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Article title: Cyber Security-Aware Network Design of Industrial Control Systems

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Cyber Security-Aware Network Design of Industrial Control Systems

Béla Genge, Piroska Haller, and István Kiss

Abstract—**The pervasive adoption of traditional Information and Communication Technologies hardware and software in Industrial Control Systems (ICS) has given birth to a unique technological ecosystem encapsulating a variety of objects ranging from sensors and actuators, to video surveillance cameras and generic PCs. Despite their invaluable advantages, these advanced ICS create new design challenges, which expose them to significant cyber threats. To address these challenges, an innovative ICS network design technique is proposed in this paper to harmonize the traditional ICS design requirements pertaining to strong architectural determinism and real-time data transfer with security recommendations outlined in the ISA-62443.03.02 standard. The proposed technique accommodates security requirements by partitioning the network into security zones and by provisioning critical communication channels, known as security conduits, between two or more security zones. The ICS network design is formulated as an integer linear programming (ILP) problem that minimizes the cost of the installation. Real-time data transfer limitations and security requirements are included as constraints imposing the selection of specific traffic paths, the selection of routing nodes, and the provisioning of security zones and conduits. The security requirements of cyber assets denoted by traffic and communication end-points are determined by a cyber attack impact assessment technique proposed in this paper. The sensitivity of the proposed techniques to different parameters is evaluated in a first scenario involving the IEEE 14-bus model and in a second scenario involving a large network topology based on generated data. Experimental results demonstrate the efficiency and scalability of the ILP model.**

Index Terms—**Industrial Control Systems, network design, security zone, security conduit, ISA-62443.**

I. Introduction

The massive proliferation of traditional Information and Communication Technologies (ICT) hardware and software into the heart of Industrial Control Systems (ICS) has given birth to a unique technological ecosystem. Modern ICS encompass a variety of objects ranging from sensors and actuators, industrial RFID, e.g., product tracking devices, video surveillance cameras, to generic PCs, networking and security devices such as industrial Ethernet, firewall, and intrusion detection systems. These advanced ICS deliver various services and features, they improve operational benefits of control, reliability and safety, and facilitate the implementation of novel infrastructural paradigms such as Smart Grid.

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This technological advancement, however, brings new design challenges and exposes critical ICS to sophisticated *cyber-physical* attacks. Unlike traditional ICT systems where the effects of disruptive cyber threats are generally limited to cyber operations, in the context of critical ICS, such attacks can result in the loss of vital services such as transportation, water and gas supply. An extensively debated example in this sense is Stuxnet [1], believed to be the first malware specifically targeted against ICS. Its ability to rewrite the logic of control hardware brought to light a new class of threats in which traditional software vulnerabilities may jeopardize the normal functioning and stability of physical processes. Stuxnet, together with the more recently reported cyber espionage weapons such as *Dragonfly* [2], continue to raise many open questions, but they also confirm serious concerns about the capabilities and the objectives of future malware.

Therefore, in this work we argue that it is imperative to incorporate security recommendations into the design of ICS. In this sense, NIST's "Guide to Industrial Control Systems" [3] and the ISA-62443 series of standards [4] include guidelines and recommendations to design and strengthen the security of ICS. In both cases, but more elaborately in ISA-62443, a commonly recognized factor is the need to partition the network into *security zones* and to identify critical communication channels between two or more zones, known as *security conduits*. However, reconciling security with traditional design requirements [5], [6], [7] is not trivial. ICS embody a variety of non-security requirements including strong determinism, real-time data transfer, and strict limitations pertaining to geographical positioning, and to the performance of communications. These are essential factors that need to be harmonized with the security prerequisites formulated by various recommendations.

To address these challenges, in this paper the ICS network design is formulated as an integer linear programming (ILP) problem. We build an ILP model that minimizes the costs of the ICS network while taking into account a variety of constraints which are essential prerequisites for the correct functioning and for the security of ICS. The ILP model assumes that traffic between different ICS end-points, e.g., sensors and hardware controllers, is routed across a communication infrastructure in which nodes are installed at locations selected from a set of feasible sites. This selection accounts for the cost of bandwidth, the cost of provisioning nodes and security equipment, as well as the capacity of nodes and of communication links. Furthermore, the ILP model provisions ICS traffic and communicating end-points into security zones and conduits (hereinafter SZC) as defined by ISA-62443. Finally, real-time communication constraints enforce that ICS-specific communication requirements are satisfied.

The security requirements of cyber assets denoted by traffic and communicating end-points are identified according to a cyber attack impact assessment (CAIA) approach proposed in this work. CAIA adopts a procedure inspired from the field of System Dynamics [8]. It compares the behavior of complex ICS in the presence and in the absence of accidental or deliberate interventions attributed to cyber attacks in order to evaluate the significance of cyber assets.

We present extensive numerical results to demonstrate the applicability of the proposed approach in various scenarios. First, a qualitative analysis is performed on an ICS installation encompassing the IEEE 14-bus model. We show that the cost of components has a direct impact on the ILP solution. At the same time, we demonstrate that the ILP model installs SZC while ensuring that real-time communication constraints are satisfied. Then, a quantitative analysis is conducted on a large-scale ICS network in order to demonstrate the scalability and efficiency of the proposed methodology.

The rest of this paper is organized as follows. Related Work is briefly discussed in Section II. ICS design requirements and an overview of the proposed approach are given in Section III. Then, the proposed ILP model for ICS network design is presented in Section IV. This is followed by the presentation of the relaxed ILP model in Section V and of the cyber attack impact assessment technique in Section VI. Experimental results including two different scenarios are detailed in Section VII. Finally, the paper concludes in Section VIII.

II. Related Work

A. ICS Network Design

ICS security has been the subject of many recent studies. Regarding security in ICS network design, NIST's "Guide to Industrial Control Systems" [3] recommends, among other, the partitioning of ICS networks into different zones in order to isolate and to better protect critical assets. This aspect was further refined by the ISA-62443 series of standards, part 03.02 "Security Assurance Levels for Zones and Conduits" [4], hereinafter denoted simply by ISA-62443.03.02. These standards define *security zones* and *security conduits*, as well as the possible procedures which may be applied to incorporate different ICS assets. On the other hand, more systematic ICS network design techniques have been proposed by academia. In [9], Carro Calvo *et al.* developed a genetic algorithm for optimal ICS network partitioning. The approach followed the traditional principles of ICS network design aimed at maximizing intra-network communications, minimizing inter-network communications, and balancing the communication over the resultant sub-networks. In [10], Zhou *et al.* formulated an optimization problem, which assumed a hierarchical switch-based ICS topology and incorporated costs in terms of the number of switches and of port utilization rates, traffic load balancing, as well as real-time traffic requirements, e.g., tolerated delays. The work of Zhang *et al.* in [11] focused on optimal ICS network design from the perspective of minimizing network delays. A relative delay metric was adopted to minimize communication delays with respect to the maximum tolerable delay. The same authors formulated in [12] an optimization problem, which enhanced their previous proposal with network reliability requirements. In [13], the sensor layout planning in water distribution systems was address by means of controllability analysis. The proposed method identifies the minimum number of nodes for the detection of contamination events within the system. The work of Genge and Siaterlis [14] showed that information regarding the impact of local actuation strategies on the behavior of other controllers may be incorporated into the ICS network design procedure in order to strengthen the resilience of physical processes. Finally, the work of Zahidi *et al.* [15] showed that modern ILP solvers are able to handle large network topologies. The effectiveness of ILP was demonstrated in optimizing the formation of clusters in Mobile Ad-Hoc Networks (MANETs).

In the traditional field of ICT, network design approaches proliferated rapidly with the development of new paradigms such as network virtualization. Here we mention the work of Capone *et al.* [16], where an ILP problem was formulated for the design of service overlay networks. In [17] Rahman and Boutaba focused on survivability in network virtualization and developed heuristics for solving the network design problem. The approach in [17] adopted fast re-routing and bandwidth pre-reservation strategies as backup on each physical link. Several other works targeting different aspects of traditional ICT network design are presented in [18], [19], [20], [21].

Despite the variety of approaches targeting the design of ICS networks, the methodologies mentioned above do not address security requirements. While we notice several approaches aimed at designing hierarchical and balanced communication networks with quality of service, reliability and resilience features, unfortunately, security requirements are not included in such methodologies. Conversely, this work is aimed at securing the communication channels of large-scale ICS topologies routed across regional and national network infrastructures, while ensuring that traditional ICS requirements such as the capacity limitations of various nodes, e.g., switches, and real-time communication constraints are satisfied. At the same time we believe that the present work complements the features delivered by previous ICS design techniques since the solutions proposed in [9], [10], [14], [15] are mostly focused on details specific to local area networks, e.g., the number of ports in network switches and the areas that are covered by nodes in MANETs. In this respect, for example, designers could adopt the methodology proposed in this work to create a large-scale ICS network topology addressing various communications and security requirements. This could be followed by local design strategies as described by previous studies, where additional details, e.g., the number of available switches and switch ports, could be used for the design of more complex and hierarchical sub-networks. To the best of our knowledge, this paper presents the first ICS network design methodology that incorporates real-time performance requirements, as well as security prerequisites defined in ISA-62443.03.02.

B. Cyber Attack Impact Assessment

In this work, an important part of the ICS network design problem is the assessment of the impact of cyber attacks on the functioning of physical processes. This procedure identifies significant cyber assets which are interpreted as security requirements in the ILP problem at hand.

There have been numerous efforts to evaluate and to finally quantify the impact of cyber attacks on ICS. Kundur *et al.* [22] proposed a graph-based model to evaluate the influence of control loops on a physical process. The approach was used to assess the impact of cyber attacks on the generated power. In [23], Sgouras *et al.* evaluated the impact of cyber attacks on a simulated smart metering infrastructure. The experiments implemented disruptive Denial of Service attacks against smart meters and utility servers which caused severe communication interruptions. The impact of cyber attacks on wide-area frequency control applications in power systems has been evaluated in [24]. Here it was shown that cyber attacks may significantly impact system stability by causing severe decline of system frequency. Bilis *et al.* [25] proposed a cyber attack impact assessment methodology for power systems based on five metrics derived from complex network theory. The combination of these metrics was used to deliver a node ranking in a graph-based representation of electricity grids. Finally, in the recent work of Krotofil *et al.* [26] and that of Genge and Siaterlis [14], the impact of attacks on the underlying physical process was measured as the time interval after which the system reaches its emergency shut-down limits.

The aforementioned research highlighted the impact of attacks on the normal functioning of physical processes from several perspectives. Nevertheless, these studies are aimed at specific scenarios, physical processes, and ICS devices. Conversely, the impact assessment technique proposed in this paper is applicable to a variety of ICS installations and may quantify the impact of cyber attacks by relying on simulation-based results or on data originating from production systems.

III. Requirements and Approach Overview

The architecture of modern ICS follows a hierarchical structure comprising of two different layers (see Fig. 1): (i) the physical layer, which encompasses a variety of sensors, actuators, and hardware devices that physically perform the actions on the system; (ii) and the cyber layer, which encompasses all the ICT hardware and software needed to monitor the physical process and to implement complex control loops. The size of ICS installations may vary from a few sensors and generic PCs to thousands of control objects, RFIDs, industrial equipment, and video surveillance cameras, organized in a hierarchical structure spread across a large geographical area.

Within such a composite technological ecosystem, control loops are provisioned at various network locations to carry out critical operations and to ensure the correct functioning of the underlying physical process. They may interact directly with sensor and actuator nodes, or remotely with other controllers in a hierarchical and distributed control system architecture, as the one depicted in Fig. 1. Essentially, control loops represent the core of ICS which need to be protected against malicious threats targeting the cyber and the physical dimensions of these critical infrastructures. Various ICS-specific cyber attacks have been elaborately studied by previous research. Real-world

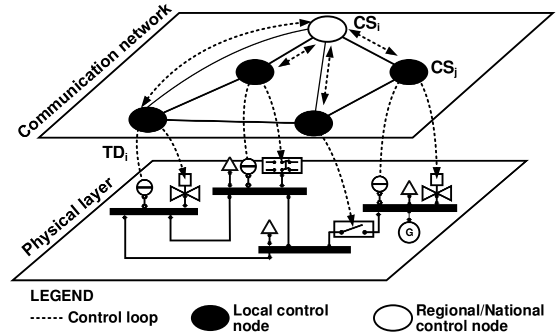


Fig. 1. Example ICS architecture.

examples such as the attack on the Maroochy Shire Council's sewage system in Queensland, Australia [27], showed that unprotected ICS communications are highly susceptible to packet injection attacks. The Stuxnet malware [1], on the other hand, demonstrated that cyber attacks incorporating in-depth knowledge on the physical process can mount sophisticated attacks against ICS. These may alter legitimate control signals in order to cause important damages. Lastly, studies such as the one of Krotofil, *et al.* [26], showed that sensor data analysis may be used to infer the optimal time for launching Denial of Service attacks on control signals. These examples are clear evidence on the necessity to address the security requirements of ICS networks at early design phases.

Specific measures for strengthening the security of ICS have been proposed in recent guidelines and standards [3], [4]. In this work we focus on the concepts of SZC as defined by ISA-62443.03.02. Here, the grouping of physical or of logical assets into zones and conduits is usually the result of a high-level assessment delivering a ranking on the significance of cyber assets. However, the provisioning of SZC into the architecture of ICS must not affect the Quality of Service (QoS) requirements pertaining to the characteristics of industrial installations, e.g., strong determinism, real-time data transfer [28], [29]. In fact, accidental or deliberate changes of network conditions, e.g., delay and jitter, pose significant threats to the correct functioning of control loops and finally to the normal operation of physical process [30]. Therefore, QoS-specific requirements are essential factors in the provisioning of ICS networks which need to be encapsulated and harmonized with the complete set of ICS design prerequisites.

Faced with these challenges, in this work we undertake the ICS network design problem from the perspective of the aforementioned requirements. We assume that the physical process is supervised through a set of *observed variables*, and its behavior is regulated through a set of *control variables*. Control nodes may take various forms, yet the best known implementation is the dedicated control hardware. Nevertheless, this work assumes that human operators are an integral part of ICS and may close significant control loops at a local, regional or national level by means of various ICT hardware and software. As a result, control loop end-points may include control nodes (in a simple or hierarchical structure), but also the measurement and the actuation nodes. Subsequently, we assume that end-points exchange data through network data flows, hereinafter called *traffic demands*, a terminology that is adopted from the field of traditional ICT network design [16], [31]. Finally, we assume that traffic demands between end-points are routed by a communication infrastructure consisting of concentrator nodes positioned at feasible locations. Concentrators may route traffic between each other according to a given connectivity matrix. In this work the mathematical model of the ICS network design is formulated as an integer linear programming (ILP) problem. As described earlier in this section, demand routing paths, end-points, and concentrator sites need to be installed in such a way to minimize the costs of the infrastructure, while ensuring that constraints regarding real-time communications and security are satisfied.

A central part of the ILP problem is the identification of cyber security requirements for assets denoted by demands and their end-points. Accordingly, this work adopts a procedure inspired from the field of System Dynamics [8] in order to assess the impact of cyber attacks on the normal functioning of physical processes. The result of this procedure is a ranking of cyber assets which is interpreted as the set of security requirements. At the core of this approach is a technique that records the *behavior* of complex ICS in the presence of accidental or deliberate interventions, e.g., faults, and cyber attacks. Essentially, the cyber attack impact assessment (CAIA) procedure calculates the co-variance of observed variables before and after the execution of an intervention. This provides a metric to quantify the significance of each control variable on the behavior of ICS and finally to rank demands and their end-points in the ILP problem at hand. Compared to state of the art, this technique is well suited for scenarios in which the process model is not available or in production systems in case control and measurement variable data series are available. The later case is particularly useful in post-event scenarios where the emphasis is placed on establishing the relative impact of specific faults and of cyber attacks. The mathematical foundation of the ICS network design problem builds on the traditional network design problem as formulated by Capone *et al.* in [16]. However, the work presented in [16] is adapted and expanded in order to accommodate characteristics of ICS networks and of ICS communications, and to integrate ICS security recommendations outlined in ISA-62443.03.02.

IV. ICS Network Design Model

This section expands the traditional ICS network design problem with security requirements aimed at constructing solutions to the design of modern ICS.

A. Preliminary Notations

1) Basic Sets and Costs: We define $I = \{1, 2, ..., i, ...\}$ to be the set of traffic demands (TD), $J = \{1, 2, ..., j, ...\}$ the set of potential concentrator sites (CS), and $S = \{1, 2, ..., s, ...\}$ the set of potential security zone levels. Then, let c_j^S to be the cost associated with installing CS j, c_{jl}^B be the cost of buying one unit of bandwidth between CSs j and l, c_{ij}^A the cost of buying one unit of bandwidth between the access end-point of TD i and CS j, c_{ji}^E the cost of buying one unit of bandwidth between the egress end-point of TD i and CS j, and c_{js}^Z the cost associated with installing zone s at CS j. It should be noted that we distinguish between access and egress end-points in order to ensure flexible and individual configuration of parameters. Therefore, their use is not limited to asynchronous, i.e., one-directional, flows. Instead, designers may use TDs as either uni-directional or bi-directional communication flows.

Finally, we define the costs associated with security conduits. Let c_{jl}^C be the cost associated with installing one elementary security conduit between CSs j and l. The exact cost associated with a specific conduit level is then obtained by multiplying the selected level of conduit on link (j, l) with the cost of one elementary security conduit c_{jl}^C.

2) Communication Infrastructure Parameters: Let d_i denote the TD i, u_{jl} the link capacity between CSs j and l, and v_j the access and egress demand capacity of CS j. Considering the geographic location of access/egress end-points for each individual TD as well as the geographic location of CSs, the following binary connectivity parameters are defined. Let a_{ij} be a binary parameter with value 1 if the access end-point of TD i can connect to CS j, b_{jl} a binary parameter with value 1 if CS j can connect to CS l, and e_{ji} a binary parameter with value 1 if egress end-point of TD i can connect to CS j.

3) Real-Time Requirement Parameters: With respect to the ICS real-time performance requirements, the following communication latency parameters are defined. Let q_{ij}^A be the latency between access end-point of TD i and CS j, q_{ji}^E the latency between CS j and egress end-point of TD i, q_{jl}^L the latency between CSs j and l, and q_j^C the latency introduced by each CS j. Finally, we define the maximum tolerated latency for each individual TD i as q_i^M.

4) Security Zone and Conduits Parameters: Depending on the outcome of the CAIA procedure, demand end-points are assigned specific security zone requirements. Therefore, we define r_{is}^A as a binary parameter with value 1 if the access end-point of demand i should be incorporated into a zone with security level s, and r_{is}^E as a binary parameter with value 1 if the egress end-point of demand i should be incorporated into a zone with security level s. Consequently, for each end-point designers may select more than one security zone, which ensures the creation of in-depth security architectures where security zones are recreated according to a layered approach [3]. The outcome of CAIA also identifies the necessary security conduit levels of each individual demand. Therefore, we define an integer parameter p_i to denote the minimum security conduit level that needs to be installed for demand i. It should be noted that security levels associated to zones and conduits are identified by means of traditional assessment methodologies that identify the criticality of devices and communications, and the possible consequences of attacks. Accordingly, security devices including traditional firewalls, e.g., with port filtering enabled, next generation firewalls with packet inspection and intrusion prevention systems, as well as intrusion detection systems, and Virtual Private Networks (VPN) can be adopted in the definition of SZC. Their performances pertaining to traditional security characteristics such as the maximum throughput of stateful packet inspection, the number of concurrent firewall connections, the maximum site-to-site VPN sessions, are well defined in technical specifications and can be used to identify the security parameters as required by the proposed ICS design model. Their associated costs, however, are vendor-specific and publicly available. Finally, we need to account for the capacity of security devices, e.g., firewall, and Intrusion Detection Systems, expressed most of the times in terms of traffic volume. Therefore, we define z_s to store the capacity of security devices installed in zone s.

5) Variables: We define g_j as a binary variable with value 1 if CS j is installed, x_{ij} as a binary variable with value 1 if the access end-point of TD i is connected to CS j, w_{ji} as a binary variable with value 1 if CS j is connected to the egress end-point of TD i, and t^i_{jl} as a binary variable with value 1 if TD i is routed on link (j,l). We define one supplementary binary variable y_{js} to enforce that installation costs associated with each zone s are added only once for each CS j if there is at least one TD end-point with security zone requirement s connected to CS j. Finally, we define the integer variable f_{jl} to store the level of the security conduit installed between CSs j and l. The range of values for f_{jl} is lower and upper bounded to the minimum and maximum conduit levels.

B. Objective Function

The objective function that minimizes the cost of the ICS installation is the following:

$$\min \left(\sum_{j\in J} c^S_j g_j + \sum_{j,l\in J, i\in I} c^B_{jl} t^i_{jl} d_i + \sum_{j\in J, i\in I} \left(c^A_{ij} x_{ij} + c^E_{ji} w_{ji} \right) d_i + \sum_{j\in J, s\in S} c^Z_{js} y_{js} + \sum_{j,l\in J} c^C_{jl} f_{jl} \right) \tag{1}$$

The objective function (1) accounts for the total installation cost of security zones and concentrators, communication links between CSs, and the total installation cost of security conduits. In particular, the term $\sum c^S_j g_j$ is the total cost of installing all selected CSs, the term $\sum c^B_{jl} t^i_{jl} d_i$ is the total cost of bandwidth for routing TDs between CSs, and $\sum \left(c^A_{ij} x_{ij} + c^E_{ji} w_{ji} \right) d_i$ is the total cost of bandwidth for access and egress end-points connected to CSs. The remaining two terms account for the cost of installing security measures: $\sum c^Z_{js} y_{js}$ is the total cost of installing security zones in the premises of CS j; and $\sum c^C_{jl} f_{jl}$ is the total cost of installing security conduits between CSs j and l.

C. Constraints

The following constraints are defined:

1) Access/Egress End-Point Constraints:

$$\sum_{j\in J} x_{ij} = 1, \sum_{j\in J} w_{ji} = 1, \qquad \forall i \in I \tag{2}$$

$$x_{ij} \leq a_{ij} g_j, w_{ji} \leq e_{ji} g_j, \qquad \forall i \in I, j \in J \tag{3}$$

These constraints limit the number of connections between access/egress demand end-points and CSs to exactly one.

2) Flow Conservation Constraints:

$$x_{ij} - w_{ji} - \sum_{l\in J} \left(t^i_{jl} - t^i_{lj} \right) = 0, \quad \forall j \in J, i \in I \tag{4}$$

These denote classical multicommodity flow conservation constraints [32].

3) Concentrator Capacity Constraints:

$$\sum_{i\in I} d_i \left(x_{ij} + w_{ji} \right) \leq v_j, \qquad \forall j \in J \tag{5}$$

These constraints impose that for each concentrator the serviced ingress and egress traffic demands do not exceed the concentrators' link capacity.

4) Concentrator Link Capacity Constraints:

$$\sum_{i\in I} d_i t^i_{jl} \leq u_{jl} b_{jl} g_j, \sum_{i\in I} d_i t^i_{jl} \leq u_{jl} b_{jl} g_l, \quad \forall j,l \in J \tag{6}$$

These constraints impose that the total demand routed between each pair of connected CSs j and l does not exceed the installed link capacity.

5) Security Zone Constraints:

$$y_{js} \leq \sum_{i\in I} \left(r^A_{is} x_{ij} + r^E_{is} w_{ji} \right), \qquad \forall j \in J, s \in S \tag{7}$$

$$\alpha^Z y_{js} \geq \sum_{i\in I} \left(r^A_{is} x_{ij} + r^E_{is} w_{ji} \right), \qquad \forall j \in J, s \in S \tag{8}$$

These constraints ensure that the objective function (1) accounts for the cost of installing a security zone of level s at CS j only if there is at least one demand with an end-point connected to j for which designers defined a security zone of level s. More specifically, the first inequality forces $y_{js} = 0$ if $\sum \left(r^A_{is} x_{ij} + r^E_{is} w_{ji} \right) = 0$, while the second inequality forces $y_{js} = 1$ if $\sum \left(r^A_{is} x_{ij} + r^E_{is} w_{ji} \right) \geq 1$. α^Z is a large integer parameter with a value greater than $\max \sum_{i\in I, s\in S} \left(r^A_{is} x_{ij} + r^E_{is} w_{ji} \right), \forall j \in J$. Subsequently, the following constraints ensure that the capacity of security zone s, i.e., the capacity of security devices, is not exceeded:

$$\sum_{i\in I} \left(r^A_{is} x_{ij} + r^E_{is} w_{ji} \right) d_i \leq z_s, \qquad \forall j \in J, s \in S \tag{9}$$

6) Security Conduit Constraints:

$$f_{jl} \geq p_i t^i_{jl}, f_{jl} \leq \alpha^C b_{jl} \qquad \forall j,l \in J, i \in I \tag{10}$$

These constraints force the selection of the maximum security conduit level between CSs j and l. Since demands with a specific conduit level may only be routed on a link implementing at least the same level of security conduit, these constraints impose the fulfillment of security conduit requirements for all demands routed on link (j,l). In particular, the first inequality defines the lower-bound of f_{jl} which shall receive at least the maximum value from all conduit levels p_i routed on link (j,l). The second inequality, however, forces an upper-bound for f_{jl} of the maximum conduit level if $b_{jl} = 1$, and of zero, otherwise. α^C is an integer parameter equal to the maximum level of security conduit, that is $\alpha^C = \max p_i, \forall i \in I$.

7) Real-Time Traffic Constraints:

$$\sum_{j\in J} \left(q^A_{ij} x_{ij} + q^E_{ji} w_{ji} \right) + \sum_{j,l\in J} t^i_{jl} \left(q^L_{jl} + q^C_j \right) + \sum_{j\in J} q^C_j w_{ji} \leq q^M_i, \qquad \forall i \in I \tag{11}$$

These constraints force the selection of routing paths that fulfill the latency requirements defined for each demand. In particular, for each demand i, the term $\sum \left(q^A_{ij} x_{ij} + q^E_{ji} w_{ji} \right)$

is the sum of latencies for access and egress links, the term $\sum t^i_{jl}\left(q^L_{jl}+q^C_j\right)$ is the sum of latencies owed to CSs and links between CSs, and the term $\sum q^C_j w_{ji}$ is the latency of the egress CS. These have been formulated in such a way that the execution of the objective function is not affected by their exclusion from the problem. This is a particularly significant aspect of network design since in real scenarios, especially at early design stages, the exact identification of all parameter values may not be feasible. Therefore, these should be viewed as an optional set of constraints, which are applied once all latency parameters have been appropriately measured.

D. Discussion

The proposed ICS model defines various parameters, which are essential for the completeness of the problem's definition. Obviously, in practical scenarios human designers may encounter difficulties in identifying their precise values. However, it is noteworthy that the complete estimation of all parameters is not a prerequisite for running the proposed model. In fact, constraints have been deliberately categorized and ordered according to their significance. At early design stages it is essential to define the feasible connectivity parameters and to run the model exclusively with constraints (2), (3), (4) activated. This solution can provide significant details on the approximate necessary bandwidth and node capacities. Then, capacity constraints (5), (6) can be activated and parameters may be further adjusted in order to better reflect the real performances of various devices. Once the possible connectivity and the capacity of devices are identified, designers may turn to assessment methodologies in order to estimate the security requirements of TDs. These will provide the data for activating security constraints (7), (8), (9), (10), and to obtain a security-enabled architecture. Finally, based on the solution generated so far designers can approximate the latency of communication links and can activate real-time traffic constraints (11). With this solution designers may revisit certain parameters in order to enhance the accuracy of results. These steps provide an effective strategy for designers to apply a complex, yet structured ICS network design model. It should be noted that with each set of constraints the solution may change (as demonstrated later by experimental results), and in some cases the problem may not be feasible. For the later extreme cases the following section defines relaxation conditions that impose an automated adjustment of capacity parameters with certain penalty costs. These constraints, i.e., (5), (6), are responsible for the distribution of connections among various CSs and may be seen as contradictory with respect to the objective function and to the remaining constraints, which aim at reducing the number of provisioned components. Therefore, by relaxing capacity constraints, an automatically adjustable balancing mechanisms is incorporated into the proposed problem, which can further aid engineers to correctly estimate parameter values.

V. ICS Network Design Problem Relaxation

Depending on the values of its input parameters, the proposed ILP may fail to construct a feasible solution that satisfies all of the constraints. This is mainly a result of connectivity parameters a_{ij}, b_{jl}, and e_{ji}, which can significantly reduce the palette of feasible connection points, and, at the same time, may impose connection options exceeding the capacity of concentrator nodes governed by v_j and u_{jl}. These assertions are confirmed by the analysis conducted with the AIMMS tool and its implementation of *irreducible inconsistent system (IIS)* identification [33]. An IIS is a subset of all constraints of an optimization problem that are self-contradictory. In other words, as soon as one of the constraints in the IIS is removed, the infeasibility is resolved. Owed to this analysis, we found that constraints (2), (3), (4), (5), and (6) may lead to an infeasible solution in case of insufficient bandwidth. In practice, however, instead of simply stopping execution it is preferable that the solver produces a feasible solution even if this entails additional penalties, i.e., additional costs.

Consequently, we revise the ICS network design problem by assuming that in case the solution is infeasible, additional bandwidth may be acquired with certain penalty costs. As such, we define $c^{B^+}_{jl}$ to be the cost associated with buying one supplementary unit of bandwidth between CSs j and l, and $c^{V^+}_j$ the cost of buying one supplementary unit of bandwidth for access and egress demand nodes connected to CS j. We further define the integer variable τ_{jl} to store the supplementary bandwidth allocated between CSs j and l, and the integer variable ω_j to store the supplementary bandwidth allocated to CS j. As a result, the objective function that minimizes the cost of the ICS installation becomes:

$$\min\left(\sum_{j\in J} c^S_j g_j+\sum_{j,l\in J,i\in I} c^B_{jl}t^i_{jl}d_i+\sum_{j\in J,i\in I}\left(c^A_{ij}x_{ij}+c^E_{ji}w_{ji}\right)d_i+\right.$$
$$\left.\sum_{j\in J,s\in S} c^Z_{js}y_{js}+\sum_{j,l\in J} c^C_{jl}f_{jl}+\sum_{j,l\in J} c^{B^+}_{jl}\tau_{jl}+\sum_{j\in J} c^{V^+}_j\omega_j\right) \quad (12)$$

Compared to (1), the objective function (12) incorporates two additional terms: $\sum c^{B^+}_{jl}\tau_{jl}$ is the sum of penalty costs owed to buying supplementary bandwidth between CSs j and l, and $\sum c^{V^+}_j\omega_j$ is the sum of penalty costs owed to buying supplementary bandwidth for demands connected to CS j.

Finally, concentrator capacity constraints (5) and (6) are relaxed by incorporating variables ω_j and τ_{jl} into their definitions, such that $\forall j\in J$:

$$\sum_{i\in I} d_i\left(x_{ij}+w_{ji}\right)\le v_j+\omega_j, \quad (13)$$

$$\sum_{i\in I} d_i t^i_{jl}\le(u_{jl}g_j+\tau_{jl})b_{jl}, \sum_{i\in I} d_i t^i_{jl}\le(u_{jl}g_l+\tau_{jl})b_{jl} \quad (14)$$

VI. Cyber Attack Impact Analysis

The description of the cyber attack impact assessment (CAIA) approach relies on the following definitions of sets: $\mathcal{T}=\{1,2,...,k,...m\}$ is the set of measurements for each discrete time moment k, $\mathcal{J}=\{1,2,...,\jmath,...n\}$ is the set of observed variables, and $\mathcal{I}=\{1,2,...,\imath,...\rho\}$ is the set of control variables. We define $Y^\imath, \imath\in\mathcal{I}$ as a bi-dimensional matrix containing m measurements of n observed variables for an intervention applied on control variable $\nu_\imath$. We use $Y^\imath_{k\jmath}$

and Y_{kj}^0 to denote the k-th measurement of the j-th observed variable for a scenario implementing a specific intervention and for a scenario without interventions, respectively.

Essentially, CAIA compares the values of observed variables before and after the execution of a specific intervention by means of calculating the cross co-variance between measurement time series. Then, the method evaluates the relative impact $\Re_i, i \in \mathcal{I}$, of the intervention on each control variable. More formally, Equation (15) defines the mean value of the j-th observed variable for interventions on the i-th control variable ($\bar{Y}_j^i$) and the intervention-free mean value for the j-th observed variable ($\bar{Y}_j^0$):

$$\bar{Y}_j^i = \frac{1}{m}\sum_{k\in\mathcal{T}} Y_{kj}^i, \bar{Y}_j^0 = \frac{1}{m}\sum_{k\in\mathcal{T}} Y_{kj}^0, \forall i \in \mathcal{I}, \forall j \in \mathcal{J} \quad (15)$$

Then, the mean value of cross co-variances for the intervention on the i-th control variable is defined as:

$$\bar{\mathcal{C}}_i = \sum_{j\in\mathcal{J}} \mathcal{W}_j \sum_{k\in\mathcal{T}} (Y_{kj}^i - \bar{Y}_j^i)(Y_{kj}^0 - \bar{Y}_j^0), \forall i \in \mathcal{I} \qquad (16)$$

where $\mathcal{W}_j$ is the weight, i.e., the importance, of changes in the j-th observed variable. This parameter ensures that CAIA can also be applied in domains, e.g., chemical, where observed variables contribute differently to the calculation of impact, e.g., according to their significance. The result of applying the CAIA procedure is a value $\Re_i$, which ranks the impact of intervention on the i-th control variable, and is defined as:

$$\Re_i = \frac{\bar{\mathcal{C}}_i}{\sum\limits_{\ell\in\mathcal{I}} \bar{\mathcal{C}}_\ell}, \forall i \in \mathcal{I} \qquad (17)$$

Finally, the values of $\Re_i$ are used to initialize r_{is}^A and r_{is}^E in the ILP problem described in the previous section. $\Re_i$ allows a human expert to select the necessary number of security zones and to define specific thresholds in establishing a cyber attack impact ranking. Depending on these thresholds, human experts may assign security zone and conduit levels to demands and end-points associated to each control variable. For example, in the particular case of energy grids control variables associated to high voltage circuit breakers may exhibit a higher impact ranking than low voltage circuit breaker's control variables. This is highly intuitive since disturbances on high voltage bus lines may have a significantly larger impact on observed variables, e.g., voltage levels. As a result, control variables with higher impact values may require higher protection levels than low impact control variables. Nevertheless, it is up to the designer to establish the significance of variations in observed variables as well as their specific ranking. For this purpose multi-level ranking methodologies such as the Smart Grid Information Security (SGIS) levels [34] may also be adopted.

VII. Experimental Assessment

In this section we evaluate the sensitivity of the proposed ICS network design approach to different parameters like the installation costs, the number of demands, the number of candidate concentrator sites, and the security configuration of demands and of their end-points. We experimentally compare the performance of the CAIA procedure to related cyber attack impact assessment techniques in order to illustrate the importance of control loops and the superior performance of the approach proposed in this work.

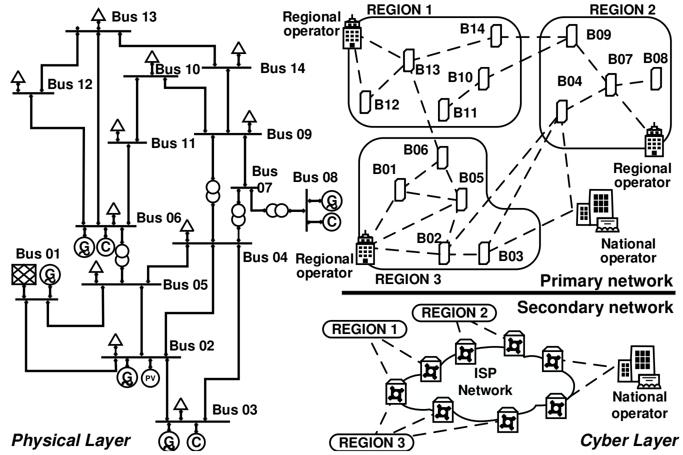


Fig. 2. Experimental ICS architecture including the IEEE 14-bus model as physical process and the cyber layer with primary and secondary networks.

Numerical results are given for two different scenarios. First, a qualitative assessment is performed on a case involving the IEEE 14-bus model [35] (see Fig. 2) enriched with data obtained from a local Internet Service Provider (ISP) and a local electricity grid operator. Then, a quantitative assessment is performed on a generated large-scale network topology in order to test the scalability of the proposed technique.

In this work we implemented the network provisioning problem in AIMMS and we adopted the popular CPLEX engine as an ILP problem solver. MATLAB PSAT toolbox [36] was used for the simulation of the physical process model.

A. Scenario A: Qualitative Assessment

In order to ensure a realistic estimation of parameters we arranged meetings with representatives of a local electricity grid operator and a local ISP. Discussions revealed that at least in the case of Romania networking solutions in the industrial sector are far behind the quality of services offered by ISPs. Therefore, industrial operators tend to adopt advanced and reliable networking solutions offered by ISPs, which is a trend followed by other companies as well [37]. Based on these discussions, in the first scenario we adopt the IEEE 14-bus system enriched with control loops specific to real-world power systems such as Power System Stabilizer (PSS), Automatic Voltage Regulators (AVR) and Turbine Governors (TG). We assume an architecture of a large-scale installation structured in three different regions. In this scenario the communication network encompasses the company's own communication lines based on fiber optics (primary network), and the communication channels leased from various national ISPs (secondary network), based on a mixture of wired and wireless networks (see Fig. 2). We further assume that *REGION 1* (R1) coincides with a mountainous region where primary communication lines involve higher maintenance costs, compared to other regions. Nevertheless, connection alternatives are available from national ISPs.

TABLE I
INITIAL PARAMETER VALUES

Parameter	Value
I, J, S	$\{1, 2, ..., 34\}$, $\{1, 2, ..., 26\}$, $\{1, 2\}$
c_j^S [MU/Mb/s]	30
c_{jl}^B [MU/Mb/s]	10 (R1), 3 (R2, R3), 1 (sec. net.)
c_{ij}^A, c_{ji}^E [MU/Mb/s]	1
c_{js}^Z [MU]	30 ($s = 1$), 300 ($s = 2$)
c_{jl}^C [MU]	300 (R1), 30 (otherwise)
$c_{jl}^{B^+}, c_j^{V^+}$ [MU/Mb/s]	100
d_i [Mb/s]	30 (data), 10 (VoIP)
u_{jl} [Mb/s]	1000 (R1), 10000 (R2, R3), 1000 (sec. net.)
v_j [Mb/s]	8000
a_{ij}, b_{jl}, e_{ji} [0-1]	according to Fig. 2
$q_j^C, q_{jl}^L, q_{ij}^A, q_{ji}^E$ [ms]	1
q_j^M [ms]	10
r_{is}^A, r_{is}^E, p_i [0-1]	according to attack impact assessment
z_s [Mb/s]	1000 ($s = 1$), 6000 ($s = 2$)
p_i [Integer]	1 (elementary conduit), 10 (advanced conduit)

1) Parameterization of the ILP Model: Table I lists the initial set of parameter values in the numerical examples that follow. We assume that $c_j^S = 30$ monetary units (MU) for all CSs, which includes the provisioning of hardware and software solutions to enable in-place fundamental concentrator features. Subsequently, we adopt a differentiated distribution of bandwidth costs across regions and networks such that $c_{jl}^B = 10$MU per Mb/s in R1, $c_{jl}^B = 3$MU/Mb/s in *REGION 2* (R2) and *REGION 3* (R3), $c_{jl}^B = 1$MU/Mb/s in the secondary communication network, and $c_{ij}^A = c_{ji}^E = 1$MU/Mb/s. We assume an increased penalty cost for supplementary bandwidth allocation of $c_{jl}^{B^+} = c_j^{V^+} = 100$MU/Mb/s, which encompasses the provisioning of additional communication lines. For the sake of simplicity, we further assume two possible security zones such that $c_{js}^Z = 30$MU when $s = 1$ for an elementary security zone, and $c_{js}^Z = 300$MU when $s = 2$ for an advanced security zone which might include state of the art next generation firewall with Intrusion Detection and Prevention Systems enabled. The cost of an elementary security conduit is $c_{jl}^C = 300$MU for R1 and $c_{jl}^C = 30$MU, otherwise.

Accordingly to the discussions with the electricity operator we assume the routing of two traffic demands from each substation to each regional operator and from each regional operator to a national operations center. The first demand is a high priority data channel encapsulating the physical process monitoring and control traffic, while the second demand is a lower priority, yet still critical channel, encapsulating Voice Over IP (VoIP) traffic. Therefore, in the present scenario we assume two different classes of traffic demands: one data communication demand of $d_i = 30$Mb/s, and one Voice Over IP (VoIP) demand of $d_i = 10$Mb/s. We assume that a pair of two such demands is routed between substations and regional operator centers, as well as between regional and national operator centers. With respect to the capacity of CS links we assume typical values learned from the two operators, that is $u_{jl} = 1000$Mb/s in R1, $u_{jl} = 10000$Mb/s in R2 and R3, and $u_{jl} = 1000$Mb/s in the secondary network. Subsequently, access/egress demand capacity of each CS is $v_j = 8000$Mb/s.

Connectivity parameters a_{ij}, b_{jl}, and e_{ji} are initialized according to the connection options depicted in Fig. 2. For the sake of simplicity, the value of each communication latency parameter is of 1ms. The maximum tolerated latency q_i^M is 10ms for real-time data [38] and 150ms for VoIP [39].

With respect to the capacity of security zones, we assume $z_s = 1000$Mb/s when $s = 1$ and $z_s = 6000$Mb/s when $s = 2$. The values of r_{is}^A, r_{is}^E, p_i are selected by means of the cyber attack impact assessment performed in the following sub-section. Finally, we assume two distinct security conduits such that $p_i = 1$ for an elementary conduit with basic security features, and $p_i = 10$ for a conduit with advanced security measures. Specific conduit requirements for each demand are identified in the following sub-section.

Obviously, the above assumptions are general and do not affect the proposed ICS network provisioning model which is applicable to any network problem and topology. The given values constitute an initial set of parameters which are then modified according to the goals of the analysis that follows.

2) Cyber Attack Impact Assessment: We aim at evaluating the applicability and effectiveness of the CAIA procedure in the context of the IEEE 14-bus model. Obviously, many different cyber attacks may be tested and, as shown by other studies as well [14], [24], [25], [26], [40], the attacker's targets may vary according to his goals. Therefore, in general, the CAIA procedure might need to be applied several times for different ICS cyber asset and attacker goals in order to obtain a more accurate and complete solution. However, for the sake of simplicity, in this work we assume that the attacker's goal is to induce bus-level failures by sending specially crafted commands to remotely controlled circuit breakers. These trigger significant disturbance that propagate over the electricity lines and may ultimately cause severe damages to distant devices. In particular, this scenario also gives us the opportunity to compare the result of CAIA with that of previous studies [25].

We applied the CAIA procedure on the IEEE 14-bus model with this attacker model, i.e., intervention, in the presence and in the absence of stabilizer and control devices. With the stabilizer and control devices in place, CAIA indicated that buses $1, 2$, and 9 are the most critical to the normal functioning of the electricity grid (see Fig. 3). This is explained by the fact that buses 1 and 2 are connected to high power generators equipped with active control devices, which greatly influence the evolution of voltage levels through the grid. In turn, bus 9 has a key position in delivering power from $69kV$ and $18kV$ areas to the $13.8kV$ area. As a result, from the perspective of network design, buses $1, 2$, and 9 are critical and demands involving these buses need to be placed in advanced security conduits and zones. Subsequently, given that ultimately national operating centers may affect the normal functioning of all buses, demands and their end-points comprising of regional and national operators need to be secured with advanced measures.

Conversely, without active control devices the results returned by CAIA are notably different. In this case buses 4 and 5 are designated as the most critical, while buses 1 and 2 seem to be less significant. This is an important finding and proof of the fact that the size of ICS nodes, e.g., the number of

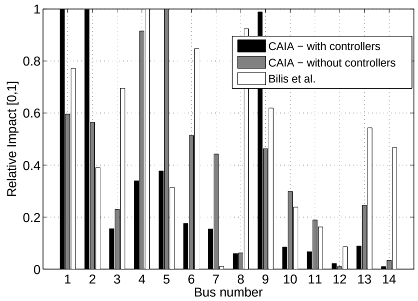
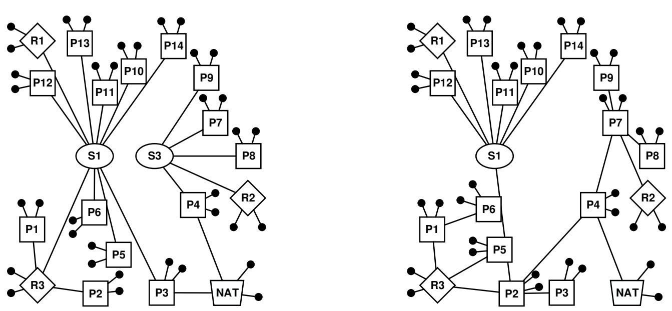


Fig. 3. Cyber attack impact assessment performed on the IEEE 14-bus model.

connections, is not necessarily a reflection of the importance of ICS nodes. In fact, we compared the output of CAIA with that obtained by applying the methodology proposed by Bilis *et al.* [25] on the IEEE 14-bus model. It should be noted that the method proposed in [25] builds on five centrality metrics adopted from graph theory and does not account for the role of each node. As shown in Fig. 3, the results of the method proposed by Bilis *et al.* exhibit a different distribution of the node's significance. Obviously, since this approach applies exclusively node connectivity principles, it is more suitable for large-scale electricity grids. However, as shown by the results of CAIA, the significance of nodes is mainly given by their role and by the devices attached to these nodes, e.g., stability controllers, which may have a decisive role in guaranteeing the stability of industrial installations.

3) Effect of Installation Costs: We evaluate the effect of bandwidth cost, of concentrator node installation cost, of security zone cost, and finally of security conduit installation cost on the performance of the ILP model.



(a) Initial parameter values. (b) Increased bandwidth costs.

Fig. 4. Effect of increased bandwidth costs. Primary CSs, secondary CSs, regional CSs, national CSs, and TD end-points are represented with boxes, ellipses, diamonds, trapezoids, and circles, respectively.

At first, we look at the graph visualization of the solutions generated by the ILP model. With the initial parameter values listed in Table I communications are mainly routed through the secondary network (see Fig. 4a) since here $c^B_{jl} = 1$MU/Mb/s, compared to $c^B_{jl} = 10$MU/Mb/s in R1 and to $c^B_{jl} = 3$MU/Mb/s in R2 and R3. However, by increasing the bandwidth costs in the secondary network to $c^B_{jl} = 6$MU/Mb/s, connections in R2 and R3 are rearranged and traffic is routed through the less expensive primary network. Nevertheless, in R1 the secondary network is still the best choice for routing demands

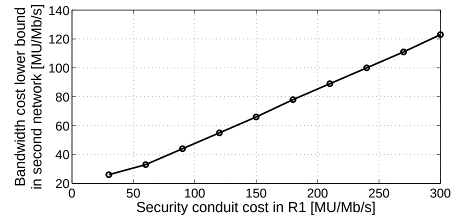


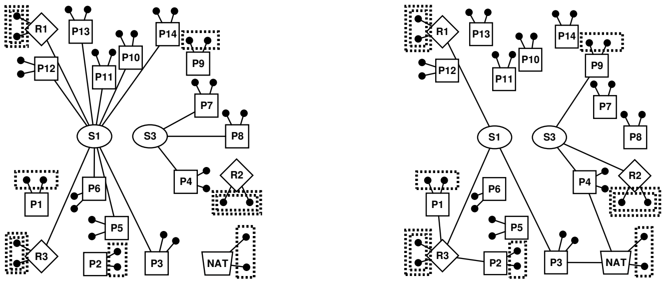
Fig. 5. Effect of security conduit costs in R1 on the required bandwidth costs' lower bound in the secondary network which is needed in order to ensure that demands are routed exclusively in the primary network.

TABLE II
DEMANDS ROUTED IN THE SECONDARY NETWORK WITH RESPECT TO BANDWIDTH COSTS (SECONDARY NETWORK) AND CONDUIT COSTS (R1).

	Conduit cost [MU]				
Bandwidth cost [MU/Mb/s]	30	60	120	210	300
1	20	20	20	20	20
5	9	9	9	9	9
10	6	6	6	6	6
15	5	5	5	5	5
20	5	5	5	5	5
26	0	2	4	4	4
30	0	2	2	2	2
40	0	0	2	2	2
50	0	0	2	2	2
80	0	0	0	2	2
100	0	0	0	0	2
123	0	0	0	0	0

between substations and the regional operator. Next, we look at the effect of cost changes on the solutions generated by the ILP model. In particular, we analyze the effect of bandwidth and security conduit cost alterations on the selection of CSs. We aim to identify the necessary cost adjustments that may influence the selection of CSs from the secondary network. Recall that the cost of one elementary security conduit in R1 is of $c^C_{jl} = 300$MU, while the cost of conduits in the secondary network is of $c^C_{jl} = 30$MU (Table I). Therefore, our analysis focuses on the repeated reduction of conduit costs in R1 and on the increase of bandwidth costs in the secondary network. As shown in Table II both parameters have a significant impact on the number of demands routed in the secondary network. By increasing the cost of bandwidth units in the secondary network, the ILP model concludes that CSs from this network can be excluded from the solution only if c^B_{jl} is at least 123MU for $c^C_{jl} = 300$MU. Nevertheless, if $c^C_{jl} = 30$MU in R1, then CSs from the secondary network are excluded if c^B_{jl} is at least 26MU. The impact of costs on the solution, and more specifically the linear interdependence between the cost of security conduits on the required bandwidth costs' lower bound is also depicted in Fig. 5. As a final note, it is important to emphasize that irrespectively of the costs or of the chosen parameter values in general, the proposed ILP model ensures that critical real-time requirements formulated in terms of communication latency are satisfied at all times.

4) Effect of Security Configurations: We illustrate the effect of security configurations on the solution generated by the ILP model with the initial set of parameters from Table I. In the previous sections the CAIA procedure found that



(a) Elementary security conduits. (b) Advanced security conduits.

Fig. 6. Security zones and conduits. Simple dashed boxes denote advanced security zones, double dashed boxes denote two zones (elementary and advanced), while missing boxes denote elementary zones. Primary CSs, secondary CSs, regional CSs, national CSs, and TD end-points are represented with boxes, ellipses, diamonds, trapezoids, and circles, respectively.

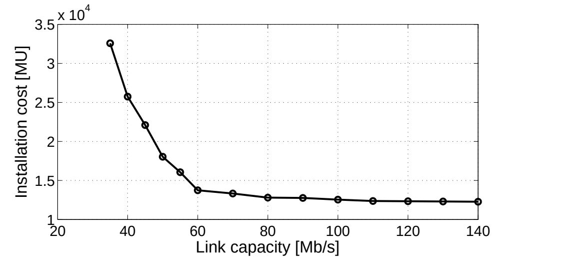


Fig. 7. Effect of link capacity variations between CSs on the total cost of the installation.

TABLE III
EFFECT OF LINK CAPACITY CHANGES ON THE GENERATED SOLUTION AND ON THE TOTAL COST OF THE INSTALLATION.

u_{jl} [Mb/s]	N_L	N_L^A	N_S	S_B [Mb/s]	$T_\$$ [MU]
140	26	21	0	0	12280
130	27	21	0	0	12310
120	28	21	0	0	12340
110	29	21	0	0	12370
100	26	22	0	0	12550
90	25	22	0	0	12760
80	26	22	0	0	12800
70	31	23	0	0	13330
60	34	23	0	0	13740
55	35	24	4	20	16060
50	35	24	3	40	18040
45	37	24	8	80	22100
40	34	23	4	120	25740
35	50	26	11	175	32580

communications with equipment installed on buses $1, 2$ and 9 require advanced security measures in terms of the provisioned conduits and zones associated with demands and their end-points. These requirements have been incorporated in the ILP model and the results have been illustrated in Fig. 6a and 6b. Here, the provisioning of advanced security zones is represented by dashed boxes, while the provisioning of elementary security zones is not highlighted with any particular symbol since all the remaining TD end-points are incorporated into elementary security zones. Conversely, the provisioning of elementary and advanced security zones (in case of regional operators) is represented by double dashed boxes. It can be seen that in both figures substation-level CSs denoted by $P1, P2$, and $P9$, as well as the national CS denoted by *NAT*, implement exclusively an advanced security zone, while regional CSs denoted by $R1, R2$, and $R3$ implement both elementary and advanced security zones. Conversely, CSs in the secondary network denoted by elliptic geometrical shapes do not implement security zones since they do not host direct connections from demand end-points. With respect to security conduits (Fig. 6b) it can be seen that advanced security conduits are implemented, according to the CAIA approach, specifically for the critical demands. As such, advanced security conduits are provisioned to protect TDs between $P1$ and $R3$, $P2$ and $R3$, $P9$ and $R2$, and between regional operator CSs $R1, R2$, $R3$ and the national operators' CS *NAT*. Elementary security conduits are provisioned for the remaining TDs (Fig. 6a). An important aspect, however, is that the ILP problem may route on the same link TDs with different security requirements. In such scenarios TDs are provisioned with the highest conduit level among the TDs selected on that particular link. In the present scenario this is visible in *REGION2*, where the requirements of TDs connected to $P9$ have led to the provisioning of an advanced security conduit between CSs $P9$ and $S3$, and between $S3$ and $R2$. However, TDs with elementary conduit requirements between $P4$, $P7$, $P8$ on one hand and $R2$ on the other hand are routed on the same advanced conduit installed between $S3$ and $R2$.

5) Effect of Link Capacity: We believe that the effect of access/egress link capacity variations on the ILP solutions and finally on the total cost of the installation is highly intuitive. In such cases the model allocates supplementary bandwidth in variable ω_j for each CS j, which increases the total cost by $\sum \omega_j c_j^{V^+}$. Therefore, in the following, we look at the effect of decreasing the capacity of links between CSs on: the total number of allocated links (denoted by N_L); the number of links with advanced security conduits (denoted by N_L^A); the number of links where supplementary bandwidth is allocated (denoted by N_S); the total allocated supplementary bandwidth (denoted by $S_B = \sum \tau_{jl}$); and, the total cost of ICS provisioning (denoted by $T_\$$). As depicted in Table III, the reduction of capacity on all links between CSs has a significant impact on the ILP solution. Starting from $u_{jl} = 140$Mb/s and down to $u_{jl} = 60$Mb/s $\forall j, l \in J$ the bandwidth deficiency is mainly resolved by increasing the number of communication lines from $N_L = 26$ to $N_L = 34$. Nevertheless, for $u_{jl} = 100$Mb/s the ILP model determines that it is more cost-efficient to allocate an additional communication line with advanced conduit, rather than to increase the number of communication lines implementing elementary security conduits. Starting from $u_{jl} = 55$Mb/s $\forall j, l \in J$, the ILP model allocates supplementary bandwidth from $S_B = 20$Mb/s for $u_{jl} = 55$Mb/s and up to $S_B = 175$Mb/s for $u_{jl} = 35$Mb/s. As a result, the penalties associated with the cost of supplementary bandwidth increase the overall cost of the installation from $T_\$ = 13740$MU up to $T_\$ = 32580$MU. The effect of link capacity variations on the total cost of the installation is also depicted in Fig. 7. Here it can be seen that the penalty costs associated with supplementary bandwidth allocations have a

TABLE IV
ILP MODEL COMPUTATION TIME.

N_I	N_T	$N_J = 20$ (s)	$N_J = 50$ (s)
10	1	0.23	1.93
10	2	0.48	2.47
10	3	2.73	4.26
50	1	1.15	9.44
50	2	2.43	19.08
50	3	46.4	19.52
100	1	3.23	21.34
100	2	6.88	35.3
100	3	135.74	36.78

dramatic impact on the total cost of the installation.

B. Scenario B: Quantitative Assessment

We tested the performance of the ILP model in terms of CPU time on several ICS cases containing 20 and 50 CSs, 10, 50, and 100 TDs, and 1, 2, and 3 access/egress TD end-point connection choices to CSs. The network provisioning problem was implemented in AIMMS, and we measured the execution time of the CPLEX solver version 12.6. The tests were run on a Windows 7 PC with a 2.2 GHz Dual Core CPU and 4.0 GB of physical RAM. In the following, we use N_I to denote the number of TDs, N_J to denote the number of feasible CSs, and N_T to denote the number of feasible TD-CS links. Results are listed in Table IV. The computing time of the ILP model increases substantially with the size of the problem. As listed in Table IV, the performance of the ILP model is significantly influenced by N_T. This is explained by noting that N_T affects the number of feasible connections for access and egress end-points. Obviously, by imposing $N_T = 1$, each TDs' end-points are fixed to specific CSs, in which case connection alternatives are not available. However, the increase of N_T above one delivers at least one connection alternative for each TD. Conversely, even though the computing time increases with the number of CSs, the additional CSs also bring new connection opportunities for TDs, which may decrease the overall computing time. For example, if $N_I = 50$ and $N_T = 3$ the computing time for $N_J = 20$ is of 46.4s, while for $N_J = 50$ is of 19.52s. This is explained by the behavior of ILP models where parameter changes do not necessarily lead to a proportional change in the problems' solution, but rather to a new optimal solution.

Lastly, we test the effect of gradually activated constraints on the generated solutions. We assume a randomly generated network consisting of 30 CSs and 60 TDs. Parameter values are initialized according to Table I. At first, we exclusively enable connectivity constraints. Then, we gradually enable capacity constraints, security constraints, and finally real-time constraints. Given the significance of connectivity parameters, we assess the effect of their uniform distribution (20%-100%) on the generated solution. Assuming that solutions are characterized by the number of selected CSs, each configuration is run 10 times and the average number of CSs is computed.

As denoted by the results in Fig. 8, the number of selected CSs depends on the connectivity parameters. By increasing the connectivity probability towards 100%, fewer CSs are selected. However, by activating capacity constrains (we assume capacities of 300Mb/s) we observe an increase in the number of CSs. Security constraints on the other hand have a contrasting effect and cause a slight decrease in the number of CSs, which is the result of minimizing the cost of SZC. Finally, by activating real-time communication constraints, the number of selected CSs is further decreased in order to ensure that maximum latency requirements are satisfied. These results showcase the multi-phase characteristic of the proposed ICS network design methodology. In this respect constraints and their associated parameters are activated once their values are properly determined. On the other hand, the results also denote the importance of connectivity parameters, which need to be defined at early design stages. Such information, however, depends on the exact installation characteristics and is available to network designers in the form of location and device characteristics. Based on preliminary results obtained with the configured connectivity parameters, network designers can then further approximate and enrich the ICS design methodology by activating additional constraints, as described in the previous sections.

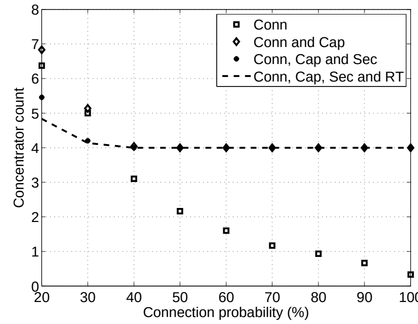


Fig. 8. Effect of gradually activated constraints on the generated solutions. *Conn*, *Cap*, *Sec*, and *RT* denote connectivity, capacity, security and real-time constraints, respectively.

VIII. CONCLUSION

We proposed an ILP problem to accommodate traditional ICS network design requirements and modern security recommendations outlined by the ISA-62443.03.02 standard. This approach saved costs on investments in the system's resources, but also enhanced the security of ICS installations with state of the art requirements on security zones and security conduits. We additionally proposed a cyber attack impact assessment technique to rank the significance of cyber assets represented by traffic and communication end-points. The ICS network design methodology was extensively analyzed in a specific scenario involving the IEEE 14-bus model and a more general scenario with large-scale network topologies. It was shown that the approach minimizes the cost of the installation, while ensuring that both real-time constraints and security requirements are satisfied. Results also proved that the technique is scalable and applicable to large ICS installations.

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