Automatic Generation of Security Argument Graphs

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Abstract—Graph-based assessment formalisms have proven to be useful in the safety, dependability, and security communities to help stakeholders manage risk and maintain appropriate documentation throughout the system lifecycle. In this paper, we propose a set of methods to automatically construct security argument graphs, a graphical formalism that integrates various security-related information to argue about the security level of a system. Our approach is to generate the graph in a progressive manner by exploiting logical relationships among pieces of diverse input information. Using those emergent argument patterns as a starting point, we define a set of extension templates that can be applied iteratively to grow a security argument graph. Using a scenario from the electric power sector, we demonstrate the graph generation process and highlight its application for system security evaluation in our prototype software tool, CyberSAGE.

I. INTRODUCTION

Critical public infrastructure systems, such as those found in the electric power and water sectors, must operate safely and reliably for decades. During their operating lifetimes, these systems are often modified to face evolving operating conditions and requirements. For example, infrastructure systems have adopted greater communication and control capabilities in recent years. However, while these advanced features enable greater system visibility and more efficient control strategies, they also open new avenues for malicious attacks on the system [1], [2], [7].

To understand evolving system requirements, operational contexts, and/or security threats, practitioners often employ graph-based reasoning techniques. Such approaches include safety cases [3], [6], [5], fault tree analysis [19], [14], [21], and attack trees/graphs [15], [16], [13], [11], [9]. Historically, development and maintenance of those graphical approaches required significant human effort. Recently, several efforts have begun in the safety and reliability communities to automate those processes [6], [5], [14], [21]. However, in the security domain, automation has been largely restricted to specific applications, such as construction of attack graphs [13]. The various challenges about security assessment were discussed in, e.g., [12], [18].

Our approach for conducting holistic security assessment is to develop security argument graphs, a graphical formalism that integrates diverse inputs—including workflow information for processes executed in the system, physical network topology, and attacker models—to argue about the level of security for the target system. In our earlier work [4], we presented an integrative security assessment framework that reasons about security by progressively combining heterogeneous types of information to construct such holistic security argument graphs. Section III will recap the proposed framework and describe the unique structure of the generated security argument graphs.

Such holistic security argument graphs are beneficial in multiple ways: they make explicit the functional interdependencies of different pieces of security-related information; also, the graph structure can be used to combine various numerical evidence to yield holistic quantitative security metrics.

In this paper, we provide a rigorous set of methods for constructing the holistic argument graphs introduced in [4]. We leverage recurring argument patterns that emerge from the need to integrate heterogeneous information about a system and possible attacks, and instantiate them as extension templates that can be iteratively and automatically applied to grow our argument graphs. Using our Cyber Security Argument Graph Evaluation (CyberSAGE) tool [20], which is currently under development, we demonstrate the automated graph generation for an example electric power grid system [3].

The remainder of this paper is structured as follows: Section II reviews our assessment framework and the structure of the resulted security argument graphs. In Section III we present the argument patterns that can be used to generate such argument graphs. In Section IV, we formalize the argument patterns as extension templates. In Section V we show how to use these extension templates to automate the argument graph construction process. A practical example of the graph construction is presented in Section VI with a use case from the electric power sector. We discuss related work in Section VII and conclude in Section VIII.

II. SECURITY ARGUMENT GRAPHS

Many safety [8], reliability [19], and security [10] assessment methodologies rely on graphical structures to organize and present information. In a security context, such “argument graphs” [12] could help provide a precise underpinning for threat modeling and quantitative evaluation of system-level metrics. A particular challenge in constructing security argument graphs is that of dealing with the heterogeneous set of information that needs to be incorporated, which may include

...
Fig. 1: The security assessment framework proposed in [4].

security requirements, business processes, system architecture, physical device specifications, known vulnerabilities, and attacker models.

In [4], we presented a high-level workflow-oriented security assessment framework, which organizes the diverse set of information inputs described above. The overall assessment process, which is illustrated in Fig. 1, relies on a unique argument graph structure that progressively incorporates Goal, System, and Attacker (GSA) information.

As a brief overview, the process starts with a precisely defined security goal, which may relate to properties such as Confidentiality, Integrity, or Availability. The analyst then identifies system processes that are relevant to the security goal, and represents them as workflow diagrams. Those workflow diagrams provide a sequence of actions and their respective actors. Those two inputs are combined to form a simple argument graph, called a Goal (G) graph, that captures information about actors and interactions that may affect the security goal. When detailed system information (e.g., actor to device mapping, network topology, or device configuration) is available, we use the G-graph to integrate that information and generate a more detailed security argument graph: the Goal, System (GS) graph. Finally, we incorporate information about possible attacker actions and capabilities into the GS-graph to generate the Goal, System, Attacker (GSA) graph.

Our GSA graph structure, which is represented in Fig. 2, is system-focused (like fault trees [19]), but allows for the modeling of attacks (like attack graphs [16]). The graph contains vertices of different types, such as system (attacker) actions and system (attacker) properties. This graph structure has no explicit vertices to denote aggregation semantics (e.g., OR relations or AND relations), as each vertex contains information that defines the aggregation of its incoming neighbors. Thus, the graph has only a single type of dependency relationship among the vertices.

III. ARGUMENT PATTERNS IN SECURITY ASSESSMENT

While applying our structured approach to generate security argument graphs (e.g., in the context of smart grid infrastructure), we observed a series of recurring argument patterns. These patterns capture direct logical relationships among different pieces of information and may be used to develop reusable extension templates that help automate the graph generation process. In this section, we give an overview of several useful argument patterns we identified in our work on security assessments of processes in the smart grid domain. We shall see that the patterns to be presented are fairly generic, so they are applicable to other domains as well. In addition, other domains might also contribute patterns that we have not yet encountered. We formalize those patterns as extension templates in Section IV-A.

In general, two classes of patterns occur in our arguments: intra-type patterns, and inter-type patterns. As the name suggests, intra-type patterns introduce and connect vertices of the same type, and inter-type patterns introduce and connect vertices of different types. The following describes the two pattern classes in more detail and provide five example patterns we identified. We number the patterns according to the order in which they typically appear in our argument graphs in the generation process.

Inter-Type patterns. Inter-type operations connect vertices of different types. For example, at a high level, a security goal is directly defined in the context of one or more workflows to which the goal is related. We characterize such a relationship by the following argument pattern $P_1$: security goals or requirements directly depend on processes that occur in the system. As another example, consider the workflow steps in our argument graph. Each workflow step is performed by one or multiple actors with certain properties. This association of workflow steps with actors is our argument pattern $P_3$: to successfully complete actions in the workflow, their respective actors need to be available. In addition, these abstract actors have to be mapped to concrete devices in the system to allow a more detailed decomposition. That is our argument pattern $P_2$: devices in the system adopt one or more workflow actor roles to provide functionality.

Intra-Type patterns. Workflows in the system have a number of actions that have to be executed in sequence. Our graph generation starts with the final step of a workflow, and then adds its prerequisite step (i.e., the generation works backwards in time). That is one of our argument patterns, pattern $P_3$: the successful completion of workflow actions may depend on the other preceding or concurrent actions. For example,
assume that the final step in a workflow depends on the receiving of a message. The intra-type pattern can be used to identify the workflow step that is related to the transmission of that message. Another important intra-type pattern relates to specific devices (within a system) that may be involved in a workflow. The refinement of device properties is pattern \( P_d \); device properties depend on sub-properties and their composition semantics. For example, the availability of a device depends on the availability of its software and hardware, so this property can be decomposed.

In general, our argument patterns capture individual direct logical relationships that make up the entire argument. Such a focus on simple patterns of abstract relationships allows us to apply the patterns with only local knowledge of the argument graph. As each argument pattern captures a generic relationship, we can construct an argument graph using a small number of patterns. For an analogy, argument patterns function like axioms that could be used to build up a mathematical proof. Like axioms, argument patterns are derived from logical relationships, best practices, common scenarios, and expert knowledge. Thus, different patterns or different ways of instantiating the same patterns are typically required to tackle security problems of different nature, (e.g., availability vs. confidentiality). The patterns presented in this paper are used to support an availability assessment use case (see Section VI).

In the next section, we show how to formalize those argument patterns by constructing extension templates. The resulting set of extension templates allow us to automatically generate an argument graph based on several classes of inputs which drive the security assessment.

IV. GRAPH GENERATION BASED ON ARGUMENT PATTERNS

So far, we have introduced the concept of argument patterns that emerge during the construction of argument graphs; we also provided several informal examples to illustrate our intuition. We now present a formalism that rigorously defines these patterns and the manner in which they can be applied. In the following, we start with a formal definition of the security argument graphs. We then formalize how to progressively generate such graphs through the application of local extensions. We define how a local extension is generated through the instantiation of an extension template, which formalizes a corresponding argument pattern. With all these building blocks in place, we then present our overall process for generating the graph.

A. Graph Structure and Local Extensions

We first define the structure of our graph and how a graph can be generated by the application of local extensions.

Graph Definition. For the following discussion, a graph \( \omega_i \) is defined to be a triple

\[
\omega_i := \langle V_i, E_i, l_i \rangle,
\]

where \( V_i \) is a finite set of vertices, \( E_i \) is a finite set of directed edges, and \( l_i \) is the labeling function. Each vertex is itself a static tuple that contains the type of the vertex, and some of type-specific additional data. The type and data are set when the vertex is created, and cannot be changed afterward. Two vertices are considered identical whenever all their static data are identical. An edge \( e = \langle v_r, v_l \rangle \) is represented by a tuple that contains references to its source vertex \( v_r \) and target vertex \( v_l \). The labeling function, \( l_i(v) \), returns the mutable attribute(s) of a vertex \( v \in V_i \). For example, a variable attribute could be the probability that this vertex’s property is true (to be determined in the graph evaluation later). Note that \( l_i(v) \) does not need to be a single numerical value; it can encapsulate a list of different types of information, such as an expression relating the attributes of its incoming neighbors to its own attribute.

Local extension. We progressively generate the security argument graph through the application of local extensions. A local extension \( r \) is defined as a tuple of its matching vertex \( v_r \) and the resulting star graph \( \omega_r \):

\[
r := \langle v_r, \omega_r \rangle
\]

The resulting star graph \( \omega_r \) contains \( v \) and at least one additional vertex. Each of these additional vertices has one outgoing edge towards \( v \). Other than those edges, there is no other edge in \( \omega_r \).

We use \( \omega_a \xrightarrow{r} \omega_b \) to denote the application of a local extension \( r \) to a graph \( \omega_a \), which generates a new graph \( \omega_b \) (see Fig. 3). Here, we assume that \( r \) is applicable, i.e., the matched vertex \( v_r \) is indeed a vertex of \( \omega_a \). Given that, the local extension is applied as follows:

\[
\omega_a \xrightarrow{r} \omega_b = \langle V_a \cup V_r, E_a \cup E_r, l_b \rangle
\]

where

\[
l_b(v) = \begin{cases} l_r(v) & \text{if } v \in (V_r \setminus V_a) \cup \{v_r\} \\ l_a(v) & \text{otherwise}. \end{cases}
\]

The additional vertices from the star graph \( \omega_r \) and the associated edges are added to the original graph. Note that the additional vertices in \( \omega_r \) may or may not be present in the original graph \( \omega_a \). For each vertex that is already present in the original graph \( \omega_a \), except for \( v \), the old labeling function is preserved; otherwise, the labeling function is taken from the star graph.

B. Extension Templates and Graph Generation

Having introduced local extensions, we now consider their generation. We introduce the notion of an extension template,

\[
\gamma := \langle m_\gamma, f_\gamma \rangle,
\]

where \( m_\gamma \) is a matching function and \( f_\gamma \) is an extension generation function. Specifically, \( m_\gamma(v, \Sigma) \) shows \( \gamma \)’s matching score for vertex \( v \), where \( \Sigma \) is the environment: a placeholder for additional information. Recall that the attribute of a vertex \( l(v) \) is a tuple that contains its type and type-specific additional
Fig. 3: Local extensions: Transformation of graph $\omega_a$ using local extension $r$ into graph $\omega_b$ (i.e. $\omega_a \xrightarrow{r} \omega_b$). The local extension $r$ matches $v_2$, and inserts $\omega_r$ in its place. Slashed arrows denote logical connections between graphs. For illustration purposes, the variable attribute of a vertex is its color.

information, both of which can be used to determine the numerical value of $m_{\gamma}(v, \Sigma)$. A value of $m_{\gamma}(v, \Sigma) = 0$ means that extension template $\gamma$ is not applicable to the generation of an extension for $v$. If multiple extension templates are applicable (i.e., several extension templates can be applied to the same vertex), then $m_{\gamma}$ could be implemented as chosen from a range, to indicate precedence. Otherwise, $m_{\gamma}$ can be implemented as a Boolean function indicating applicability of $\gamma$.

If an extension template $\gamma$ is applicable to a vertex $v$, the local extension generation function $f_{\gamma}(v, \Sigma)$ uses the information from vertex $v$ and environment $\Sigma$ to generate a local extension that can be used to expand $v$. In that case, $\Sigma$ is a placeholder for various pieces of information that are relevant to the transformation of the graph, such as the workflow information, the actor-to-component mapping, or the network topology graphs. We use $\Gamma$ to denote the set of extension templates.

**Graph Generation Algorithm.** We define graph generation as the repeated application of a set of extension templates to a graph. More formally, it is the application of $\Gamma$ to a graph $\omega_a$, using the environment $\Sigma$. The underlying algorithm is summarized as pseudocode in Algorithm 1 below.

| ID   | Comment                              |
|------|--------------------------------------|
| $T_1$ | Template to connect goal node to assessed workflow(s) |
| $T_2$ | Template to look up required previous steps in a workflow |
| $T_3$ | Template to create requirements for the actor of a workflow step |
| $T_4$ | Template to create device requirements for an actor |
| $T_5$ | Template to decompose requirements for devices |
| $T_6$ | Template to identify potential attacks on leaf properties |
| $T_7$ | Template to create requirements for an attack step |

**Algorithm 1: Graph generation loop**

1. function GENERATEGRAPH($\omega_a, \Gamma, \Sigma$)
2. \[ U \leftarrow VERTICES(\omega_a); \]
3. while $U \neq \emptyset$
4. \[ v \leftarrow \text{GETONEELEMENT}(U); \]
5. \[ \Gamma_v \leftarrow \text{GETMATCHINGTEMPLATES}(v, \Gamma); \]
6. \[ \forall \gamma \in \Gamma_v : \]
7. \[ r \leftarrow f_\gamma(v, \Sigma); \]
8. \[ \omega_a \leftarrow \omega_a; \]
9. \[ U \leftarrow U \cup (V_r \setminus V_a); \]
10. \[ U \leftarrow U \setminus \{v\}; \]
11. end while
12. return $\omega_a$.
13. end function

In the pseudocode, $VERTICES(\omega_a)$ returns all vertices of the graph, while $\text{GETMATCHINGTEMPLATES}(v, \Gamma)$ returns a set $\Gamma_v$ of all templates applicable to $v$, and $\text{GETONEELEMENT}(U)$ simply picks an arbitrary element of the set $U$. Note that when no template is applicable, $\Gamma_v = \emptyset$, whereas when several templates are applicable, the one with the highest matching score $m_{\gamma}$ is chosen. In Table I we list some of those extension templates and describe their functions. The template numbering corresponds to the pattern numbering in Section III; the set has been expanded to include two additional templates, which relate to attacker modeling. Here, we concentrate on extension templates related to availability of a process, matching our case study in Section VI. We are currently working on additional extension templates to model the transmission path of messages, human-machine interactions, and more complex workflow mechanisms.

V. USING EXTENSION TEMPLATES TO GENERATE ARGUMENT GRAPHS

Our security assessment process [4], shown in Fig. 1 contains three types of security argument graph: the G-graph, GS-graph, and GSA-graph. All of those graphs are generated through application of Algorithm 1, the differences arise from the specific inputs provided and the extension templates used for graph generation. The meta-process for constructing the argument graphs is:

\[
\begin{align*}
\omega_g & \leftarrow \text{GENERATEGRAPH}(\omega_0, \Gamma_g, \Sigma_g) \\
\omega_{gs} & \leftarrow \text{GENERATEGRAPH}(\omega_g, \Gamma_s, \Sigma_s) \\
\omega_{gsa} & \leftarrow \text{GENERATEGRAPH}(\omega_{gs}, \Gamma_a, \Sigma_a)
\end{align*}
\]
In the following three subsections, we describe individual steps, their inputs, and the associated templates in greater detail. Finally, in Section V.D, we focus on a single template to illustrate the level of specification required, and the importance of templates in automating the graph generation process.

A. Graph Generation Using Workflow Input

To generate the first stage of our argument graph, the G-graph, Algorithm 1 is called as follows: \textsc{GenerateGraph}(\omega_0, \Gamma_g, \Sigma_g). That will generate the G-graph, which includes the workflow input in \Sigma_g, and is based on an initial base-graph \omega_0 and a set of extension templates \Gamma_g. The initial graph will contain only a vertex representing the goal of the assessment. \Gamma_g contains \( T_1, T_3, \) and \( T_5, \) the formal extension templates for patterns \( P_1, P_2, \) and \( P_3 \) as defined in Section III.

**Workflow information in \( \Sigma_g \).** The workflow input describes how the system provides a functionality, and identifies necessary actors as well as the information they exchange. Our internal structure for this input is a workflow graph: \( \omega_w = (V_w, E_w, l_w) \). For \( v \in V_w \), \( v = (\text{type, attributesTuple}) \). Workflow vertices have only one type of vertex: \text{Type}(v) \in \{\text{WorkflowStep}\}. A vertex’s attributesTuple field depends on its type. For simplicity, in the following we consider only sequential workflows, with workflow steps vertices. The attribute tuple of each workflow step vertex has two static attributes: \text{actor} and \text{action}. Thus, the attributeTuple is \( (\text{actor, action}) \). The labeling function \( l_w \) is used to store additional workflow information, e.g., on branching, merging, and conditions in the workflow.

**Argument graph vertex types and templates \( \Gamma_g \).** We construct our argument graph iteratively, starting with \( \omega_0 \), which is a directed graph with the assessment goal as its only vertex. The assessment goal determines which properties of the system we are interested in, for example, the availability of the components involved in a workflow. The goal vertex is directly created from user input, without any need for an extension template. This goal vertex is then connected to the final step of the assessed workflow, using extension template \( T_1 \) (which implements \( P_1 \); see Section III). Then, that final workflow step vertex is connected to the required previous steps in the workflow using \( T_2 \) (implementing \( P_2 \)), and those steps are expanded as well. All vertices generated by \( T_1 \) and \( T_2 \) will be of type “ActionAvailability.” In addition, required properties for each actor, such as actor and communication link availability, are added using extension template \( T_3 \) (implementing \( P_3 \)). That will add vertices of type “ActorAvailability” and “MessageAvailability.” A vertex with type “ActionAvailability” has static attributes \text{action} and \text{actor}. For example, in the context of the smart grid, the action can be “MeterReading,” and the actor can be “Utility”. A vertex with type “ActorAvailability”, has static attribute \text{actor}. For example, the actor can be “Utility.” We call the resulting graph at this stage the G-graph, as it models the immediate requirements related to the goal of the assessment.

Fig. 4: Examples of a device type hierarchy (a) and composition tree (b). The device types are based on the power grid substation example, with an HMI (Human-Machine Interface), PLC (Programmable Logic Controller), and RTU (Remote Terminal Unit).

B. Graph Generation Using System Input

As the next step, the argument graph \( \omega_s \) is expanded using Algorithm 1 this time with different operands: \textsc{GenerateGraph}(\omega_s, \Gamma_s, \Sigma_s). Here, the operands are the system information \( \Sigma_s \) and a set of extension templates \( \Gamma_s \). Here, \( \Gamma_g \) contains \( T_4 \) and \( T_5 \), the formal extension templates for patterns \( P_1 \) and \( P_3 \).

**System information inputs.** The system description contains multiple types of inputs, including the following.

- An actor-to-component mapping: This is similar to the deployment diagram in UML. It maps the actor from the workflow to a componentType.
- A network topology graph \( \omega_n = (V_n, E_n, l_n) \), where each vertex \( v \in V_n \) is a physical device in the system, and each edge \( e \in E_n \) is a link (which can be a single-hop physical communication link, a network path, or physical). The attribute function \( l_n(v) \) describes various attributes of a device \( v \), including its type, physical location, and access privileges, among others. For a link \( e \), \( l_n(e) \) describes its attributes, like type, capacity, and delay.
- A componentType hierarchy diagram as depicted in Fig. 4a.
- The device composition information as depicted in Fig. 4b.

**Vertex types and templates for GS-graph generation.** Based on those inputs, two extension templates can be applied to the argument graph: \( T_4 \) and \( T_5 \). \( T_4 \) makes it possible to connect the abstract actor in the workflow with the concrete device that executes this action, thus introducing “ComponentAvailability” vertices to the graph. A vertex of that type has 2 static attributes: component and componentType. The componentType is taken from a hierarchy of device types with increasing specificity towards the graph’s leaves. The component is taken from a tree that describes the subcomponents for each componentType. If no subcomponent tree is available for a given componentType, the subcomponent tree of a parent componentType will be used instead. We describe \( T_5 \) in more detail in Section V.D.

C. Graph Generation Using Attacker Input

As the last step, the argument graph \( \omega_a \) is expanded using Algorithm 1 this time with different operands: \textsc{GenerateGraph}(\omega_a, \Gamma_a, \Sigma_a). Here, the operands are the...
Algorithm 2 Template $T_5$

1: function $T_5(v, \Sigma_a)$
2:     $\omega_r \leftarrow \text{NEWGRAPH}(\{v\}, \emptyset, 0)$;
3:     $ot \leftarrow \text{GETCOMPONENTTYPE}(v)$;
4:     $\omega_c \leftarrow \text{GETCOMPOSITIONINFO}(ot, \Sigma_{gs})$;
5:     $oc \leftarrow \text{GETCOMPONENT}(v)$;
6:     $C \leftarrow \text{GETSUBCOMPONENTS}(oc, ot, \omega_c)$;
7:     $\forall c \in C$:
8:         $v_c \leftarrow \text{NEWVERTEX}(c, ot)$;
9:         $\omega_r \leftarrow \omega_r \cup \{v_c\}$;
10:     $E_r \leftarrow E_r \cup \{(v_c, v)\}$;
11: return $\langle v, \omega_r \rangle$;
12: end function

(a)

Construction of $\omega_r$ :

Step 2: 

Step 3-4: 

Component Types

Step 5:

Subcomponents

Step 6:

(b)

Fig. 5: Details on extension template $T_5$: (a) Pseudocode of the extension function $T_5(v, \Sigma_a)$. (b) Visualization of the process.

system information $\Sigma_a$ and a set of extension templates $\Gamma_a$. The two patterns for the extension templates $T_5$ and $T_7$ in $\Gamma_a$ were not introduced earlier. They are similar to $P_2$ and $P_3$, but relating to the attacker (instead of the system).

Attacker information input. The input placeholder $\Sigma_a$ here contains the attacker model, which contains a set of attacker properties and a set of attack sequences $\Omega_r$ (a set of star graphs). Each star graph $\omega_r$ contains a potential attack step and its immediate prerequisites. The vertices in $\omega_r$ are of type “AttackStep” and “AttackerProperty.” Attacker property information relates to methods, knowledge, and physical access of the attacker, e.g., access to a company’s compound or server room.

Vertex types and templates for GSA-graph generation. In the GSA-graph, new vertices of type “AttackStep” and “AttackerProperty” are introduced (matching the nodes from the attacker model). Under this model, only single step attacks and their corresponding requirements can be modeled, however we are developing additional vertex types to incorporate multi-step attacks.

D. Automatic Generation using Templates

In the previous sections, we have introduced several extension templates that we distilled from common argument patterns that we observed. As part of our effort toward automating the security assessment of complex systems, we are compiling an extension template library. All of the extension templates in Table I are defined in pseudocode. In this paper, we present only the core set of templates we are currently working on: additional extension templates are omitted from this paper because of space limitations. We use the extension template $T_5$ (device decomposing requirements) to illustrate the underlying extension process.

Extension template $T_5$ relies on component type and device composition hierarchies, which are specified as an input to the security assessment (part of $\Sigma_{gs}$). Fig. 4 presents examples of the composition hierarchies, which were discussed in Section V-B. Template $T_5$ uses the supporting hierarchies to expand a single graph vertex $v$. We show the extension generation function in Fig. 5a and represent the process graphically in Fig. 5b. In particular, the local extension for a component property is created by finding the best matching componentType from the componentType tree. That best componentType is then used to find the matching property composition tree, and to look up the next decomposition for the current property. All potential decomposition nodes are added to a star graph $\omega_r$, and returned together with the node $v$ as a local extension.

That precise description of the extension template application process and required input information allows the extension templates to be readily implemented in a software tool. In the next section, we present an example security assessment, and show that the process can be automated using a supporting software tool that is currently under development.

VI. APPLICATION: AN ELECTRIC POWER GRID USE CASE

In this section, we apply the algorithms and templates presented earlier to an illustrative use case from the electric power sector. We start by manually deriving a security argument graph to explain important details. We then discuss graph generation in CyberSAGE [20], a security assessment tool that is currently under development. Using CyberSAGE, we can generate the argument graph automatically, based on a library of extension templates and a set of inputs.

A. Assessment Input

We consider an example power system use case adapted from [3]. This scenario is a typical supervisory control and data acquisition (SCADA) operation, connecting a utility company’s network with intelligent field devices that manipulate physical power grid parameters. In this example, a central distribution management system (DMS) monitors the voltage at a specific point (i.e., bus) in the low voltage (LV) power distribution network as reported by the power quality sensor (PQS) there, and uses that information to trigger a control action in another device located in the network. The control device in this example is a distributed energy resource (DER),
B. Security Argument Graphs

Knowledge of the assessment goal, the workflow (Fig. 6a), and the system (Fig. 6b) inputs, the actor componentType mapping, and an attacker model allows us to apply the extension templates defined in Table I to construct a security argument graph according to our framework. The graph generation process is depicted visually in Fig. 7. First, the base graph (representing the goal) is extended using workflow input. Extension templates $T_1$ to $T_3$ are used during this stage to identify dependencies between actions and actors. Next, templates $T_4$ and $T_5$ are used to enrich the argument graph with system-specific information (GS-graph). The fully developed GSA-graph, formed by applying $T_4$ and $T_6$, is shown at the bottom of Fig. 7.

This complete security argument graph (GSA-graph) organizes security-related information that originated from disparate sources and formats. The human-readable structure is intended to help system designers and other stakeholders understand dependencies and possible security threats in a complex system. In particular, it is clear from Fig. 7 that the distribution management system (DMS) is critical to the voltage control process—it is involved in 3 separate actions, occurring at different times. However, since the DMS is located in the utility’s back-office network it may pose less of a security risk than the DER, which is a field device. While this analysis is qualitative, the GSA-graph can be used for quantitative security assessment as well. In [4] we outline an approach for quantitative evaluation over the argument graph. That quantitative evaluation has been refined and is implemented in our software tool, which is discussed below.

## C. Automation in the CyberSAGE Tool

We implemented the proposed template-based graph generation using our prototype assessment tool, which we call CyberSAGE (Cyber Security Argument Graph Evaluation) [20]. Based on the inputs described in Section VI, CyberSAGE is able to automatically generate the argument graph. Screenshots of the system input and part of the GSA-graph are shown in Fig. 8a and Fig. 8b, respectively.

The workflow and system inputs are given to CyberSAGE in XML format. Currently, our tool does not provide functionality to edit these inputs; it depends on other applications, such as XML/text editors, to obtain and modify them. For example, CyberSAGE imports the system topology input directly from save files of the CSET tool. Once CyberSAGE has imported those files, it builds its internal data structures and visualizes their contents in a user-friendly manner (see Fig. 8a).

The remaining inputs, namely the attacker models and extension templates, are currently static and provided by CyberSAGE. With the extension templates implemented, CyberSAGE automatically builds the argument graph by following Algorithm 1. It takes the tool less than 1 second to produce the final argument graph, which contains around 50 vertices. The tool also provides some degree of customization, such as

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1The Cyber Security Evaluation Tool: ics-cert.us-cert.gov/satool.html
Fig. 7: Manually derived security argument graphs for the distribution automation use case. Each edge is annotated to show the extension template applied during graph generation.
allowing the user to enable or disable a particular subset of extension templates when building the graph.

VII. RELATED WORK

We see parallels between our work on security argument graph generation and work from the safety and reliability communities, as well as related efforts within the security domain. In this section, we discuss related efforts in graph-based modeling and highlight unique features of our framework.

Safety case generation. A safety case uses certain argument strategies to organize a body of evidence so as to provide a compelling case for supporting certain safety claims (goals) [8]. Safety cases are typically constructed manually. Recent efforts (e.g., [6], [5]) have begun to introduce formal semantics to help automate the safety case generation process. Compared with those recent efforts, our proposed approach focuses on argument patterns that incorporate various security-related evidence, including security goals and attacker models. We also formalize the template in a local way, which simplifies the definition and instantiation of the template while still
allowing progressive generation of the argument graph.

**Fault tree generation.** Fault tree analysis is a classic deductive method used to determine what combinations of basic component failures can lead to a system-level fault event [19]. While fault trees are usually constructed manually in practice, there has been a steady stream of efforts to automate the fault tree generation process. For example, Pai et al. [14] propose a method to transform a UML system model to dynamic fault trees. Joshi et al. [21] propose a method to automatically generate a dynamic fault tree from an Architectural Analysis and Design Language (AADL) model. Recently, Xiang et al. [21] propose an automatic synthesis method to generate a static fault tree from a system model specified with SysML.

Compared with that line of work, our proposed approach not only considers various security-specific information, but also intends to cover a broader scope of security-related claims and heterogeneous pieces of evidence.

**Attack trees and other security assessment techniques.** Attack trees and their variations (e.g., attack graphs [16], [13], ADVISE [11], and attack-defense trees [9]) have been shown to be useful for security assessment. Inspired by the fault tree formalism, an attack tree graphically represents how an attacker can use staged attacks to compromise certain assets in a network. ADVISE [11] automates the search of attack strategies. Those efforts differ from ours in that they do not provide a framework that can automatically integrate heterogeneous pieces of evidence (e.g., relating to security goals, workflows, system information, and the attacker) to produce a holistic security argument.

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