AsIf: Asset Interface Analysis of Industrial Automation Devices

Thomas Rosenstatter, Christian Schäfer, Olaf Saßnick, Stefan Huber
Josef Ressel Centre for Intelligent and Secure Industrial Automation
Salzburg University of Applied Sciences
Salzburg, Austria
{thomas.rosenstatter, christian.schaefer, olaf.sassnick, stefan.huber}@ fh-salzburg.ac.at

***Abstract*—As Industry 4.0 and the Industrial Internet of Things continue to advance, industrial control systems are increasingly adopting IT solutions, including communication standards and protocols. As these systems become more decentralized and interconnected, a critical need for enhanced security measures arises. Threat modeling is traditionally performed in structured brainstorming sessions involving domain and security experts. Such sessions, however, often fail to provide an exhaustive identification of assets and interfaces due to the lack of a systematic approach. This is a major issue, as it leads to poor threat modeling, resulting in insufficient mitigation strategies and, lastly, a flawed security architecture.**

We propose a method for the analysis of assets in industrial systems, with special focus on physical threats. Inspired by the ISO/OSI reference model, a systematic approach is introduced to help identify and classify asset interfaces. This results in an enriched system model of the asset, offering a comprehensive overview visually represented as an interface tree, thereby laying the foundation for subsequent threat modeling steps. To demonstrate the proposed method, the results of its application to a programmable logic controller (PLC) are presented. In support of this, a study involving a group of 12 security experts was conducted. Additionally, the study offers valuable insights into the experts' general perspectives and workflows on threat modeling.

I. Introduction

A. Motivation

Due to the advancement of Industry 4.0, systems considered as Operational Technology (OT), such as Industrial Control Systems (ICSs) or Industrial Internet of Things (IIoT) are increasingly utilizing Information Technology (IT) solutions. The focus also shifts towards using open standards rather than proprietary protocols. Prominent examples are communication protocols, such as IPv4/IPv6 or Open Platform Communications Unified Automation (OPC UA). This leads to an increase of interconnectivity within shop level machines and enterprise systems and also throughout the internet. With this increasing connectivity also comes the need for advanced security. This is especially relevant for Cyber–Physical Systems (CPS), as their physical interactions can lead to severe consequences, such as damage to the environment, property or loss of human lives (safety) [1].

However, the problem when applying traditional IT security solutions to industrial systems is that they are not adapted to the unique requirements of industrial systems. Stouffer et al. list various points in [2], such as performance-, availability- or long spanning lifetimes criteria, which are not always considered in such measures.

To address such concerns, international organizations have developed a variety of standards and guidelines to enhance security in OT environments. Two of the most common ones are the IEC 62443 and NIST Special Publication 800–82. However, these documents do not provide a step-by-step guide on how to implement security, as each system is different and has its own, unique set of requirements. Therefore, before designing a security architecture, security experts must first understand the system, its assets, its functionality, and its threats. For that, proper modeling of systems becomes paramount for all further activities and can serve as a reference for security analysis later on. However, the complexity of OT systems makes modeling and understanding them challenging, especially for non-security experts responsible for these systems. Conversely, security experts may lack familiarity with OT systems and may not fully comprehend their specific requirements.

B. Problem Statement and Contribution

Currently, threat modeling processes for OT systems often rely on structured brainstorming sessions with experts from both domains. However, this approach may not be sufficient, as important aspects might go unnoticed [3]. This non-exhaustive approach is not suitable and may lead to insufficient system models. As a result, threat modeling efforts are often incomplete, lacking in-depth analysis, and fail to capture all potential threat scenarios relevant to the industrial systems.

These shortcomings further translate into deficient security architectures for industrial systems [3]. Inaccurate identification of risks and vulnerabilities lowers the quality of security measures, leaving the systems vulnerable to cyber-attacks. Without a solid security architecture, industrial systems are susceptible to data breaches, operational disruptions, and potential physical harm. Therefore, the foundation for a secure system is a thorough understanding and modeling of the system and its assets.

In this paper, we aim to overcome the challenges of modeling OT systems and further conduct a study to gain insights into industry's current view on threat modeling. More specifically, we contribute to the following research questions:

- **RQ.1** How can we effectively address the challenges of exhaustively modeling OT systems?
- **RQ.2** What are the current industrial perspectives on threat modeling practices and their impact on security posture?

We address *RQ.1* by treating OT systems foremostly as distributed, cyber-physical systems. From this viewpoint, we propose *AsIf*, which is guided by the ISO/OSI model and helps with the exhaustive identification and classification of the interfaces used by the asset. The proposed bottom-up approach, starting with the physical interfaces allows for a thorough analysis in each layer enriching the *interface trees*. These trees visualize the system based on its interfaces. For the evaluation, we apply *AsIf* to a real-world example in a industrial automation testbed, namely a Programmable Logic Controller (PLC).

Moreover, we conduct a study involving domain experts to evaluate the methods utility and superiority over their currently used method. In addition to the respondents evaluation of *AsIf*, they provide valuable insights regarding their work in threat modeling (*RQ.2*) and share our findings.

The remainder of the paper is organized as follows: First, a brief introduction on threat modeling is given in Section II, followed by the proposed method in Section III. The method is then applied to a real-world example in Section IV. An evaluation of the results and discussion of the respondent's views on threat modeling is given in Section V. Finally, the conclusion is presented in Section VI.

II. Related Work and Background

The concept of a *dark factory* focuses on enabling fully autonomous production operations through advanced automation and machine autonomy requiring four design principles of Industry 4.0 [4]: *Interconnection*, *Information Transparency*, *Decentralized Decisions* and *Technical Assistance*. However, due to these principles and the change of requirements, new cyber security challenges arise for industrial systems, where traditional security measures are not sufficient enough [5]. The term *OT security* is used to describe these differences and challenges. As a crucial part in securing OT system, system and threat modeling processes must be adapted to the new requirements, too.

A. Related Work

Before threat modeling can be applied, the system must be analyzed, broken down into its components and modeled in a way that enables the identification of potential threats. This is the crucial first step, on which all further processes are based and on which this paper puts the focus.

Shostack [6] recommends the use of *software-centric* approaches, as he includes the responsible software developers in the modeling process. Using the documentation and the software code, a complete model of the system is created. Hollerer et al. [7] suggest using system identification based on the ISA 95 network layout and using technical documentation as reference material for modeling OT systems. This approach tackles the overall system with all its components and their communication paths in the network. The MITRE ATT&CK framework supports the asset analysis in the way that it provides a list of assets which is also mapped to threats, albeit it does not provide means to systematically analyze the system in question.

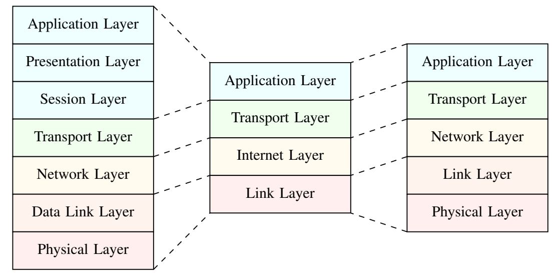

Figure 1. Comparison of the different network models: ISO/OSI model (left), the TCP/IP model (center) and Tanenbaum's hybrid TCP/IP model [9] (right).

Khalil et al. [8] identified assets by collaborating with system owners, developers and operators. They also included various documentation and block diagrams describing the system. This approach is similar to a brainstorming session, where all participants contribute their knowledge and expertise.

However, the question is, whether these approaches are suitable for OT systems. They either consider the system as a complete white-box, which requires a thorough understanding of the underlying software and needs the involvement of the responsible developers. Or the assessment is done in a big-picture manner, which potentially disregards important details of single components. Even though the first approach is more thorough, it is not always possible to involve the responsible persons or to get access to the source code. Especially for legacy systems, this is often not possible. Therefore, a method is needed, that combines the advantages of both approaches and substantiates its quality with a comprehensive approach.

B. Hybrid TCP/IP Model

The TCP/IP model is a layered model, similar to the ISO/OSI model, used to describe the communication between multiple systems. Compared to the 7-layer ISO/OSI model, it comprises 4 layers: *link*, *internet*, *transport* and *application layer*. In contrast, the ISO/OSI model contains the session and presentation layer, however, according to Tanenbaum [9], these are of little use to most applications – the functionalities are already implemented in the application layer. Regarding the TCP/IP model, Tanenbaum criticizes the lack of a physical layer, which describes the medium required for the transmission of bits, such as copper, fiber or wireless. Although this may not be needed for the typical use of TCP/IP, it is relevant in this work. Therefore, the 5-layered *hybrid TCP/IP* model by Tanenbaum [9] is used in this work. It separates the physical layer from the link layer, as shown in Figure 1.

C. Threat Modeling

Once the system under consideration has been analyzed and a complete model can be created, the next step is to identify potential threats. There are multiple safety and security modeling methods available, each focusing on different aspects: STPA-sec [10] focuses on system safety, HAZOP [11] on hazards and system operability, SAHARA [12] on hazard, risk, and security, PASTA [13] on the process for attack simulation and OCTAVE [14] on operationally critical threats and assets.

In this work the STRIDE model is used in our demonstration, as it is lightweight and provides a systematic way for modeling threats [15]. There is already research using STRIDE in industrial domains [16], indicating its applicability across various sectors. For instance, domains such as smart-grid, Internet of Things, health-care and automotive [15], [17]–[19].

Each letter in STRIDE represents a threat type, i.e., spoofing, tampering, repudiation, information disclosure, denial of service and elevation of privilege. STRIDE was developed by Microsoft and is a structured approach to identifying potential threats to a system. The method requires an already specified system architecture, its components, and their communication paths. This modeling of the communication pathways can be achieved using Data Flow Diagrams (DFDs). Once the system is fully modeled, STRIDE can be applied and each component can be analyzed against each threat type.

Although our demonstration is based on STRIDE, we note that *AsIf* can be used in combination with any threat modeling technique that follows some system model, such as a DFD.

III. Methodology

Besides the technical challenges of a *dark factory* regarding automation and autonomy aspects, security is a major concern in this context as well. To develop a proper security architecture, a thorough understanding of all systems and their potential interactions throughout their lifecycles is necessary. Factories typically consist of systems manufactured by a variety of manufacturers, who often provide sparse or no documentation for the entire system internals. Adding to that, the documentation varies from manufacturer to manufacturer. Therefore, a systematic and independent approach is required to assess the properties of each system individually.

In our approach, the system is first broken down into its components and analyzed individually. Once the individual requirements are defined, the overall system can be discussed in a second step. This paper focuses on the first step, the detailed analysis of the individual components.

The challenge we focus on is the security analysis of a single component. Our primary concerns revolve around the interfaces of the device, whether they are physical or logical, as these serve as potential entry points for attackers, in addition to human errors and physical harm. There is a lack of guidance when modeling the system's interfaces potentially leading to analyses based on an incomplete model. Thus, a systematic approach to evaluate all interfaces is needed.

OT systems are distributed systems comprising several computing units communicating with each other. These units each have their own communication stack allowing the mapping to the ISO/OSI model. Therefore, we utilize the hybrid TCP/IP model [9] (see Figure 1) as the starting point for the asset interface analysis. Compared to the classic TCP/IP model, we also need to model physical interfaces, therefor we depend on the separation between physical and network layer. In addition, modern protocols in OT are IP-based, hence the ISO/OSI model would also be more general than needed. Layers 5-7 would also require a deep understanding of the running applications, libraries, and parts of the operating system. However, obtaining such exhaustive data on these layers is impossible without access to the source code. Unlike other layers, there is no definitive method to identify services or interfaces, often leading to guesswork or reliance solely on documentation. The hybrid model consolidates these software technologies into a unified application layer, simplifying the focus on threat modeling for relevant applications. This approach is advantageous for security experts, especially those unfamiliar with the target device, as it streamlines the assessment process.

Table I
Methods for identifying interfaces and protocols.

L.#	Layer	Exemplary Methods*
5	Application Layer	Individually, based on the transport layer results from `Nmap` scan and `tcpdump` for open TCP & UDP ports
4	Transport Layer	`Nmap` scan for supported IP protocols
3	Network Layer	`Wireshark` and `tcpdump` traffic analysis
2	Link Layer	Derived from Physical Layer
1	Physical Layer	Physical inspection

*Note, based on the environment, further methods may be useful.

We propose to start the device analysis at the bottom and to then move upward towards the application layer. For each layer, the interfaces and protocols used are considered and the dependencies to the lower layers are noted. To achieve this, we suggest individual identification methods for each layer, outlined in Table I. It should be noted that the `Nmap` scans are technically performed one layer below than indicated, however, the results of these scans are used for the layers as indicated in the table. To apply the presented identification methods in a comprehensive manner, it may be necessary to consider the entire system lifecycle. For example, different services (i.e., interfaces) may be present in a maintenance or firmware update phase. Additionally, one needs to account for rare events, such as diagnostic data transmissions occurring only at fixed intervals.

This approach has the advantage of being systematic and comprehensive, as it covers every network-related aspect of potential interfaces and data flows that could be potentially exploited by malicious actors. The TCP/IP model describes the internet architecture and as such does not provide options to model physical interfaces, such as USB ports, DIP selectors and card slots for CF/SD cards. To include use cases where operators interact with the hardware (by pressing buttons, setting switches), we extend the model and add *physical user inputs and interactions* in the physical layer (L.1).

By approaching the system in such a bottom-up manner, an *interface tree* can be created, providing information about

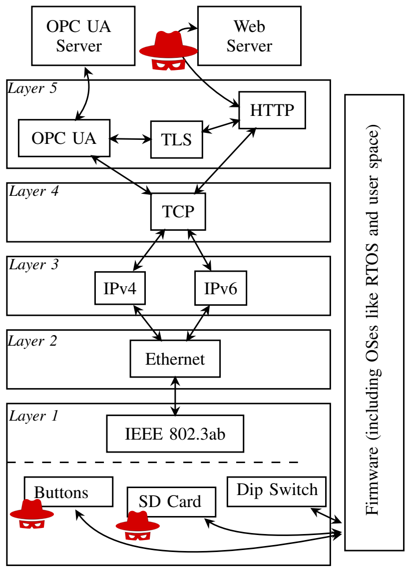

Figure 2. Extended TCP/IP model with example protocols. It shows the interfaces of an exemplary industrial device, which provides access via OPC UA and an HMI via a HTTP web server. As the firmware contains not only the applications, but also the software stacks and drivers for all other interfaces, it is modeled across all layers.

all active interfaces and the underlying services. This allows for a comprehensive overview of the system's functionalities and enables an exhaustive modeling of the environment. Using this model, DFDs can be more easily derived for the threat modeling process. An example of such an *interface tree* is given in Figure 2. In this figure, we also want to draw attention to the physical layer at the bottom, which not only houses IEEE 802.3ab, but also other physical, human-machine interfaces on the device. Other examples could be proprietary network protocols or ports for serial communication. As these may not always use upper layer services, we add a generic firmware application in parallel to the model, to visualize the dependencies in a more understandable way.

IV. Use Case

To demonstrate the benefits of using *AsIf*, we analyze a PLC. As it is typically used in industrial automation and also provides a wide range of physical, human-machine interfaces, it is a good example for showcasing the use of our proposed approach. Figure 3 illustrates in which step of the entire threat modeling process *AsIf* is applied. It also highlights the importance of a thorough asset analysis during the modeling as all other steps rely on the correctness and completeness of the provided information. Missing or incorrect modeling could ultimately lead to an insecure system; for instance, interfaces would not be considered.

We follow the steps outlined in Figure 3 until DFD creation, to highlight how this method can be applied in practice. The focus lies on the thorough identification and analysis of the interfaces following the proposed bottom-up approach and the creation of a DFD.

Table II
Layer 1 Interfaces of the PLC. The top section shows classical network protocols. The lower section displays all other physical interfaces.

Interface	Description
IEEE 802.3ab	1000BASE-T Gbit/s Interface for Ethernet
IEEE 802.3u	100BASE-TX FE Interface for Powerlink
Fieldbus connectors	Interface for the proprietary used fieldbus
RS232	Serial connection with a programming device
Analog I/O	Read/write analog signals
CF Card Slot	Application storage
USB Ports	Can be used for USB peripherals
RS232	Serial interface
Button	Resets the device
DIP Selector	Selects the boot mode
2x DIP Selector	Set the network address for programming
Extension Interface	Enables adding more extension modules

A. Hardware

The device under consideration features an ATOM 1.0 GHz processor, 256 MByte DDR2 RAM, and a Compact Flash card slot for interchangeable program memory. The device can be connected to a network via Ethernet or Powerlink, and provides a RS232 interface for serial communication. Two modules for analog I/Os are available, as well as a port for a proprietary fieldbus. There are multiple DIP selectors, which can be used to set the network address and boot mode. Via a button, a device reset can be initiated. To program and configure the PLC, a proprietary software is used. This software and its documentation can be used as sources of information for this analysis. The PLC was programmed with a Windows 10 computer connected via Ethernet.

B. Applying the Method

For each layer of the model (see Figure 1 and Table I), the interfaces are determined in a manner, that is appropriate. The following describes the utilized methods and lists the identified interfaces for each layer.

Physical Layer. Within this first, adapted, layer of the model, the physical interfaces are described. Because of this adaption, not only network- but also human-machine interfaces are encompassed. While these components are not primarily used for communication, they present potential attack vectors causing severe outcomes. As layer 1 deals with signal transmission technologies, we argue that interfaces for human-machine interaction also fall in this layer, as interacting with them involves electrical transmission of signals. Table II shows all identified interfaces in the physical layer of the PLC. The identification is done based on information from the documentation and physical inspection of the device including the inspection for possible interfaces behind the casing.

Link Layer. The second layer contains the communication protocols used on the physical layer. The PLC supports Ethernet, Powerlink and a proprietary fieldbus. Additionally, we argue, that USB and RS232 communication also fall in

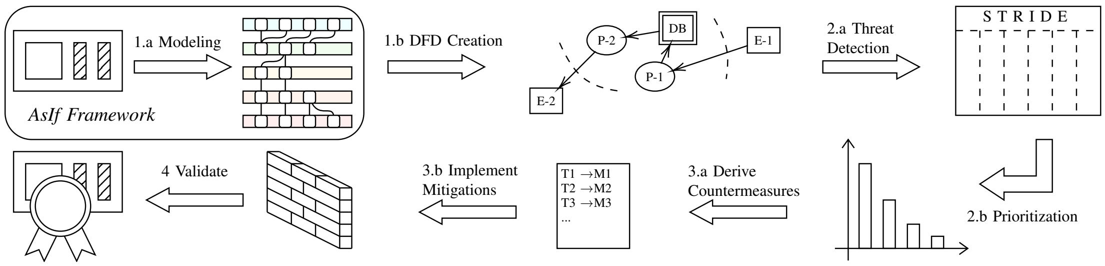

Figure 3. A threat modeling workflow, ranging from the system analysis and modeling (1.a) to the creation of a DFD (1.b), the threat analysis (2.a) and prioritization (2.b), with STRIDE and CVSS exemplary, to the identification (3.a) and implementation (3.b) of countermeasures and lastly their validation (4). The use of STRIDE is exemplary, any threat modeling method can be used based on *AsIf*.

this layer. The information about the supported protocols is deduced from the previous layer and the documentation.

Network Layer. The protocols for network-wide communication are analyzed in this layer. Tools such as the network protocol analyzer `Wireshark`[1] can be utilized for sniffing the traffic at this layer and to derive the active protocols. The traffic is captured during the boot process and normal operation to capture most active communication processes. From this information, we were able to see that IPv4, IPv6 and ARP were used. Fieldbus and serial communication protocols do not have routing capabilities, so they do not exist in this layer and beyond.

Transport Layer. At this layer, the documentation did not provide any more information about which protocols besides TCP and the UDP are supported or active. The network mapper `Nmap`[2] is chosen as it allows to run an IP scan, which exhaustively iterates through all possible IP protocol numbers. Depending on the responses `Nmap` receives, it interprets the protocols that are supported by the host[3]. In this use case, it was revealed that the PLC not only supports TCP, User Datagram Protocol (UDP) and ICMP, but also SCTP.

Application Layer. Networked applications typically operate utilizing ports for communication, thus the PLC is scanned for open ports using `Nmap`. This scan provides insights about active services running on the system. The scans[4] are performed on all 65535 TCP and UDP ports. The internal port-service mapping of `Nmap` may not be correct for all services as some manufacturers may use proprietary protocols. Hence, we recommend a manual verification.

The port scan in combination with the programming software and its documentation may help to further identify the running services on the PLC. In this use case, multiple web servers acting as Human Machine Interfaces (HMIs), an OPC UA server, a TFTP server, a DHCP client, a RPCbind server and a remote configuration service are identified.

Once all the interfaces on the target system are known, a model can be created to visualize the dependencies across all layers. The model, the *interface tree* follows the architecture of the hybrid TCP/IP model and can help security experts to get a better understanding of the systems internals. Figure 4 shows the *interface tree* for the investigated PLC. The Figure also highlights the protocols that were found during the assessment, but which were not documented.

C. Generating a Data Flow Diagram

When constructing DFDs it is essential to focus on two layers: the application layer and the physical layer. Firstly, by analyzing running applications within the system, associated processes and data flows can be derived. These are ultimately responsible for communication both within and beyond the system, making them primary targets for potential security threats. Secondly, the physical interfaces require special attention, as they enable human-machine interactions independent of the network and thus allow cybersecurity measures to be bypassed. For instance, an adversary could disguise as a service technician and potentially be able to substitute the CF card containing malicious firmware or exploit the serial interface to reprogram the device.

An important aspect of industrial devices are the different phases of their lifecycle, as they may have different requirements for security. For instance, during the installation and maintenance phases, access must be allowed for configuration tools to obtain the device. Security measures must also consider these situations. On the other hand, during operation, these interfaces should be disabled. Therefore, we chose to draw multiple diagrams, each depicting a different phase of the lifecycle. This way, the diagrams are not too complex and additional awareness for the different phases is raised.

For the described use case, a DFD of the PLC during a generic ‘service’ phase is depicted in Figure 5. The service phase includes configuration, maintenance and update activities. The DFD illustrates three external entities (EE-1 to EE-3) interacting with the PLC. The hardware configuration (DF-1) uses input through physical interfaces (see Figure 4) such as the USB-connected keyboard, DIP switches and a button. The access to the web services is provided through the three identified HMIs, which in turn interact with the runtime. On the right side, the DHCP server is shown, as it is used for receiving a valid IP address and further network information (DF-16). Last, the development environment may interact via two configuration interfaces (L.5) provided by either TCP or UDP (L.4). In addition, the service technician may also

[1]Wireshark: https://www.wireshark.org/
[2]Nmap: https://nmap.org/
[3]command: `nmap -p0- -sO -T4 [ip address]`
[4]command: `nmap -p0- -s[S|U] -T4 [ip address]`

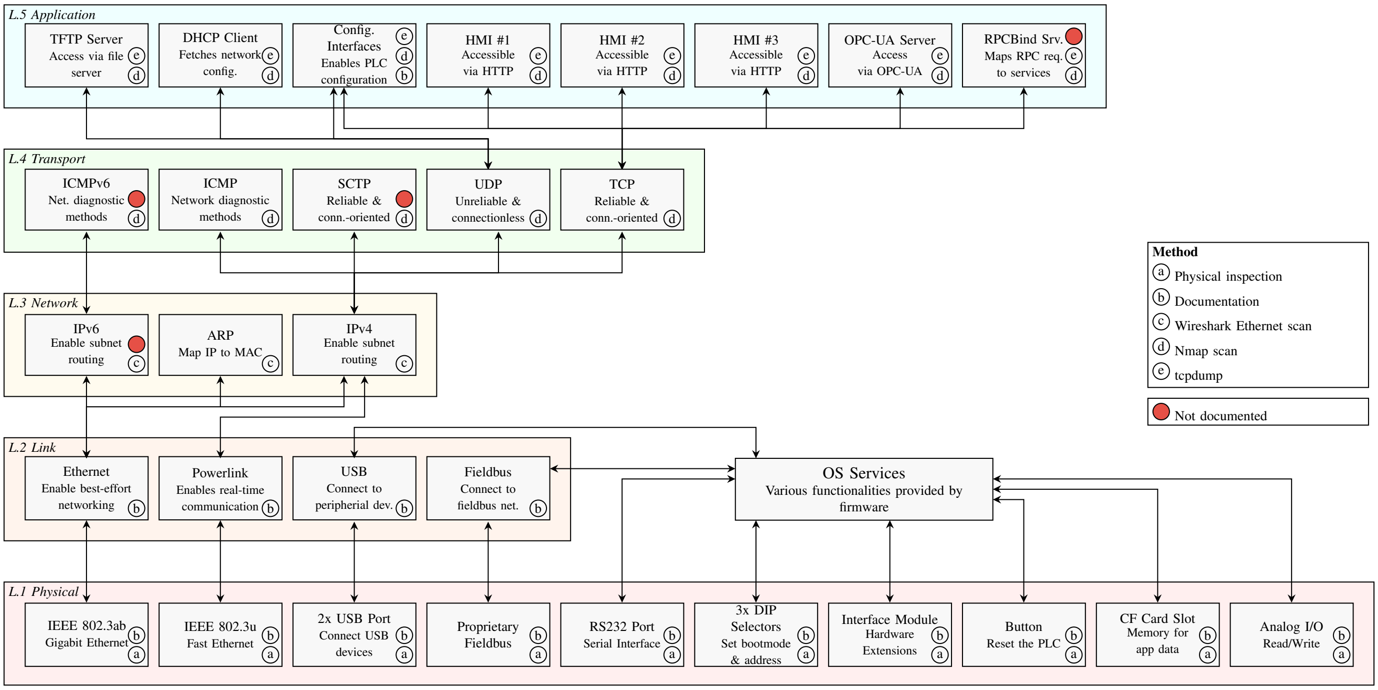

Figure 4. Resulting interface tree after applying the *AsIf* method on the PLC.

manipulate or replace the CF card (L.1), thus also altering the system.

Figure 5 highlights the importance of a systematic analysis as we propose, as otherwise relevant data flows simply could have been forgotten which ultimately might result in a security incident halting the entire production.

V. Evaluation

The practicality and benefits of using the *AsIf* framework for identifying assets through interface analysis in a structured manner was evaluated by domain experts. The details of the study and its results are analyzed and presented below. The framework was primarily perceived as useful and considered to improve the existing processes the experts are currently using. 7 out of 11 respondents consider to implement the proposed framework. In the following sections the design of the study through a questionnaire is discussed, and the experts' general view on the need for threat modeling and its challenges (*RQ.2*) are presented. Thereafter the feedback to the *AsIf* framework is discussed in more detail.

A. Design of the Study

The evaluation is designed to address security experts working in automation or other companies within this industry (e.g., security consultant and researchers). It is explicitly targeted at employees from R&D departments or similar. The aim is to get direct feedback from experts in closer proximity, thus the evaluation material is provided in German. Given that all participants in the study are working in the Central European region, the results might be biased toward the prevailing regional working culture. The material consists of an introductory video[5] and a follow up questionnaire[6]. First, questions to the background of the respondent are asked, e.g., domain, and experience in safety and security. These questions are followed by investigating the respondent's perception on the need for threat modeling and the challenges they face. These insights are used to contribute to *RQ.2*. Last, questions about our proposed framework are asked.

We received 12 responses to the questionnaire with the majority (75% resp. 9) working in organizations with more than 250 employees. Furthermore, the majority of the respondents (7) have worked in cybersecurity for five or more years. Their safety background is more limited. Seven of the respondents have experience in safety for less than 2 years. Despite having received responses from only 12 participants, this initial feedback is highly valuable for evaluating the framework. Particularly, because the respondents are experts in the targeted domain. Their specialized insights ensure that even this small set of people provides a robust foundation for assessing the utility of the framework and its further development.

B. Industry's Perception on Threat Modeling

Following the steps of threat modeling as illustrated in Figure 3, the participants were asked about the perceived complexity and involvement required for each step. As shown in Figure 6, the steps modeling, threat detection, and implementing mitigation techniques were generally regarded as

[5]Video: https://www.youtube.com/watch?v=2GpFI3XDmgA

[6]Questionnaire and presentation: https://doi.org/10.5281/zenodo.11201810

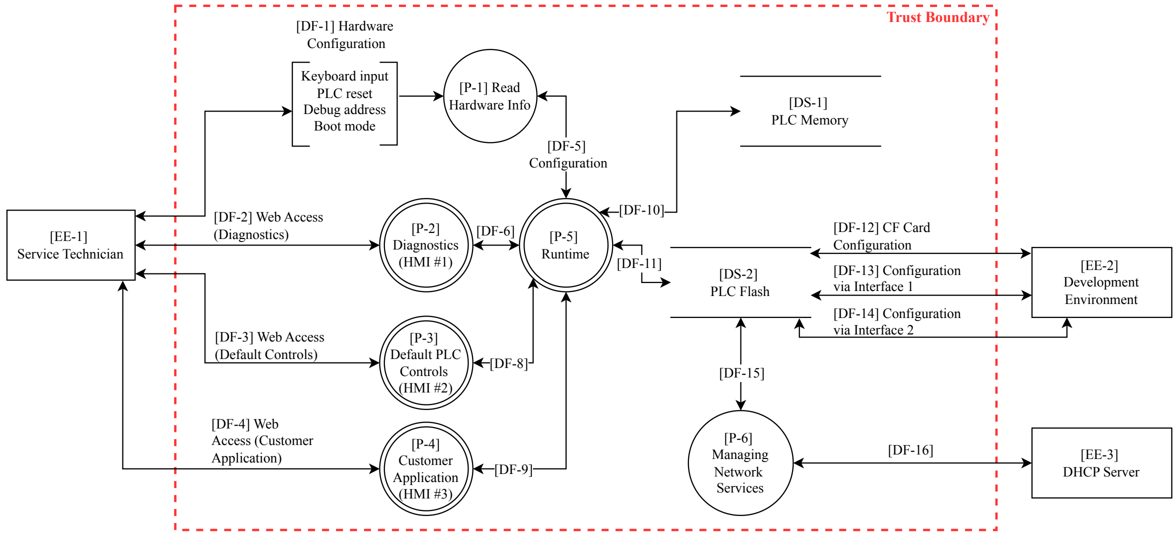

Figure 5. Data flow diagram of the PLC during the service phase.

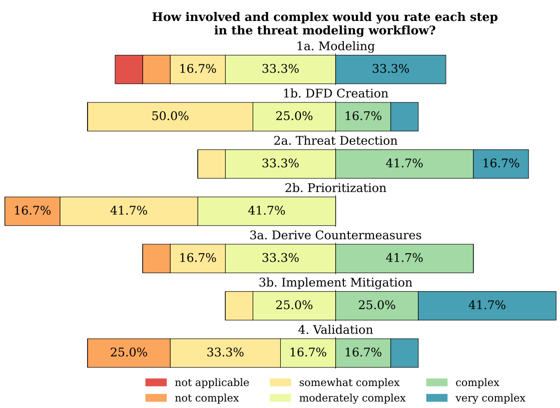

Figure 6. Response to the question on how involved and complex the experts perceive each step in the presented threat modeling workflow (n=12).

involved and complex. Prioritization and validation on the other hand, were considered to be the least involved and complex.

When asked about the most challenging topics, nine participants stated that the identification of attack vectors is challenging or very challenging. Building knowledge about current security topics was also considered by more than half as challenging or very challenging. This is probably caused by the fast pace at which cybersecurity evolves. Moreover, having a systematic approach and comprehensible documentation was considered challenging by a third of the respondents.

The challenges to have a systematic approach for threat modeling and the involvement modeling requires is specifically what the *AsIf* framework aims to provide support. However, the questionnaire also shows some other aspects in which experts would benefit from support. For instance, one respondent argued that more practical approaches are needed. Several respondents see traceable documentation and automation of the threat analysis as the biggest areas for improvement. While the proposed *AsIf* framework does not directly address automation, thereby improving the scalability, some of the individual identification methods in Table I can be carried out in an automated manner.

C. Framework Evaluation

The last part of the evaluation consisted of six questions about the framework. Five questions could each be answered on a scale ranging from 1 corresponding to *no* to 5 corresponding to *yes*. A free text question was added last to get further remarks on the framework.

Figure 7 summarizes the response of the first five questions[7]. The overall response to the framework is very positive. *AsIf* is considered as a useful tool for systematic analysis (Q16) and would improve the existing processes for asset identification (Q18). Furthermore, more than 50% (who rated 4) would consider using this methodology (Q19) underlining the practicality of the framework. The majority also believes that *AsIf* or a comparable approach would help them in the systematic evaluation of their system (Q20). Interestingly, the answers to the question (Q17) whether the respondents already use a comparable analysis was answered quite mixed, showing no specific trend. Four participants even answered with a clear *no* (rated 1).

We only received two full text comments. The first is addressing the lack of automation in *AsIf*. We agree that the method, as it is proposed, is difficult to automate, since it requires the manual investigation of the system under consideration throughout all layers. The second comment is acknowledging that it is especially useful when analyzing

[7]Note that each question was originally formulated as question. They are only shortened for illustrational purpose. For the precise formulation see the additional material https://doi.org/10.5281/zenodo.11201810 .

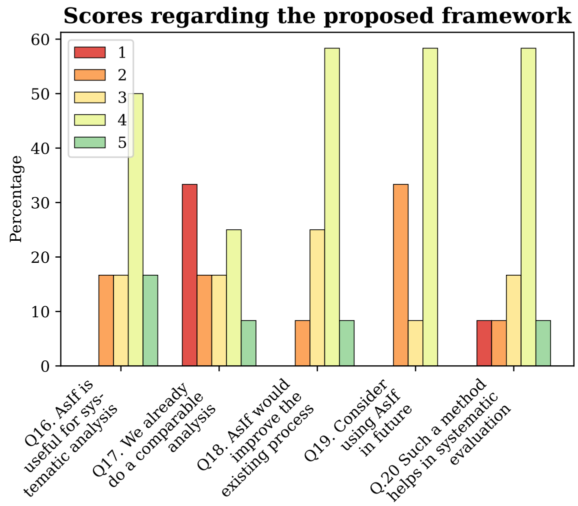

Figure 7. Responses to the *AsIf* framework. Each question (Q#) could be answered on a scale ranging from 1/*no* to 5/*yes*.

existing systems, however, the respondent also highlights that *AsIf* would not add additional support when designing the system, as the architecture, interfaces and functions are defined during the design phase. The same respondent also added that the proposed illustration in form of an *interface trees* is a great supporting tool to graphically represent the connections and discuss them in the team.

VI. Conclusion

A comprehensive asset analysis is essential to model the system in sufficient detail, as this represents the initial step in threat modeling. Given that operational technology systems are distributed cyber-physical systems, the proposed *AsIf* framework is inspired by the TCP/IP model allowing for a systematic analysis of the interfaces across all communication layers. By introducing *interface trees* for modeling and visualization, *AsIf* enhances traceability of interfaces throughout all layers. This approach also reinforces the consideration of lifecycles, as, for instance, some physical interfaces are only required in specific operation modes.

The evaluation of the framework is twofold: initially, a use case demonstrated the application of *AsIf*, followed by a study to gather feedback from security experts in the industry. The positive response not only underscores the effectiveness of *AsIf* in enhancing evaluation processes but also indicates a strong inclination to adopt similar methodologies in the future.

In addition to the study, we engaged with industry experts to collect their insights on threat modeling, aiming to identify critical areas for further research.

Acknowledgment

The financial support by the Christian Doppler Research Association, the Austrian Federal Ministry for Digital and Economic Affairs and the Federal State of Salzburg is gratefully acknowledged.

References

[1] B. Zhu, A. Joseph and S. Sastry, “A Taxonomy of Cyber Attacks on SCADA Systems,” in *2011 Int. Conf. on Internet of Things and 4th Int. Conf. on Cyber, Physical and Social Computing*, Oct. 2011, pp. 380–388. DOI: 10.1109/iThings/CPSCom.2011.34.

[2] K. Stouffer, M. Pease, C. Tang, T. Zimmerman, V. Pillitteri and S. Lightman, “Guide to Operational Technology (OT) Security,” U.S. Department of Commerce, Tech. Rep., 2023. DOI: 10.6028/NIST.SP.800-82r3.

[3] N. Messe, V. Chiprianov, N. Belloir, J. El-Hachem, R. Fleurquin and S. Sadou, “Asset-Oriented Threat Modeling,” in *2020 IEEE 19th Int. Conf. on Trust, Security and Privacy in Computing and Communications (TrustCom)*, Dec. 2020, pp. 491–501. DOI: 10.1109/TrustCom50675.2020.00073.

[4] M. Hermann, T. Pentek and B. Otto, “Design Principles for Industrie 4.0 Scenarios,” in *2016 49th Hawaii Int. Conf. on System Sciences (HICSS)*, Jan. 2016, pp. 3928–3937. DOI: 10.1109/HICSS.2016.488.

[5] J. Weiss, *Assuring Industrial Control System (ICS) Cyber Security*. Center for Strategic and International Studies, 2008.

[6] A. Shostack, *Threat Modeling: Designing for Security*. Indianapolis, IN: Wiley, 2014.

[7] S. Hollerer, W. Kastner and T. Sauter, “Towards a Threat Modeling Approach Addressing Security and Safety in OT Environments,” in *2021 17th IEEE Int. Conf. on Factory Communication Systems (WFCS)*, Jun. 2021, pp. 37–40. DOI: 10.1109/WFCS46889.2021.9483591.

[8] S. M. Khalil, H. Bahsi, H. O. Dola, T. Korõtko, K. McLaughlin and V. Kotkas, “Threat Modeling of Cyber-Physical Systems - A Case Study of a Microgrid System,” *Computers & Security*, vol. 124, Jan. 2023. DOI: 10.1016/j.cose.2022.102950.

[9] A. S. Tanenbaum and D. J. Wetherall, *Computer Networks*, 5th. USA: Prentice Hall Press, Sep. 2010.

[10] W. Young and N. G. Leveson, “An integrated approach to safety and security based on systems theory,” *Communications of the ACM*, vol. 57, no. 2, pp. 31–35, Feb. 2014. DOI: 10.1145/2556938.

[11] T. A. Kletz, *Hazop & Hazan: Identifying and Assessing Process Industry Hazards*. Boca Raton: CRC Press, 1999. DOI: 10.1201/9780203752227.

[12] G. Macher, H. Sporer, R. Berlach, E. Armengaud and C. Kreiner, “SAHARA: A security-aware hazard and risk analysis method,” in *2015 Design, Automation & Test in Europe Conference & Exhibition (DATE)*, Mar. 2015, pp. 621–624. DOI: 10.7873/DATE.2015.0622.

[13] T. UcedaVelez and M. M. Morana, *Risk Centric Threat Modeling: Process for Attack Simulation and Threat Analysis*, 1st. Wiley Publishing, Apr. 2015.

[14] C. J. Alberts, S. G. Behrens, R. D. Pethia and W. R. Wilson, “Operationally Critical Threat, Asset, and Vulnerability Evaluation (OCTAVE) Framework, Version 1.0,” Carnegie Mellon University, Report, Jun. 1999. DOI: 10.1184/R1/6575906.v1.

[15] R. Khan, K. McLaughlin, D. Laverty and S. Sezer, “STRIDE-based threat modeling for cyber-physical systems,” in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Torino: IEEE, Sep. 2017, pp. 1–6. DOI: 10.1109/ISGTEurope.2017.8260283.

[16] O. Saßnick, T. Rosenstatter, C. Schäfer and S. Huber, “STRIDE-based Methodologies for Threat Modeling of Industrial Control Systems: A Review,” in *2024 IEEE 7th International Conference on Industrial Cyber-Physical Systems (ICPS)*, St. Louis, USA: IEEE, May 2024, pp. 1–8. DOI: 10.1109/ICPS59941.2024.10639949.

[17] M. R. A. Asif, K. F. Hasan, M. Z. Islam and R. Khondoker, “STRIDE-based Cyber Security Threat Modeling for IoT-enabled Precision Agriculture Systems,” in *2021 3rd Int. Conf. on Sustainable Technologies for Industry 4.0 (STI)*, Dec. 2021, pp. 1–6. DOI: 10.1109/STI53101.2021.9732597.

[18] A. Omotosho, B. Ayemlo Haruna and O. Mikail Olaniyi, “Threat Modeling of Internet of Things Health Devices,” *J. of Applied Security Research*, vol. 14, no. 1, pp. 106–121, Jan. 2019. DOI: 10.1080/19361610.2019.1545278.

[19] K. Tuma, G. Calikli and R. Scandariato, “Threat analysis of software systems: A systematic literature review,” *J. of Systems and Software*, vol. 144, pp. 275–294, Oct. 2018. DOI: 10.1016/j.jss.2018.06.073.