeasures that can be put in place. In practice, threat modeling is a collaborative process combining stakeholders' perceptions in a holistic view of the threat landscape. However, this paper points out that related work mainly focuses on adapting models to technical aspects of architectural decisions. Thus, non-technical stakeholders are not included in the process.**

This paper proposes *CoReTM*, a novel overarching approach to applying well-established threat modeling methodologies in a collaborative setting. The resulting approach allows organizations to extend threat modeling to non-technical stakeholders in an automated way while supporting on-site, remote, or hybrid operations in a synchronous or asynchronous fashion.

***Index Terms*—Threat Modeling, Collaboration, Risk Management, Threat Intelligence**

I. Introduction

Threat modeling is a well-known method for precisely designing systems, networks, and businesses. After identifying potential threats, appropriate countermeasures can be considered, communicated, and implemented [1]. Threat modeling comprises two main abstractions: *(i)* the notion of assets, such as processes, users, software components, or data sources, that need to be protected and *(ii)* the attack targets and vectors [2].

As postulated by security experts and researchers, collaborative approaches are essential for threat modeling [3], especially with the growing number of information systems, employees, and critical assets requiring protection [4]. Furthermore, the increased frequencies at which cyber-attacks are launched [5], [6] impose constant changes in the threat landscape of today's systems. Accordingly, threat models must evolve fast, requiring organizations to collaborate on refining such models. Thus, they must frequently analyze models post-*mortem* to assess their adequacy [7]. Hence, threat modeling tools should adapt to the work style to enable collaboration and be flexible to enable threat modeling among the relevant stakeholders.

Current tools (*e.g.,* Office Suites, MTMT, and diagrams.net) do not support collaborative aspects of threat modeling for remote users. In the same way, depending exclusively on physical meetings may lead to delayed iterations of the threat modeling process. For that reason, a remote, or hybrid meeting style enables the participation of geographically distant members. Thus, an asynchronous approach allows members to collaborate without any dependency on time and location.

Remote work is not a temporary trend: the majority of knowledge workers and software engineers were projected to work in a remote workspace at the end of 2021 [8], [9]. Thus, to assure threat models remaining correct and up-to-date, capabilities for collaborative threat modeling are critical.

In addition, it is vital that a diverse set of stakeholders are included in the process. The importance of including diverse subject and domain experts depends on the type of asset being threat modeled. Combining a broad set of perspectives and capabilities in the threat modeling process highlights why collaborative approaches are required to securely design systems, processes, or projects. *E.g.*, threat modeling solely on the basis of existing source code would exclude business representatives. Furthermore, existing tools are not sufficiently supporting modeling among collaborators in modern processes (*e.g.,* agile methodologies and DevSecOps) since these tools are bound to the underlying methodology [10], [11].

This paper proposes *CoReTM*, a methodology overarching approach to enable threat modeling in a collaborative setting, including fully distributed employment settings. The approach is specifically crafted to enable modeling in an on-site, remote, or hybrid setting while allowing both asynchronous and synchronous contributions. The prototypical implementation of *CoReTM* provides *(i)* an annotation-based collaborative editor, *(ii)* automated threat reporting, and *(iii)* DevOps integration to support threat modeling in all combinations of meeting styles. Furthermore, *CoReTM* enables collaboration between a wide range of stakeholders with diverse backgrounds and skills by implementing a methodology selector, visual annotation libraries, and method descriptors. Compared to other tools, *CoReTM* provides an open and accessible platform to apply different methodologies, as shown in a case study covering different threat modeling scenarios.

The remainder of this paper is presented as follows. Section II introduces fundamental methodologies and reviews existing modeling tools. Section III develops the *CoReTM* approach, while Section IV shows an evaluation based on a case study. Finally, Section V concludes this work and comments on future work.

II. Background and Related Work

At the core of each threat modeling tool is a methodology that defines the model semantics and modeling procedures. [1] provide a survey over such methodologies. However, a plethora of software implementing these methodologies has emerged. Further, it is unclear to which degree these applications enable and foster collaborative settings.

A. Threat Modeling Methodologies

Most threat modeling methodologies focus on the threat discovery phase. *STRIDE* aims to do so by providing a high-level categorization of threat families [1] [12]. Since no specific procedures or a repertoire of prevalent threats are provided, derivatives and combinations of this methodology are common [2] [1]. Other methodologies focus on finding relevant threats based on an enumeration of concrete threats. *CAPEC* provides a publicly accessible inventory of common attack patterns described from an adversarial perspective [13]. To provide operational context, Adversarial Tactics, Techniques & Common Knowledge (ATT&CK) is often cross-referenced in these descriptions [14]. Finally, some threat enumeration libraries focus on specific technologies. While such technologies like OWASP can help organizations to increase the awareness of specific threats [15], they are often considered complementary to other threat modeling methodologies [2]. Some merely offer a representation of modeled threats to provide a way to reason about threats [2]. With *Attack Trees*, high-level threats can be decomposed into a hierarchy of related threats [1].

Methodologies that go beyond the discovery of threats exhibit higher complexity. *PASTA* is an exemplary methodology that begins with the definition of business objectives and finally provides a risk analysis [16]. *NIST SP 800-154* follows a similar, yet more technology-oriented, approach to such a risk assessment [17].

B. Threat Modeling Tools

There are numerous dimensions by which threat modeling tools can be categorized. This survey considers the collaborative features of 18 popular tools and categorizes them into one of five identified approaches, as presented in Table I. Tools that provide similar features, but are not known to be used for threat modeling, such as *Notion* [18], are not included. **General Purpose-Tools** are widely used applications that do not follow a specific methodology. Nevertheless, their flexibility allows threat modeling to be carried out. *Whiteboards* are popular for rapid modeling, although they do not support asynchronous and remote settings [2]. Similarly, office suites provide a flexible way to share threat models asynchronously. Finally, *diagrams.net* is an online diagramming tool for which threat modeling add-ons are available. Aside from limited support regarding the inclusion of remote collaborators, none of these platforms provide any guidance to untrained users [19].

Microsoft Threat Modeling Tool, *OWASP Threat Dragon*, *TRIKE*, *SeaMonster*, and *CAIRIS* are all **manual modeling applications** that contain a diagram drawing component.

TABLE I: Comparison of Toolkit Support for Collaboration

	Async & On-site	Async & Remote	Sync & On-site	Sync & Remote
General-Purpose Tools (3)				
Whiteboards	✗	✗	✓	✗
Office Suites (Desktop)	✗	✓	✓	✗
Office Suites (Web-based), diagrams.net	✗	✓	✓	✓
Manual Threat Modeling (5)				
MTMT, TRIKE, OWASP Threat Dragon, SeaMonster, CAIRIS	✗	✓	✓	✗
Automated Threat Modeling (4)				
IriusRisk, securiCAD	✗	✓	✓	✗
Tutamantic	✗	✓	✗	✗
MAL	✗	✗	✗	✗
Integrated Threat Modeling (3)				
ThreatSpec, Threagile, raindance	✗	✓	✗	✗
Hybrid Modeling Approaches (4)				
pytm, SDElements	✗	✓	✗	✗
ThreatModeler	◐	✓	◐	◐
CoReTM	✓	✓	✓	✓

✓ = provides property, ✗ = does not fully provide property, ◐ = support unclear

However, they all follow a threat modeling methodology and are thus coupled to this methodology. Since many of these tools are web-based applications, it is possible to use them in asynchronous and remote settings to some extent. However, according to our knowledge and related surveys [10], [19], it is not feasible to create models synchronously. Furthermore, being tightly coupled to a specific methodology makes them only applicable to collaborative settings where said methodology is also applicable [2], [19].

In recent years, two novel threat modeling trends have emerged. **Automated Threat Modeling** approaches use existing artifacts such as source code or architecture diagrams to automate the discovery of threats and their countermeasures. Related applications such as *IriusRisk*, *Tutamantic*, *securiCAD*, *MAL* do not enable modeling in synchronous settings. Furthermore, the tight coupling to the underlying methodology and relying on existing input may render certain collaborative use cases such as workshops impossible. However, the presence of automated threat discovery implies that some form of knowledge base exists in the system. Thus, inexperienced users can still discover threats without having to be security experts [19].

Similar features can be discovered when looking at the second modeling approach which is being followed by tools such as *ThreatSpec*, *Threagile*, and *Raindance*, which aim to **integrate** and link threat models to the software development life cycle by relying on sources such as markdown files and source code [19].

Finally, *pytm*, *ThreatModeler*, *SDElements* combine the previously described approaches into **hybrid approaches**. Therefore, these tools compare similarly in terms of support for collaborative settings [2], [19].

III. The *CoReTM* Approach

CoReTM is a tool-supported approach to enable collaborative threat modeling among diverse stakeholders in real-time and asynchronously. *CoReTM* features a flexible modeling editor, methodology selection procedures, action-driven process guidance, knowledge bases, and integration to existing systems. By introducing an overarching meta-modeling process, all of these features are detached from specific methodologies. Under this process, various existing methodologies, including high-level methodologies such as STRIDE and Attack Trees, technology-oriented methodologies (*e.g.,* OWASP and CAPEC), and domain-driven risk-centric methodologies (*e.g.,* OCTAVE and PASTA), are supported. For that, a variety of input formats can be annotated in a compatible way.

Thereby, *CoReTM* promotes collaboration under circumstances where participants are not able to collaborate at the same time or location. Knowledge or skill gaps related to cybersecurity are bridged by enabling process guidance and knowledge bases. Finally, the consideration of unstructured input data as well as the integration with other systems ensures threat models are not isolated, so that collaboration is prolonged into other processes of the development cycle.

A. Architecture

The architecture of *CoReTM* is depicted in Figure 1 and described as follows. Different scenarios are applicable to model threats, including combinations of on-site, remote, synchronous, and asynchronous meeting styles. All users access *CoReTM* through a web-based interface that provides all user-facing functions. Initially, the user is carried through the modeling process defined here. There, he/she can configure the threat modeling scenario. The automated walkthrough application guides this user through the setup procedure, where a meeting style is defined, and appropriate methodologies are selected. For example, an administrating user creates two separate workshop spaces. One for project managers, focusing on modeling threats of a process model using STRIDE, and a second space to be used to model web application threats of an existing architecture component by relying on OWASP Application Security Verification Standard (ASVS).

Once participants access the web-based interface during the actual workshop or meeting, the application guides them through the defined methodology. Thereby, the underlying methodology is explained and followed. Depending on the methodology, additional knowledge bases are available to search for specific threats. In any case, the modeling process starts with a definition of assets. Many organizations already hold representations of their assets. *CoReTM* solves the issue of heterogeneous input sources by implementing an application that renders unstructured data such as PDF documents and pictures. In the same way, users can create new models using an integrated, minimalist version of the *diagrams.net* editor [20]. Both of these modeling applications use annotations as a means to define the semantics so that it is possible to automate report generation and integration even in the presence of multiple input data sources.

Once participants have modeled the assets, the walkthrough application guides the threat discovery phase based on the selected methodology. Discovered threats are stored using annotations so that threats elicited on structured and unstructured data sources can be processed into reports. Thus, *CoReTM* provides *(i)* graphical elements, *(ii)* process descriptions, and if applicable to the methodology, *(iii)* knowledge bases to discover threats.

To manage these elicited threats, all threats annotated on respective documents are automatically compiled into one report, where users can describe and prioritize threats. With that, *CoReTM* allows teams to leverage heterogeneous data sources, methodologies, and users to create one threat modeling report. Finally, users can link elicited threats to GitHub issues using the GitHub API. Thus, threat model reports can be automatically updated based on DevOps pipelines on GitHub.

B. Flexible Modeling

As *CoReTM* enables modeling for stakeholders of different meeting styles and backgrounds, the core of *CoReTM* is defined to be extensible. This includes a collaborative, real-time editor that allows annotation-based threat modeling with a variety of methodologies and sources. This is possible due to the incorporation of multiple flexible key components.

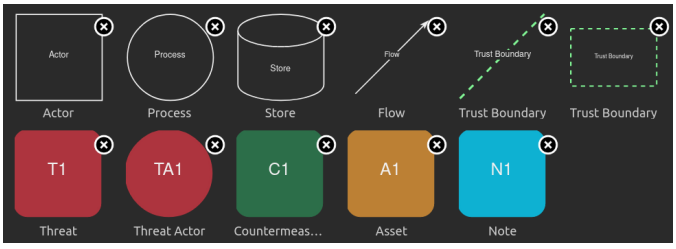

Fig. 2: Data-flow Diagram Library Used in the Diagram Editor

The real-time editing capabilities are provided by a flexible editor that supports modeling with diagrams and with existing, unstructured artifacts. The XML-based editor allows new diagrams to be created or imported. This diagram-based approach ensures that diagrams can be created for all the supported methodologies and for specific domains. *CoReTM* provides a set of abstract visual elements used across multiple methodologies. These elements contain additional meta-data so that diagrams are machine-readable. Custom libraries to enable Data-Flow-Diagram (DFD) and attack-tree modeling are provided, since with these abstractions, threats can be annotated on newly created or imported diagrams. To annotate threats, two mechanisms are present. First, a specific color palette is prepared. Thus, in existing diagrams, users can color-code elements without having to replace parts of the diagram. Secondly, a set of visual elements can be used to create new diagrams. Figure 2 illustrates visual elements for modeling threats using a DFD and Listing 1 shows the internal representation of a *coretm-threat* element which highlights the annotation meta-data.

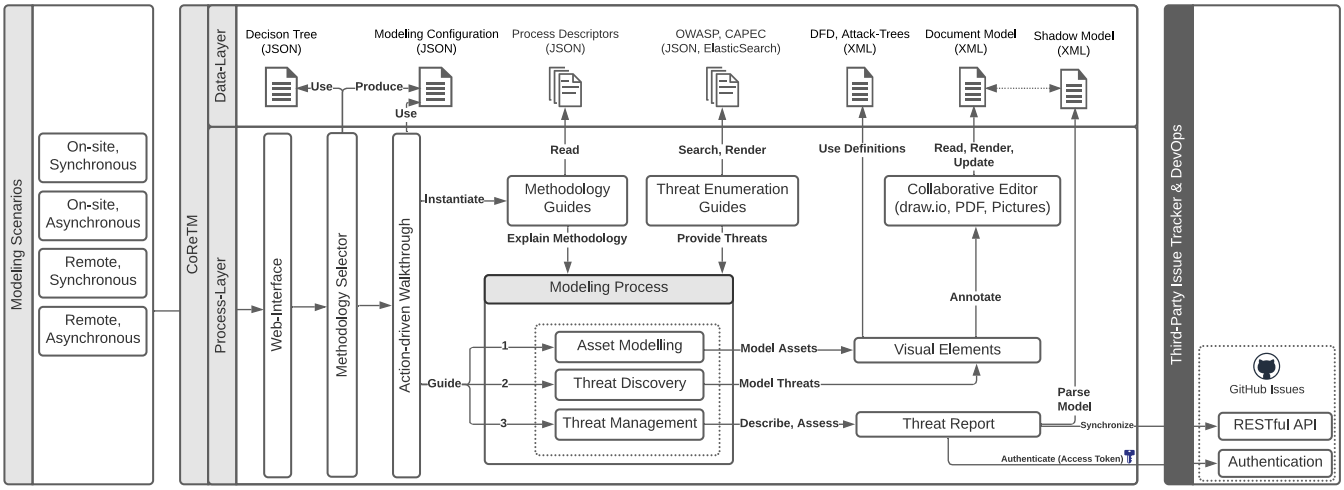

Fig. 1: Overview of *CoReTM* Components and Interfaces

With the aforementioned editor and their related visual libraries, users can apply different methodologies to model threats. To support all meeting styles, the underlying representation of the model needs to be carefully synchronized. Thus, to enable asynchronous modeling, a shared workspace with centralized access to the model is sufficient. In addition, participants can annotate models using notes, similar to how one may leave a sticky note on a whiteboard. Modeling in a synchronous manner presents greater challenges due to the possibility of synchronization conflicts. Since reliable transport is ensured through the web-based interface, a reliable storage component is used to mirror changed models to other participants. Unlike other solutions, no regular intervals are used to exchange models. Furthermore, differential synchronization algorithms are not applicable since they depend on fuzzy text-based algorithms that are not optimal for structured content such as the stored models [21]. To reduce potential collisions, each workspace is divided into multiple documents. Then, changes to the respective documents are synchronized using a three-way merge.

```
<mxGraphModel>
  <root>
    <object coretm-type="threat" id="2">
      <mxCell vertex="1" parent="1">
        <mxGeometry width="80" height="80">
      </mxCell>
    </object>
  </root>
</mxGraphModel>
```

Listing 1: XML Representation of "Visual Element" Annotating Threats

C. Methodology Agnosticism and Model Heterogeneity

Section II introduced numerous tools that are closely related to the implemented threat discovery methodology. With that, some of these tools are able to provide powerful features, such as code-based modeling, automated threat discovery, or DevOps integration. However, depending on such input data can also pose a high entry barrier. For example, creating a threat model of an architecture may not be possible with these tools if the software will be developed from scratch. Similarly, relying on code as a medium for modeling may exclude certain stakeholders such as program managers, architects, testers, or requirements engineers. When it comes to threat discovery, attack enumeration-based methodologies (*e.g., OWASP* or *CAPEC*) are already focused on specific technologies and are therefore only applicable to certain scenarios.

CoReTM addresses this problem with two key functionalities. First, *CoReTM* provides an abstract modeling process to which existing methodologies can be mapped. This process is implemented in an application that actively helps users choose, combine, and set up the right methodology. Based on a survey of existing methodologies, the methodology is chosen according to applicability and requirements derived from an interactive questionnaire, as shown in Figure 3. Since methodologies can be complementary, it is desired that in certain cases multiple methodologies are selected. For example, for users who do not have a definition of assets, the definition may be driven by the *PASTA* methodology, but for the discovery of threats, *STRIDE* can be applied. In any case, the respective methodology can then be applied using the previously described editors, which allow a wide variety of input formats. With that, threats gathered with any methodology are automatically compiled into the report and can be managed from there.

Secondly, a set of knowledge bases are implemented into *CoReTM*. Specifically, procedural knowledge bases help users to apply and navigate the asset and threat identification steps defined by the respective methodology. Furthermore, searchable threat enumeration databases allow for a directly accessible list of specific threats. Integrating multiple methodologies ensures that users do not have to search through various web pages in order to find threats in the appropriate abstraction.

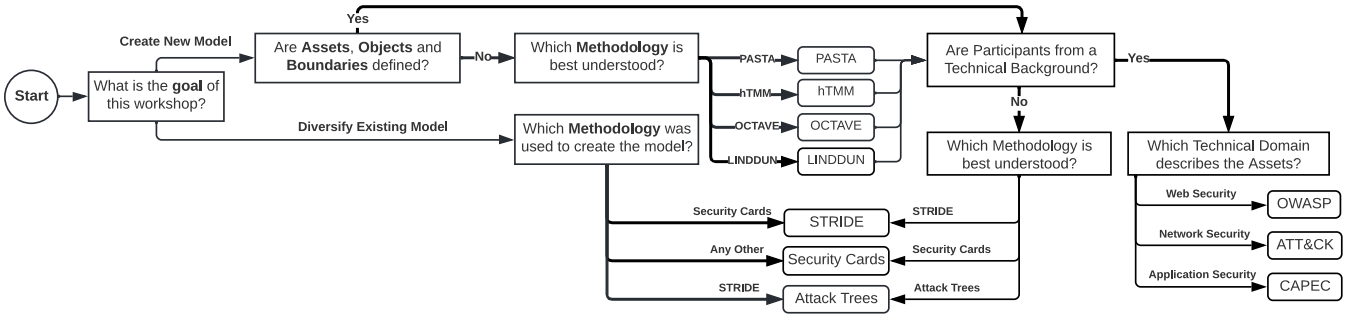

Fig. 3: Methodology Selection Graph

D. Automation and Integration

Many diagram-based modeling applications do not provide machine-readable documents that preserve semantic aspects related to threat modeling. Thus, reporting is often seen as a tedious task with little value added to proceeding activities [2]. *CoReTM* implements an automation step to create simplified reports which can be linked to other processes. By linking the generated threat model to other processes, the model provides direct value.

Parsing models is enabled by the usage of annotations. First, the encoded models are parsed to machine-readable XML. Using XML attributes and color codes, the semantics of the elements can be extracted. Specifically, a simple visualization displays threats in a tabular fashion, where additional information can be flexibly entered by users.

Once such a threat report is created, it can be further used for collaboration. First, in asynchronous settings, users can communicate over elements of the report using text notes. Next, threats can be converted to a *GitHub issue* with a single click, which causes the platform to issue a request against the RESTful API provided by GitHub.

By following these approaches, a threat model can be used in other collaborative settings, such as the software development process. This also ensures that a model does not go stale. For example, once countermeasures are implemented and the respective issues are cleared in the version control system, the threat model within *CoReTM* mirrors this state. Thus, once a threat model is updated, it will automatically show the current state. This linkability is not provided, when threat models are created in third-party diagram editors, whiteboards, or spreadsheets.

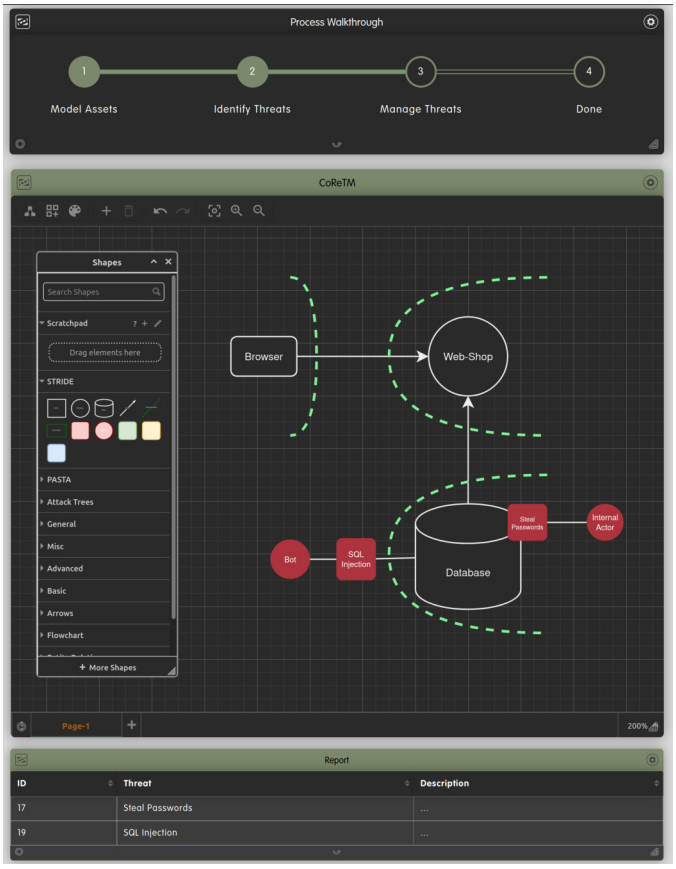

Fig. 4: Editor, Report, and Walkthrough Components of the *CoReTM* User Interface

E. Prototype Implementation

A prototype was developed to show the feasibility of the *CoReTM*. Due to the popularity of the *diagrams.net* editor among software engineers [22], this editor was considered. Since *diagrams.net* has a complex implementation and the already integrated storage providers (*e.g.,* Google Drive and Microsoft OneDrive) cannot be considered open platforms for further development, a custom storage integration was developed. To ensure collaborative editing, *diagrams.net* is run in an embedded mode, using *iframe* elements to render the User Interface (UI). Although the editor does not encourage extension [23], it exposes a clear *JSON* protocol in this mode [24]. With that, it was possible to leverage the editing capabilities on a different platform, as shown in Figure 4.

To provide a digital whiteboard and shared storage, the orchestration platform *dizmo* was targeted, since it provides programmatic orchestration for micro frontends. Furthermore, the web-based platform can be set up on the user's premises to alleviate data privacy concerns. An XML-based custom library of visual elements to allow annotation was developed

for the *diagrams.net* editor. All elements in this library contain metadata so that it is possible to create a machine-readable model of the diagram without relying on specific interfaces of the editor. Specifically, another micro frontend consumes the annotated model using a publish-and-subscribe data exchange and represents modeled threats in a table. Here, the user can freely add additional information or synchronize the threat with a GitHub issue.

The previously described elements cover general demands of the approach and thus are not related to any technology, standard, or process. In contrast, the guided brainstorming component that provides additional inspiration for threat discovery was implemented to reflect the *STRIDE* methodology. Additionally, the threat enumeration micro frontend is implemented with regard to the OWASP ASVS library. However, other libraries, including bespoke ones that an enterprise may hold, can be integrated by adding additional micro frontends.

All implemented UI components are implemented using a micro frontend's architecture. In total, the *CoReTM* prototype implements seven micro frontends. A full description of each available component is available in [19]. This choice is decisive for the prototype, since micro frontends show two clearly beneficial features to this use case.

Firstly, additional components can be added without increasing the complexity of the existing ones. For example, to add another threat discovery methodology, one could implement a new frontend without the need to modify or even understand the existing ones. This allows for a decoupling of the tool from the underlying methodologies. Secondly, micro frontends can be run as dedicated applications. Thus, one can open the same component multiple times on the same workspace, effectively decreasing the collision domain. *E.g.*, it is possible for two teams to use two instances of an editor on the same workspace and perform modeling with different methodologies.

IV. Case Study

The effectiveness of the prototype implementing the *CoReTM* approach is demonstrated in a two-part case study. It is assumed that a government body aims to implement a digital COVID-19 certification scheme that provides digital evidence of recovery, vaccination, or negative diagnosis [25].

This use-case demonstrates the applicability of *CoReTM*. Firstly, following the "complete protection" principle [26], which postulates that the security of the overall digital certification approach cannot be considered in a piecemeal manner. Thus, it is insufficient to consider the security of information systems from a purely technical perspective.

Secondly, such a digital certification approach naturally involves experts from many domains such as software engineers, healthcare employees, and government authorities. These key properties highlight, why this case study underlines the strength of *CoReTM*, which is the inclusion of stakeholders despite differences in geographical location, time, and security-related skills.

A. Business Process Threat Modeling

Following a risk-based approach, an effective application of cybersecurity measures requires a notion of the importance of the asset to be protected [27]. By focusing the threat analysis on important assets, threat modeling can be carried out with economic effectiveness in mind. Thus, it is critical not to start a threat model from a purely technical perspective. Hence, an initial threat modeling workshop is envisioned involving an expert from a COVID-19 testing laboratory, a healthcare system representative, and government personnel. Aside from such domain experts, a software and security expert are present. Due to the ongoing pandemic, it is assumed that technical experts are working in an on-site setting, while the remaining three stakeholders are dispersed over multiple physical locations. Furthermore, it is critical that at the end of the threat modeling workshop, a report of the findings can be sent to the head of the public health department.

Since a cybersecurity expert is present, he/she can set up an initial workspace in the *CoReTM* prototype by accessing the web-based interface. There, he/she opens a new instance of the *Questionnaire*, which helps him/her set up the threat modeling workshop for the audience. Since there is already an existing business process description, the questionnaire moves forward to the identification of skills in the audience. Since most of the stakeholders are not software engineers and no threat modeling methodology is known to the participants as they hold no cybersecurity knowledge, the tool determines that no asset modeling methodology is necessary, and that threat identification is best performed using the high-level *STRIDE* methodology. The tool automatically configures the modeling *editor* to provide visual elements for the *STRIDE* approach. Furthermore, the *walkthrough* component is automatically initiated to show the progress of the workshop and the *STRIDE* component provides information on how to apply the respective methodology.

At this point, the workshop leader can distribute the URL to participants using any communication channel. At the time of the scheduled meeting, all participants can open the application from their browser and work on the shared workspace in real-time. First, the software architect uploads the existing process model using the editor. By changing the colors of those elements that denote assets, the solution is able to inventorize assets. Now, the *walkthrough* component shows that participants can start identifying threats. For that, the *STRIDE* component iterates over the six mnemonic threat types so that each participant can brainstorm, discuss, and annotate relevant threats in the diagram editor. Once all six threat types are considered, the *walkthrough* component moves to the threat management phase of the life cycle. Here, all annotated threats are rendered to a list, where participants rate the risk sensitivity using a qualitative labeling. At this stage, only the domain knowledge is captured. Metrics, such as the vulnerability of an asset or the cost of an attack, are not yet considered. With this procedure, the threat modeling workshop conducted with *CoReTM* allowed for the identification of two

critical assets and three critical threats to the system, although participants had lacking cybersecurity knowledge and were not able to meet on-site. First, it appears that the largest threat to the certificates stems from personnel authorized to request certifications. Here, it appears vital that procedural controls are enacted to alleviate the threat of having tampered information in the system. This finding stresses that not all threats are embodied in technical components. Thus, it is critical to consider domain experts who can be included in the presented solution. Furthermore, since certificates hold personal and health-related information, there is a clear risk that such information is being disclosed. Finally, since certificates are issued by an information system, threats related to the elevation of privilege or data tampering are considered with respect to certificate issuance. The applicability of such threats from a system vulnerability perspective has to be further modeled.

This result can be shared with the head of the public health department in an interactive form, since the full workspace can be shared by the workshop participants. In that sense, such an application is advantageous over static reports, since the full context is available, no efforts in creating a report are necessary and the possibility of extension is enabled due to the interactivity provided. These results serve as a baseline for the second threat modeling iteration, where the highlighted threat areas are investigated on a technical level to analyze the criticality of threats and vulnerability of the systems regarding these threats. Furthermore, these initial findings can already be used to justify to the management why the implementation of process control for certificate issuance needs attention.

B. Software Threat Modeling

In a second iteration of the threat modeling workshop, a geographically distant security expert asynchronously guides a technically versed audience. Again, the questionnaire component guides the leader toward a "sensible" configuration. Existing diagrams depict the technical perspective of the architecture, and all participants understand the technical background of the Web application to be modeled. The questionnaire advises *(a)* using the existing diagram and *(b)* to model threats via the *OWASP ASVS*.

Once all the components are set up, the actual workshop is driven by the *OWASP* component without the need for the cybersecurity expert to be present at the same time or location, as it provides procedural and informational support to apply the methodology. First, the proper of the three security levels is determined using a questionnaire Since the system stores sensitive medical data, the highest level is proposed. Thus, the component automatically parametrizes itself to show threats relating to this security level. It is critical to highlight that according to the *OWASP ASVS* standard, this level of security cannot be achieved in a purely automated manner, but requires *"[. . .] access to [. . .] the people involved in the development process"* [28], stressing the necessity of a collaborative system.

Threats can then be discovered by either searching through the catalog based on keywords or by browsing through the threat categorizations. However, as shown in Figure 5,

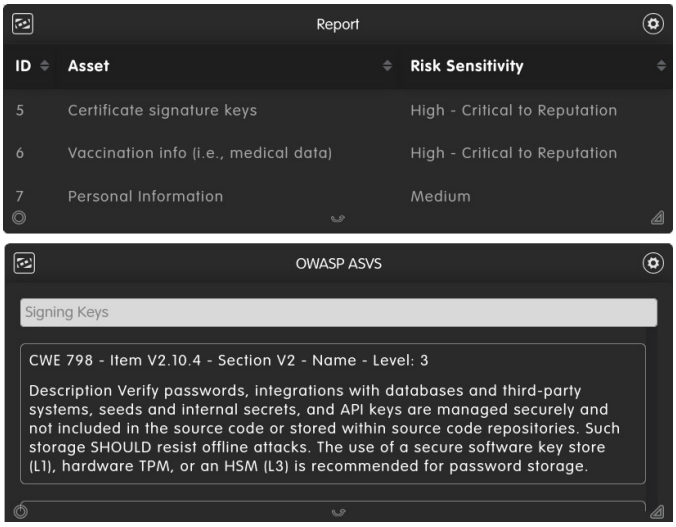

Fig. 5: Searching in an Indexed Catalog of the OWASP ASVS Standard using Asset Labels as Keywords

searching for the keywords, that are used to describe assets already shows a promising subset of threats to be considered. This is facilitated by the reporting component summarizing annotated assets. For example, one term involved to denote the security of the certificate asset is the *cryptographic keys* to sign certificates. A simple search for this term already yields the following recommendation:

> "Verify that cryptographic keys used in verification are stored securely and protected against disclosure, using a (..) Hardware Security Module (HSM), or an OS service that can use this secure storage." [28]

Furthermore, searching for *medical data* yields additional threats relating to protecting that data at rest, which can be annotated on the diagram and further outlined in the report component. For example, *OWASP ASVS* advises protecting such data at rest to mitigate privacy-related threats. Thus, based on interaction on the *CoReTM* platform, multiple critical threats including cryptographic key management and data privacy are discovered and assessed. In contrast with conventional reports, the resulting threat model is interactive so that it can be directly integrated into the software development process. Furthermore, it can be used in an asynchronous manner, such as to conduct an audit by security experts or to convince senior management of a key finding or countermeasure.

This scenario demonstrates that technical personnel can collaboratively derive threats to a piece of software without in-depth cybersecurity knowledge. Being able to collaboratively assess threats is particularly useful, since this phase showed that only the builders of the application can assess the relevance of threats discovered. By using a collaborative approach, all technical activities are driven by business value, since threat modeling is centered around critical assets. Bridging such gaps in technical knowledge is achieved with a flexible approach toward methodology selection and application.

V. Summary, Conclusions, and Future Work

This paper introduced *CoReTM*, a collaborative approach to discovering, assessing, and managing assets and threats surrounding them. *CoReTM* stands as a tool for risk management and architecture development even in cases, where domain and subject experts are not able to collaborate due to differences in geographical location, time, or skills. Therefore, *CoReTM* provides a collaborative editor, where assets and threats are flexibly modeled. Based on the methodology that was chosen by navigating the questionnaire, *CoReTM* guides collaborators through the threat modeling process and the underlying methodology.

To the best of the authors' knowledge, *CoReTM* is the first platform designed around threat modeling supporting remote collaboration, while considering a meta-modeling framework that integrates the breadth of available methodologies with the goal of optimizing threat modeling. As demonstrated in the case study, *CoReTM* enables focusing threat discovery and assessment around a notion of critical assets surrounded by a holistic threat model, so that relevance to the business is preserved.

The implemented and running prototype of *CoReTM* is publicly available at [29]. This prototype is flexible and allows various methodologies to be applied, even when collaborators cannot meet because of availability or geographical location. This approach addresses the limitation of current tools that do not support virtual collaborations. Furthermore, by decoupling the methodology from the tool itself, *CoReTM* stands as an extensible open source tool so that organizations can implement their own methodologies to address specific use cases and demands.

Future work includes formulating and validating a threat discovery methodology for such business processes. Furthermore, this work still assumes that automated threat modeling cannot completely replace human insight, especially when assessing the value of assets and the relevance of discovered threats. However, as part of future work, novel techniques (*e.g.,* business process mining or natural language processing) will be investigated with respect to their potential for business process threat modeling.

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References

[1] S. Hussain, A. Kamal, S. Ahmad, G. Rasool, and S. Iqbal, "Threat Modelling Methodologies: A Survey," vol. 26, pp. 1607–1609, 01 2014.

[2] A. Shostack, *Threat Modeling: Designing for Security*. John Wiley & Sons, 2014.

[3] Threat Modeling Manifesto Working Group, "Threat Modeling Manifesto," November 2020, https://www.threatmodelingmanifesto.org, Last Visit April 2022.

[4] CONCORDIA Consortium, "Cybersecurity Roadmap for Europe," November 2021, https://www.concordia-h2020.eu/roadmap/, Last Visit March 2022.

[5] Akamai, "2021: Volumetric DDoS Attacks Rising Fast," March 2021, https://blogs.akamai.com/2021/03/in-our-2020-ddos-retrospective, Last Visit December 2021.

[6] Cloudflare, "DDoS Attack Trends for 2021 Q2," July 2021, https://blog.cloudflare.com/ddos-attack-trends-for-2021-q2/, Last Visit December 2021.

[7] M. Franco, J. Von der Assen, L. Boillat, C. Killer, B. Rodrigues, E. J. Scheid, L. Granville, and B. Stiller, "SecGrid: a Visual System for the Analysis and ML-based Classification of Cyberattack Traffic," in *IEEE 46th Conference on Local Computer Networks (LCN 2021)*, Edmonton, Canada, October 2021, pp. 140–147.

[8] I. Gartner, "Gartner Forecasts 51% of Global Knowledge Workers Will Be Remote by the End of 2021," June 2021, https://www.gartner.com/en/newsroom/press-releases/2021-06-22-gartner-forecasts-51-percent-of-global-knowledge-workers-will-be-remote-by-2021, Last Visit December 2021.

[9] B. Doerrfeld, "Majority of Software Engineers Want Remote Work Options," August 2021, https://devops.com/majority-of-software-engineers-want-remote-work-options/, Last Visit January 2022.

[10] K. Bernsmed, D. Cruzes, M. Jaatun, and M. Iovan, "Adopting Threat Modelling in Agile Software Development Projects," *Journal of Systems and Software*, vol. 183, p. 111090, 09 2021.

[11] C. Bush, "Continuous Security: Threat Modeling in DevSecOps," November 2021, https://bishopfox.com/blog/threat-modeling-in-devsecops, Last Visit April 2022.

[12] Microsoft, "Microsoft Threat Modeling Tool threats," March 2022, https://docs.microsoft.com/en-us/azure/security/develop/threat-modeling-tool-threats, Last Visit March 2022.

[13] CAPEC, "About CAPEC," April 2019, https://capec.mitre.org/about/index.html, Last Visit March 2022.

[14] ——, "CAPEC - ATT&CK Comparison," 2019 October, https://capec.mitre.org/about/attack_comparison.html, Last Visit March 2022.

[15] OWASP® Foundation, "OWASP Top Ten," October 2021, https://owasp.org/www-project-top-ten/, Last Visit March 2022.

[16] T. Ucedavélez and M. M. Morana, *Risk Centric Threat Modeling: Process for Attack Simulation and Threat Analysis*. John Wiley & Sons, 2015.

[17] National Institute of Standards and Technology (NIST), "Guide to Data-Centric System Threat Modeling," March 2016, https://csrc.nist.gov/publications/detail/sp/800-154/draft, Last Visit March 2022.

[18] Notion Labs, Inc., "Notion – One workspace. Every team," May 2022, https://www.notion.so/product, Last Visit May 2022.

[19] J. von der Assen, M. F. Franco, C. Killer, E. J. Scheid, and B. Stiller, "On collaborative threat modeling," IFI-TecReport No. 2022.04, Zürich, Switzerland, Tech. Rep., apr 2022. [Online]. Available: https://files.ifi.uzh.ch/CSG/staff/vonderassen/extern/publications/IfI-TR-2022_04.pdf

[20] JGraph Ltd, "Diagram Software and Flowchart Maker," https://www.diagrams.net/, Last Visit March 2022.

[21] N. Fraser, "Differential Synchronization," in *ACM Symposium on Document Engineering (DocEng'09)*, New York, USA, 2009, pp. 13–20. [Online]. Available: http://neil.fraser.name/writing/sync/eng047-fraser.pdf

[22] M. Rauer, "Draw.io Diagramming in Confluence Is Currently the Most Successful App in the Atlassian Marketplace," 2019 April, https://blog.seibert-media.com/2019/04/18/draw-io-diagramming-in-confluence-is-currently-the-most-successful-app-in-the-atlassian-marketplace/, Last Visit April 2022.

[23] JGraph, "GitHub - jgraph/drawio: Source to app.diagrams.net," January 2022, https://github.com/jgraph/drawio#open-source-not-open-contribution, Last Visit March 2022.

[24] JGraph Ltd, "Embed mode," November 2020, https://drawio.freshdesk.com/support/solutions/articles/16000042544-embed-mode, Last Visit March 2022.

[25] G. Karopoulos, J. L. Hernandez-Ramos, V. Kouliaridis, and G. Kambourakis, "A Survey on Digital Certificates Approaches for the COVID-19 Pandemic," *IEEE Access*, vol. 9, pp. 138 003–138 025, 2021.

[26] K. S. Anne Kohnke, Dan Shoemaker, *The Complete Guide to Cybersecurity Risks and Controls*. Boca Raton: Taylor and Francis, 2016.

[27] E. Wheeler, *Security Risk Management: Building an Information Security Risk Management Program from the Ground Up*. Elsevier, 2011.

[28] OWASP® Foundation, "OWASP Application Security Verification Standard," October 2021, https://owasp.org/www-project-application-security-verification-standard/, Last Visit April 2022.

[29] J. von der Assen, "CoReTM: Collaborative and Remote Threat Modeling," April 2022, https://github.com/CoRe-TM, Last Visit April 2022.