BUCEPHALUS: a BUsiness CEntric cybersecurity Platform for proActive anaLisys Using visual analyticS

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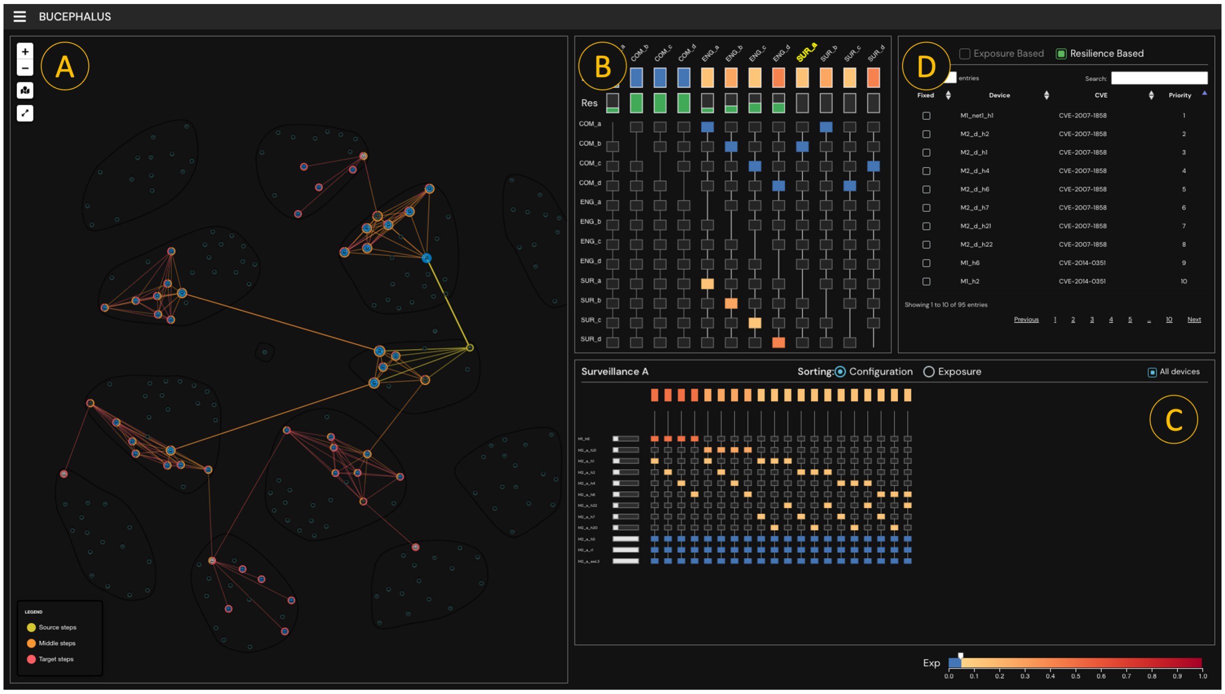

☐ Exposure Based ☑ Resilience Based

entries Search:

Fixed	Device	CVE	Priority
☐	M1_net1_h1	CVE-2007-1858	1
☐	M2_d_h2	CVE-2007-1858	2
☐	M2_d_h1	CVE-2007-1858	3
☐	M2_d_h4	CVE-2007-1858	4
☐	M2_d_h6	CVE-2007-1858	5
☐	M2_d_h7	CVE-2007-1858	6
☐	M2_d_h21	CVE-2007-1858	7
☐	M2_d_h22	CVE-2007-1858	8
☐	M1_h6	CVE-2014-0351	9
☐	M1_h2	CVE-2014-0351	10

Showing 1 to 10 of 95 entries

Previous 1 2 3 4 5 … 10 Next

Surveillance A Sorting: ● Configuration ○ Exposure ☑ All devices

Figure 1: BUCEPHALUS is composed of four different panes, giving the security operator the possibility to investigate the relationship between the devices in the monitored network and the supported business functions. The *Network Pane* (A) shows the attack graph, highlighting in yellow the sources of attack, in orange the intermediate attack steps, and in red the steps toward a target device. At the same time, the *Business Pane* (B) gives the overview of the business functions' status and their inter-dependencies, allowing to explore the exposure and resilience levels. Choosing a business function to investigate ("Surveillance A", SUR_a), the *Dependencies Pane* (C) shows in a matrix-like view the relations between devices (rows) and equivalent configurations (columns), representing how the cyber-exposure affects the business functions working state. Finally, the *What-if analysis Pane* (D) proposes two strategies for mitigating the exposure (attack paths based and resilience based), listing the pair device-vulnerability in accordance with the chosen strategy. The security operator can conduct a what-if analysis by simulating mitigations, obtaining a mitigation plan that raises the resilience of the business functions of the organization.

ABSTRACT

Analyzing and mitigating the threats that cyber-attacks pose on the services of a critical infrastructure is not a trivial activity. Research solutions have been developed using data about the devices used for implementing the services, services dependencies, network topology, and the vulnerabilities that can be exploited to attack the network. However, most of the proposed solutions fail to consider these aspects in an integrated fashion, allowing the user to understand global dependencies and weaknesses. This paper contributes this issue with BUCEPHALUS, a Visual Analytics solution providing a) a visual overview of the existing relationships among business functions, devices, and vulnerabilities, and b) a what-if analysis scenario, in which the user is supported on making decisions on which vulnerabilities are more appropriate to fix. BUCEPHALUS has been developed and validated within a user-centered design project involving security professionals.

Index Terms: Cybersecurity—Business Impact Analysis—Network Hardening—Attack graphProactive analysis; Visual Analytics—What-if analysis

1 INTRODUCTION

The management of the security risks due to cyber-attacks or failures of critical infrastructures is gaining increasing attention: a non-exhaustive list of research topics include the identification of business dependencies on supporting systems, the analysis of the network vulnerabilities and the associated threats, the automated

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assessment of business risk, and the support of the hardening of the system through proactive actions. Even if business functions continuity and cyber-exposure are the key issues to deal with while hardening a critical infrastructure, most of the proposed solutions fail to consider these two aspects in an integrated fashion, as reported in Section 2. This paper describes the Visual Analytics solution, which is under development within the collaboration between Sapienza University of Rome and the MBDA company, for monitoring and hardening the MBDA products. MBDA, a world leader in the military aviation sector, is a multinational company with approx. $10,000$ employees working in France, the UK, Italy, Germany, Spain, and United States. Moreover, MBDA is the only defense company that provides missiles and missile systems for each branch of the armed forces (air, sea, land). There are many similarities between MBDA products and critical infrastructures; for this reason, a large part of the requirements expressed by MBDA engineers to meet the needs of their products can be borrowed and also applied to critical infrastructures. The proposal presented in this paper relies on the modeling of the three critical aspects associated with the security analysis and hardening processes presented in Section 3. The system business functions are the core of the analysis, and the adopted model allows for describing dependencies among functions and linking each function to the devices it relies on. The second aspect is associated with the cyber-threats modeled through a topological attack graph that provides the means for computing the exploitation likelihoods it poses on the devices used by the business functions. Finally, the third aspect is the resulting business quality, modeled in terms of function exposition to failure and resiliency. The Visual Analytics system presented in Section 4, which is under development to address the MBDA requirements, builds on such models to visually inform the users about the dependencies among business functions and between business functions and devices, clearly showing the threats the actual attack graph poses on supporting devices and how this affects the quality (business functions exposure and resilience) of the organization. Moreover, the system supports hardening activities by computing strategies for fixing the attack graph vulnerabilities; in this way, the security operator can focus on the most relevant vulnerabilities, i.e., the vulnerabilities that have the highest impact on the network exposure or the organization's business. Finally, acknowledging that some business constraints could prevent the straightforward application of the optimal fixing order, the system provides the user with a what-if environment in which she can simulate fixing one or more vulnerabilities, observing the improvement of the business quality.

Summarizing, the key novel features of the proposed solution are:

- a Visual Analytics solution, designed with MBDA security experts and allowing for analyzing in an integrated fashion the security issues associated with both the system business dependencies and network weaknesses;
- a proactive what-if scenario supporting the user in exploring both the optimal vulnerability fixing sequence and sub-optimal strategies associated with business constraints;
- the validation of the system through two usage scenarios.

2 RELATED WORK

Looking at previous proposals for monitoring the state of operation of an enterprise with respect to cybersecurity, several contributions exist that focused on the monitoring and analysis of the cyber-exposure level, where most of them are based on the attack graph visualization and analysis [3, 6, 12, 15, 30, 31, 37]. All those approaches have in common that they focus only on the network attack surface perspective, not considering how it can affect the business layer of an organization.

Linking cyber-exposure data to other perspectives, in the context of raising situational awareness, is an activity conducted by several researchers. Pike et al. [33] correlate network anomalies and attacks to real-world social or geopolitical events. Ferebee et al. [16] apply similar considerations, providing requirements for security visualization and for business impact analysis visualization by building on previously gained knowledge on understanding weather maps used in meteorology. DAGGER by Peterson [32] is a modeling and visual framework for representing knowledge and information from network security data for decision-makers. In our work, the Business Centric view can be looked at from three different perspectives: (1) the service level that each business function provides during operations, (2) the exposure to cyber-threats that each of the functions can potentially suffer, and (3) the resilience that each of the functions shows with respect to the cyber-exposure.

Starting from the first perspective, Motzek et al. [26] propose a business dependency model normalization and matching approach by exploiting structures and dependencies of business resources, in order to model the dependencies between the business functions of an organization. Matthes et al. [25] provide a three-phase method to systematically identify dependencies between business capabilities and other elements of an Enterprise Architecture. Bouchaala et al. [9] developed DAT, a dependency analysis tool for Business processes expressed in Business Process Model and Notation (BPMN). A recent survey from Stein Dani et al. [35] explores the different methods for visualizing information coming from those models. With respect to their six classes classification (Augmentation of existing elements, Creation of new elements, Exploration of the 3D space, Information visualization, Visual feedback concerning problems detected in process models and Perspectives), we position our proposal into the "Visual feedback concerning problems detected in process models". Overall those works focus only on representing the dependencies and not on linking them to cyber-exposure data as our approach does.

With respect to the link between the cyber-exposure of a device and the supported business function, Motzek and Möller [28] provide a formal, mathematical model for bias and context-free mission impact assessment, eventually applied to a cybersecurity scenario [27]. Chen et al. [11] introduce a new business process impact assessment method that measures the impact of an attack towards a business-process-support enterprise network. The impact scores for business processes are the function result of the severity of the vulnerabilities and the relations between vulnerabilities and business processes. Those papers propose only automatic models without any visualization or support for visual exploration and decision-making. There exist instead solutions that provide visual support and actionability to those models. Goodall et al. [18] propose Camus, a system to automatically map cyber assets to the users who depend on them, to the missions they support, and to the services they provide. Tannian [36] proposes a design study on visualizing the effects of cyber-attacks on business continuity, conducted with seven IT professionals from the Des Moines metropolitan area. However, this work focuses only on the reactive aspects, with an ongoing attack, and does not focus on the resilience of the business functions or their exposure (proactive analysis). Angelini and Santucci [4] propose a visual metaphor (Corruption of area) to represent the degradation of service level for critical infrastructure business functions superimposed on a geographic map. This work focuses only on the service level and does not consider the resilience to cyber-threats of business functions. The authors extended this work by considering high-level management personnel to support during the review of the operational status of an enterprise [5]. However, this solution provides only an overview, aggregated at the lowest level of detail, and does not allow actionability for any countermeasure. On the contrary, Jajodia et al. [22] present Cauldron, a solution that provides visualization of attack paths, with automatically generated mitigation recommendations, along with analysis of mission impact from attacks. While not visually sophisticated as our solution, their paper focuses only on the impact on service level and not on business resilience. Finally, CyGraph is a system by Noel et al. [29] that links together assets to mission and dependencies among mission requirements; results are explorable in a set of task-driven visualizations. Gonzalez-Granadillo et al. [17] propose a proactive and reactive management system that evaluates a cyber-threat scenario, considering the likelihood of success, the induced impact, the cost of the possible responses, and the negative side-effects of a response. However, no visual environment nor capability for the user to explore the results are provided.

With respect to the last perspective, Horn and D'Amico [21] present an initial effort to use visual analytics to support the modeling of the computer network defense (CND) decision process of an organization and tracing relationships between decision goals, sub-goals, and data sources, like IDS alerts, asset management, and network flows. At the top there is the one overarching goal that captures the mission of an organization from observations of its practices. This overarching goal can be decomposed into sub-goals. Differently from our approach, however, they do not use an explicit representation of the business assets and functions and do not exploit modeling of original data sources like attack graphs. Finally, their design is based on superimposing this information over a node-link hierarchical structure. Still D'amico and Sals [14] discuss a 3D representation of information security breaches, assets involved, and their support to mission-critical aspects. One proposal similar to our approach is the work by Hao et al. [19]. The authors introduce VisImpact, a visualization technique that represents operational business data into valuable information reducing data complexity and abstracting the most critical factors, called impact factors, which influence business operations. While the authors propose a case study on fraud-analysis, the focus is on the business flow-graph and it takes into account in a limited form the cyber-exposure of the organization, as our contribution does. Creese et al. [13] present CyberVis, a 3D visual system that combines traditional network diagram icons with BPMN, a risk-propagation logic that connects the network and business-process and task layer, and a flexible alert input schema able to support intrusion alerts from any third-party sensor. CyberVis abstracts the visuals to show only noteworthy information about attack data and indicates potential impact both across the network and on enterprise tasks. Different from our approach, they do not consider the resilience level of a business function and how far it could be from being degraded, but only relations between exposure and service level.
Finally, some visualization works exist that coped with the concept of the resilience of an organization (e.g., [10, 38]). However, those works target resilience to a phenomenon not necessarily tied to cybersecurity, like natural disasters or physical security.

3 BUSINESS EXPOSURE MODEL

This section provides details about how BUCEPHALUS models the relationships between cyber-exposure, service level, and resilience of a business function. It first introduces the cyber-exposure model that describes the cyber-exposure level of devices inside a network organization. Then it moves on to describe the business dependency model, which illustrates the relations and inter-dependencies existing between devices and supported business functions, and among business functions themselves. Finally, it introduces a linkage between the two, which we define as the Business Exposure model, that allows for describing the effect of cyber-exposure both on a business function service level and its resilience.

3.1 Attack Graph model

An *Attack Graph* (AG) represents possible ways via which a potential attacker can intrude into a computer network by exploiting a series of vulnerabilities on various hosts and gaining certain privileges at each step. Many different AG models have been defined in the literature depending on the specific semantics assigned to nodes and edges of the graph [23].

In this paper, we will focus on *host-based Attack Graphs* where a node represents a specific level of privilege gained by the attacker on a specific host (e.g., *None*, *User* or *Root* on the host h_i) while an edge between node p_s and node p_t represents the possibility to exploit a vulnerability on the destination host h_t gaining a privilege p_t stating from the privilege p_s earned on the source host h_s.

Given an attack graph $\mathcal{AG}$ and two hosts h_s and h_t, it is possible to compute all the existing *Attack Paths* between two hosts[1] h_s and h_t simply by computing all the possible paths existing over $\mathcal{AG}$ connecting any privilege existing on h_s with any level of privilege gained on h_t. The result is a collection of alternate sequences of nodes (i.e., level of privilege over a host) and exploitable vulnerabilities where each path has the form p_s, vul_j, p_j, vul_k, p_k, $\ldots$, vul_t, p_t denoted as and is called *multi-step attack path*.

3.2 Business Dependency Model

Failure or compromising of elements in the ICT network may have a strong impact on the ability of a company to correctly provide its services. Several studies exist trying to relate elements characterizing the ICT network layer (e.g., host or other devices connected to the network) with the business processes supported by the ICT Infrastructure. Bahşi et al. [7] provide a systematic literature review of existing frameworks for assessing the impact of cyber actions on missions or business processes up to 2018. Among all the existing models for representing dependencies between business processes and network devices, we decided to use a general, simple, and flexible model similar to those used Gonzalez-Granadillo et al. [17]. In particular, we will consider a model representing dependencies as direct relationships between dependency nodes. A dependency node could be any of the following:

- *Business process or function*: it represents a functional process needed to support the company's mission (e.g., environmental monitoring for a company working in cultural heritage or billing sub-system for a generic service provider);
- *Host/device involved in services provisioning*: it represents an element of the ICT network that contributes to the implementation and support one or more business process (or functions).

Given two dependency nodes n_i and n_j (either two business nodes, a business and a host node or two host nodes), we will say that n_i *depends on* n_j (i.e., there exists a dependency between n_i and n_j) if *a failure or compromising of* n_j *impacts the correct functioning of* n_i.

This model allows the extraction of "equivalent configurations" of devices supporting a business function, allowing to define a degree of redundancy for a business function. Nominally, if a business function is supported by n different equivalent configurations, it means that just one of them is needed to be operational in order to support the business function to the desired service level. This implies, at least nominally, that the added $n-1$ redundant configurations make more resilient the business function. For $n = 1$, the redundancy is zero, and the business function is the least resilient possible.

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[1] For ease of explanation, we just considered here one source and one target host. However, attack paths can be computed between any set of source and any set of target hosts by simply iterating.

3.3 Linking the two worlds: the Business Exposure model

Let us note that even if attack graphs and business dependency models can be defined and studied independently of each other, in that way each of them represents only a partial view of the resilience posture of the organization. Matching them instead allows modeling the effect of cyber-exposures on a business function and its correct working state. The correct working state of a business function depends on a set of conditions that have to be satisfied (related through a logical AND). Each condition corresponds to the correct working state of another business function, or of a single device supporting the business function, or of a group of redundant devices (grouped by a logical OR) where only one of them has to correctly behave for the corresponding business function to operate correctly. The presence of logical ORs in the resulting dependency tree generates multiple configurations, that we call "equivalent configurations" (meaning that only one of them is needed to work for the supported business function working correctly), supporting the correct working state of a business function despite the potential impairment of a subset of its supporting devices. The execution of this joint model, called the Business Exposure model, gives the capability to:

- analyze the direct effect on business functions caused by exposure to a specific set of attack paths computed by using the attack graph (**Effect on service level**);
- evaluate the effects that cyber-exposure has on the business dependencies themselves, where some of them could be very resilient and guaranteed at their nominal value defined in the business dependency model, while others could results weaker, or worse already compromised due to high exposure of their supporting devices (**Identification of weak dependencies**);
- weighting "equivalent configurations" on attack paths, it is possible to compute the real level of redundancy, and so of the resilience of a business function. For example, if a business function has three equivalent configurations, $\langle c_1, c_2, c_3 \rangle$ but it exists in the attack graph an attack path that includes a device from c_2 and a device from c_3, the real redundancy will get lowered from 2 to one, expressing a less resilient business function (**More accurate evaluation of resilience**);
- connected to the previous point, capability to automatically suggest a mitigation plan that is driven by business function resilience (**Resilience-driven mitigation plan**).

Exposure The dependencies of a business function f_i can be expressed as the logical AND among all its functions dependencies, and the logical OR among all its equivalent configurations.

$$f_i \rightarrow (f_1 \wedge f_2 \wedge \cdots) \wedge (c_1 \vee c_2 \vee \cdots)$$

The exposure to attacks E is defined for devices, equivalent configurations, and business functions. From the attack graph model, each attack path has associated a likelihood l expressing the probability that the path will be instantiated during an attack. The exposure of a device is defined as the maximum likelihood among all the attack paths that involve that device. The exposure of an equivalent configuration $E(c_1)$ is defined as the maximum exposure of the devices involved in the equivalent configuration. The exposure E of a business function f is defined as follows.

$$E(f) = \max \Big[\max[E(f_1),\, E(f_2),\, \cdots] \,,\, \min[E(c_1),\, E(c_2),\, \cdots] \Big]$$

Resilience For a business function f, the set of its equivalent configurations is $\mathcal{C}_f = \{c_1,\ c_2,\ \cdots\}$. Given an exposure threshold t, we can assume that if $E(c_1) < t$ this particular equivalent configuration has a low probability of being compromised. The resilience R of a business function f expresses the proportion of how many equivalent configurations have a low probability ($< t$) of being compromised.

$$R(f,t) = \frac{\|\{\forall c_i \in \mathcal{C}_f \ ,\ E(c_i) < t\}\|}{\|\ \mathcal{C}_f\|}$$

4 VISUAL SUPPORT TO BUSINESS EXPOSURE MODEL

This section describes how we designed a Visual Analytics environment supporting the Business Exposure model. We first introduce the requirements collection process, intertwined with the main design decisions and intermediate results that led our process. Following this, the description of the final version of the `BUCEPHALUS` environment is provided in Section 4.2.

4.1 Requirements collection

To design the proposed solution, we worked in conjunction with the MBDA company, which has relevant needs for monitoring the cyber-exposure of their products, not only in terms of degraded services but also in terms of resilience to possible cyber-threats and proactive prevention of cyber-attacks. Inside MBDA's Weapon Systems, the workstations allow the operator to interact and control the system. The design and development of the human-machine interface is a crucial aspect of the quality of the entire product. Five key-personnel figures were involved during the design process: one Administrator, one Technical officer, one operative, all experts in managing cyber-exposure and business continuity monitoring and analysis, and two experts from the MBDA area dedicated to Human Factor studies, which main objective is to provide and guarantee MBDA's customers a Product conceived and built with the user in mind. The design activities spanned one year and started reasoning on an existing initial solution for the visual analysis of pure cyber-exposure of an enterprise network, MAD [2]. This solution proved very good in representing the cyber-exposure status (proactive and reactive) for the devices of the organization. However, it did not provide any help in relating those data to business function exposure and business function resilience. Through a set of five think-aloud sessions (two initial sessions of brainstorming, three following meetings with mock-ups and prototypes), lasting on average from 1.5 to 3 hours each, we designed the solution presented in Section 4.2. During the first two meetings, we set up the initial goals for a new system capable of managing and representing the structure and dependencies among the business functions of the organization (**Requirement RQ1: Capability to see the overview of business functions structure and inter-dependencies**) and their operational level (**Requirement RQ2: Capability to see the overview of business functions operational level**). This led to the proposal of the first mock-up of the visual interface that would be able to support the analysis of those data. Limitations were reported in terms of the inability to relate the business functions' service levels to the originating cause of problems. Additionally, it was reported that operators tend to consider both perspectives (i.e., business functionality and cyber-exposure of the enterprise devices) at the same time. This led us to consider in the first revision of our design two additional requirements: **Requirement RQ3, Capability to see the cyber-exposure level of the monitored environment**, and **Requirement RQ4, Capability to proactively analyze the resilience of business functions with respect to cyber-exposure of their supporting devices**. While RQ3 was the direct consequence of what our stakeholders reported, RQ4 derived from the considerations that the link between cyber-exposure of devices and degradation of their supported business function(s) is not the only perspective that can be considered in a proactive analysis. Even the "distance" of a business function from its possible degradation is very useful in managing correctly the cybersecurity posture of an organization. The more the core business functions are distant from their degraded state, the more the organization will be resilient to cyber-attacks.

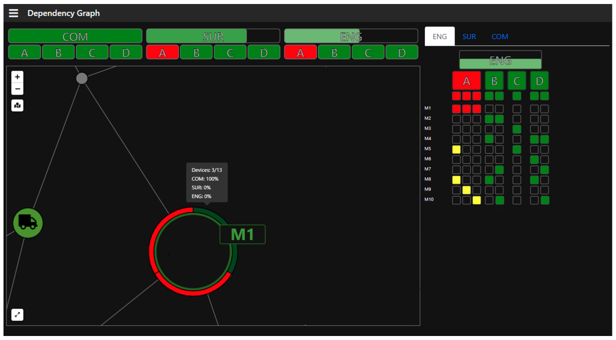


Figure 2: Intermediate prototype (cold mock-up) produced during the user-centered design iterations. It is visible how dependencies between devices and business functions are represented in a matrix-style view, while the inter-dependencies among business functions are detached and moved on top of the topology view.

This time a cold mock-up was produced, with some functionalities running for the cyber-exposure representation, inspired by previous work on pure visual representation of cyber-exposure [2,8]. At the same time, a new part concerning the representation of the relations between business functions and devices' cyber-exposure was added, visible in Figure 2. It used a matrix-like visualization, where the devices were represented by rows and the business functions by columns. Each cell of this sparse matrix could be colored with respect to cyber-exposure, and so contributing to understanding the impact it has on the business function. Business functions could contribute to the functionality of other business functions. This behavior was captured by the hierarchical representation on the top part of Figure 2, where bottom layer functions contribute to higher-level functions. The use horizontal bars represented the current exposure for each function. During a new face-to-face meeting, it was noted that the association between devices and business functions in a direct form, without considering the possibility to visualize equivalent configurations of devices that still supported the business functions was a good overview, but that those kinds of details should be actionable on-demand. Additionally, it was noted that the visualization of inter-dependencies among business functions needed a higher level of detail. Combined, they contributed to the formulation of a new requirement: **Requirement RQ5, Usage of a top-down approach for the whole visual environment**. This requirement follows the classic visual information seeking mantra ("Overview first, zoom and filter, details on demand") [34] and was explicitly required by the stakeholders to respect the common way in which business and security analysts use visual systems. This requirement had been followed even during the previous design phases but was considered a hard requirement from this moment on for all the remaining design aspects. Interestingly, what at first could seem a classic requirement for a visual environment, was coupled with two additional requirements coming directly from the security operators' workflow: the first one, **Requirement RQ6**, requires to have the **capability to reduce the analysis only on the devices and/or business functions that present problems in terms of exposure and/or resilience**. The additional requirement, **Requirement RQ7**, asked instead for **positional stability of visual elements for the main visualizations, where the user needs to find the same information in the same part of the screen all the times she wants to access them**. The union of RQ6 and RQ7 asked for careful visual design choices that are discussed in Section 4.2, and led to the first release of the system. By a new meeting in which the system was presented, arose the final requirement, **Requirement RQ8, capability for the system to suggest possible mitigation plans, with the decision-maker having the final word on which actions to perform**. This requirement includes also the capability to conduct what-if analysis scenarios, in which the operator is able to simulate the effects of a mitigation action and eventually confirm it for real execution. This requirement was implemented and contributed to the final design of the system that is presented in the following section.

4.2 The BUCEPHALUS Visual Analytics environment

The user-centered design presented in the previous section led to a Visual Analytics environment subdivided into four panes (see Figure 1). The experts' need to monitor the cyber-exposure of the enterprise devices (**RQ3**) requires an explicit representation of the monitored network that is visible in the *Network Pane* (Figure 1A). This pane shows a node-link representation of the network topology on which the attack graph is projected. Homer et al. [20] present methodologies that can automatically identify portions of an attack graph that do not help a user to understand the core security problems and automatically group similar attack steps as virtual nodes in a model of the network topology, to immediately increase the understandability of the data.

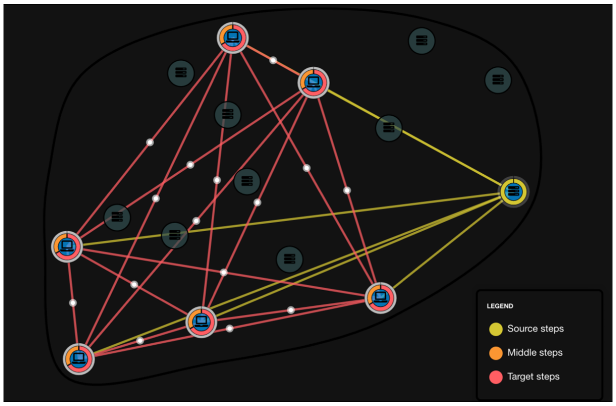


Figure 3: Detail of the *Network Pane* showing the attack graph projected on a node-link representation of the network topology. The color of the edges represents the type of step, yellow for the source step, orange for the middle step, and red for the target step. The nodes encode in the same way this information in a donuts chart showing the cardinality of attack paths in which the node is included.

We follow a similar approach for visualizing aggregations of attack paths, showing the different roles that the nodes play in the paths according to the encoding presented in Blasilli et al. [8] (see Figure 3). The background color of a node represents the higher privilege reached by all the attack paths involving that device: gray, blue, and purple stand for none, user and root privileges, respectively. The attack path proportions on nodes are shown with the internal donut chart: red color identifies the final step of an attack, yellow is used to identify attack paths source nodes, and orange represents every intermediate step. The external donut chart represents in gray the proportion of vulnerabilities of the node used by the current attack paths, while in blue the subset of them which can be used for performing privilege escalation.

The general requirement of a top-down approach for the analysis (**RQ5**), coupled with the need to relate the business functions and the devices that support them, calls for a hierarchical visualization that provides a high-level overview of the business functions attributes and gives the possibility to analyze on-demand their relations with the devices functioning. This requirement combined with the need for visual stability (**RQ7**) of the main visualizations led us to the creation of two different panes: the *Business Pane* (see Figure 1B) and the *Dependencies Pane* (see Figure 1C).

The *Business Pane* (see Figure 4) adopts a matrix-like representation in which the rows and the columns are the business functions. The matrix has two additional rows (the first two rows) that encode the exposure E (**RQ2**) and the resilience R (**RQ4**) of each business function, as defined in Section 3.3. In the first row, the color of the element encodes the exposure of the function; the element is encoded in blue when the exposure is below a configurable threshold (e.g., 0.05), otherwise it is colored according to a yellow-red color scale. The exposure of the functions does not consider their resilience to cyber-attacks. To convey this information, the second row shows the resilience level of each function through a bar-chart encoding. The height of the bar is proportional to the number of equivalent configurations that have an exposure below the threshold.

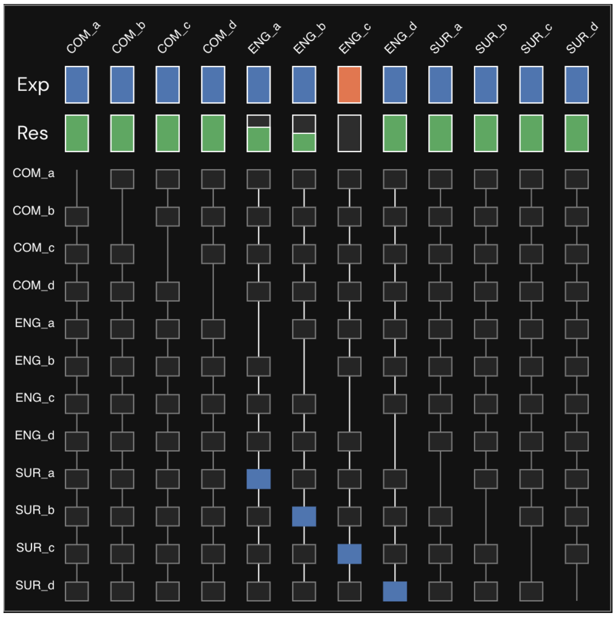


Figure 4: The *Business Pane* shows the exposure and resilience levels of the business functions and the dependencies between them. The first row shows the exposure *Exp* of each function, encoding in blue when the exposure is below a threshold (e.g., 0.05), otherwise it is colored according to a yellow-red color scale. The second row shows the resilience *Res* encoding the height of the bar proportionally to the number of equivalent configurations that have an exposure below the threshold. The rest of the matrix represents the dependencies between the functions.

While this part of the visualization provides an overview of the business functions status, it does not provide any details on the relationships between them (**RQ1**). The underlying matrix encodes the dependencies between the functions; for each column of the matrix, the cells of functions that support the function represented by column (through a logical AND) are colored according to their exposure. The visualization is enriched with vertical lines loosely inspired by UpSet [24] recalling how to interpret the dependency matrix: a line represents a logical AND among the elements that it traverses.

While this pane provides an overview of the business functions and their relations, it still not describes the dependency of the functions from their supporting devices (**RQ4**). By selecting a function from this pane, the *Dependencies Pane* is updated showing the dependencies of the selected function from the correct operation of the devices. Remembering how the Business Exposure model works (see Section 3), we represented the dependencies and equivalent configurations in a matrix-like view.

The matrix rows represent the devices that contribute to supporting the business function while each column represents one equivalent configuration (see Figure 5). An additional row is added on top of the matrix which encodes the maximum exposure of the devices on which the configuration depends. Being the configurations computed considering the availability of a single device for each OR group, their number is equal to the product of the cardinalities of the OR groups of devices leading potentially to a high number of configurations. The need to reduce the analysis only to the elements that present problems in terms of exposure (**RQ6**) is supported by a slider that allows reducing the number of rows and columns by excluding from the analysis the devices and the configurations with exposure below a threshold.

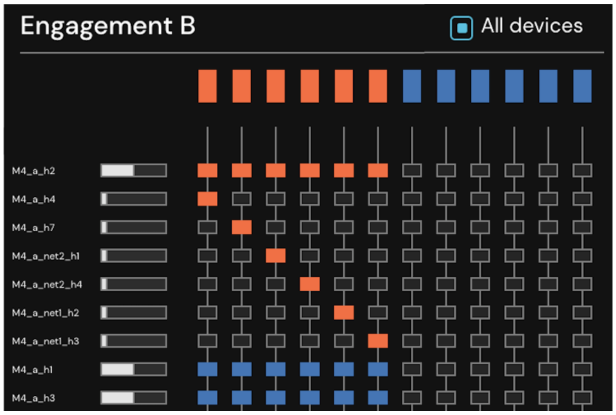


Figure 5: The *Dependencies Pane* showing the equivalent configurations supporting the correct working state of the selected business function, i.e., "Engagement B". In the matrix, rows represent devices and column equivalent configurations. Each cell represents the dependency of the configuration from the device, with the corresponding exposure level encoded. For each device an horizontal bar shows the number of configurations on which it takes part.

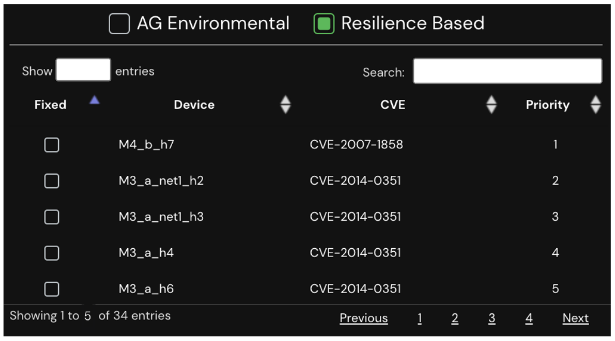
The analysis of the matrix (which has dense areas for non-redundant devices and sparse areas for redundant ones) is aided by a horizontal bar-chart aligned with the list of devices that encodes the number of configurations in which a device is present. Furthermore, the rows of the matrix are sortable according to the number of configurations on which the device occurs or to its level of exposure.

The selection of the devices in this pane is synced with the selection in the *Network Pane*; the analyst can, thus, identify devices of interest in one analysis (network-driven or business-driven) and see their role in the other one easily switching between them.

The presence of multiple configurations and the need to include multiple functions in the analysis can make it difficult to prioritize the devices according to their exposure or their contribution to the correct working of the function(s) (**RQ8**). The *What-if Analysis Pane* supports this task by presenting the list of device-vulnerability pairs that are present in the Attack Graph. The list is sortable according to two different strategies:

- **Attack Paths Based**: this mitigation strategy has been defined in VULNUS [1], as *AG Environmental Strategy*. It aims at reducing the number of attack paths considering only topological information. It considers the role that each device-vulnerability pair has in the attack paths. Pairs are ordered according to their number of presence in the attack paths. The first proposed vulnerability is the one that allows to interrupt the greatest number of attack paths, and so on.
- **Resilience Based**: this strategy prioritizes device-vulnerability pairs whose exploits play central roles for the resilience level

of the business functions. The aim of this strategy is to increase the resilience level of either all the business functions, or a subset of them which are chosen by the user. The strategy, by considering topological and business information of the functions suggests fixes that improve the resilience of the functions.



☐ AG Environmental ☑ Resilience Based

Show ☐ entries Search: ☐

Fixed	Device	CVE	Priority
☐	M4_b_h7	CVE-2007-1858	1
☐	M3_a_net1_h2	CVE-2014-0351	2
☐	M3_a_net1_h3	CVE-2014-0351	3
☐	M3_a_h4	CVE-2014-0351	4
☐	M3_a_h6	CVE-2014-0351	5

Showing 1 to 5 of 34 entries

Figure 6: The *What-if Analysis Pane* supports the analysis of the proposed fixing strategies. The analyst simulates the application of a fix by clicking on the toggle next to the vulnerability to fix. The other panes update showing the state that corresponding to the fix.

The analyst can analyze the impact of the fixing of one or more vulnerabilities by selecting them from the table and looking at their effect in the other panes. A video demonstration of `BUCEPHALUS` showing the described functionalities is available at `https://aware-diag-sapienza.github.io/BUCEPHALUS`

Table 1: `BUCEPHALUS` requirements coverage.

	Network Pane	Business Pane	Dependencies Pane	What-if Analysis Pane
RQ1		•		
RQ2		•		
RQ3	•			
RQ4		•	•	
RQ5	•	•	•	
RQ6			•	
RQ7	•	•	•	•
RQ8				•

5 USAGE SCENARIOS: THE MBDA ORGANIZATION

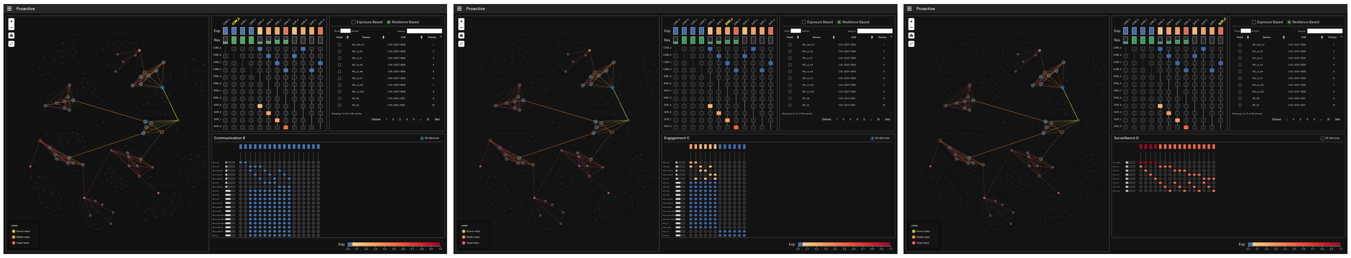
To show the added capabilities that visually assisted business-centric analysis provides with respect to classic cyber-exposure analysis, and to understand whether the proposed solution effectively covers the collected requirements, we tested our system on two usage scenarios. Those scenarios have been developed in conjunction with MBDA personnel and are modeled on one of their product. We remember that for "product" we mean a complex installation composed of multiple devices and business functions, interconnected among them. In the represented scenarios this installation is a weapon system, composed of 242 devices, 52 distinct vulnerabilities, and 12 business functions (belonging to three main classes, Surveillance, Engagement, Communication). In the first scenario, the proactive analysis of business functions resilience will be the core activity that the security analyst wants to execute, while the second scenario will focus on the difference between a global mitigation plan that takes into account only cyber-exposure aspects with respect to a mitigation plan that focuses on overall business functions resilience. Both plans are generated by our system and the security analyst can conduct a what-if analysis by testing several alternatives from them.

5.1 Scenario 1: Analysis of the resilience of a business function

The first usage scenario has the goal of allowing the security operator to explore the business functions' service level and their resilience with respect to potential cyber-threats. For service level we mean the business function exposure to cyber-threats, namely how probable is that the business function will be degraded if a cyber-threat occurs. She begins the analysis by looking at the top part of the *Business Pane* that reports information about aggregated exposure per business function and aggregated resilience level per business function. She is interested in identifying three types of conditions, presented in decreasing order of importance for inspecting anomalies:

- **Resilient business functions**: those are business functions that are working at the desired service level and that present a good level of resilience, meaning that not only they guarantee now the desired service level, but they are resilient (i.e., they exhibit redundancy) that helps them in guarantee the same service level even if under the effect of a cyber-threats;
- **Working business functions**: those are business functions that are guaranteeing the nominal service level, but that at the same time do not present an adequate resilience, meaning that a single cyber-threat can lower the desired service level;
- **Degraded business functions**: those are functions that present a degraded service level due to their exposure and lack of resilience, that lower their service level under a threshold defined by the Administrator. In this case, it becomes crucial to eliminate the causes for this degradation first, and then reason about resilience level afterward. The resilience level can be variable, depending on the number of equivalent configurations compromised by the cyber-exposure of the supporting devices.

The security operator is able to spot all three cases, as visible in Figure 7a for the first class, Figure 7b for the second and Figure 7c for the third class. She focuses on the function *SUR_d* (Surveillance d), which seems the most degraded and exposed at the same time. She first looks at inter-dependencies among business functions in the *Business Pane*. It is visible that the *SUR_d* function depends on the *COM_c* function. Given that the *COM_c* function is operating at its nominal conditions and it presents its maximum resilience, the security operator does not look at it as the cause of the degradation. She proceeds to explore the dependencies between the *SUR_d* function and its supporting devices in the *Dependencies Pane*. She spots (looking at the color-coding) that the device `M2_d_h20` plays a strong part in degrading the first four equivalent configurations. She then clicks on its label, and the *Network Pane* gets updated accordingly, to show the portion of the attack graph that includes this device. The device prsents a high number of vulnerabilities and cannot be restored easily. Additionally, its restoration cannot be enough to recover any equivalent configuration, given that it works in conjunction (AND rule) with `M2_d_h1`, `M2_d_h2`, `M2_d_h4` and `M2_d_h6` devices. The security operator then proceeds to other devices in order of their effect on resilience. She spots that the device `M2_d_h1` can be easily fixed, along with `M2_d_h7`, `M2_d_h21`, and `M2_d_h22`, given that they are all affected by CVE-2007-1858. Their combined fixes will result in three equivalent configurations restored, meaning that the business function could operate at a higher service level (due to lower exposure) and gain potentially a slighter higher resilience (we have three different equivalent configurations, but unfortunately all of them depends from the same device `M2_d_h1`). From the *What-if analysis Pane*, she simulates the fixes one by one, in an incremental way, to check the effects they have on the *SUR_d* exposure and resilience. The result is visible in Figure 8(left), where the function *SUR_d* shows a reduced exposure (light orange versus initial strong orange), but resilience is still not present. Considering promising the identified devices, the security operator continues inspecting them and she solves an additional vulnerability (CVE-2014-0351). At



(a) Business function COM_b: good service level and maximum resilience (b) Business function ENG_c: degraded service level, with a potential residual resilience to exploit (c) Business function SUR_d: completely degraded service level, with no resilience

Figure 7: Three different business functions, each of them representing an example from the three classes defined in scenario 1.

this time the *SUR_d* function has recovered the correct service level (reducing its exposure) and it presents a slight degree of resilience (different equivalent configurations can support its nominal service level), as visible in Figure 8(right). She can iterate on this workflow, exploiting the Business Exposure model information, to preserve the business functions service levels (reducing the exposure driven by business functions requirements) and increasing their resilience.

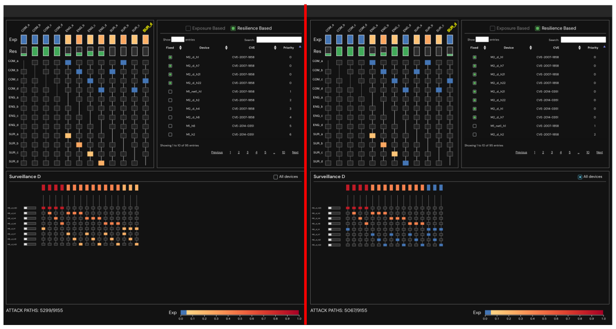


Figure 8: On the left is reported the intermediate fixing of business function *SUR_d*. It shows how exposure is reduced but resilience is still not present. On the right instead is reported the result at the end of the work. This time the business function has recovered its nominal working state and it presents a slight amount of resilience.

5.2 Scenario 2: Business driven mitigation strategies

The workflow described in usage scenario 1, while targeted at specific business functions behavior (i.e., in the case in which the operator clearly identified a subset of business functions to work on) can be a long activity to conduct. Otherwise, if she is interested in global optimization of the business exposure, she can rely on the what-if analysis capabilities provided by `BUCEPHALUS`. In this scenario, the goal of the analyst is to identify a suitable mitigation strategy to improve the security level of the installation. The high number of vulnerabilities and their spread in the network make it difficult to prioritize them. The analyst can thus be guided in the analysis by the strategies proposed in the *What-if Analysis Pane*. The first strategy, exposure-driven, focuses on the reduction of the exposure surface; it thus aims at reducing the number of attack paths with the minimum number of vulnerability fixings. The vulnerabilities are thus ordered according to the number of attack paths they enable. This strategy effectively reduces the number of attack paths: fixing the first five vulnerabilities drastically reduces the attack paths and contributes to improving the overall level of exposure and resilience (see Figure 9). This strategy is effective in reducing the exposure and improving the resilience of six business functions, i.e., *ENG_a*, *ENG_b*, *ENG_c*, *SUR_a*, *SUR_b*, *SUR_c*. However, this strategy does not impact the security level of the two business functions with the highest exposure, i.e., *ENG_d* and *SUR_d*. This is mainly because the contributions of the devices to the configurations that support the business functions are not taken into account. Vulnerabilities on devices that are compromised in few attack paths but that are essential to function resilience are therefore overlooked in favor of those that enable several attack paths, regardless of their impact on the overall exposure and resilience.

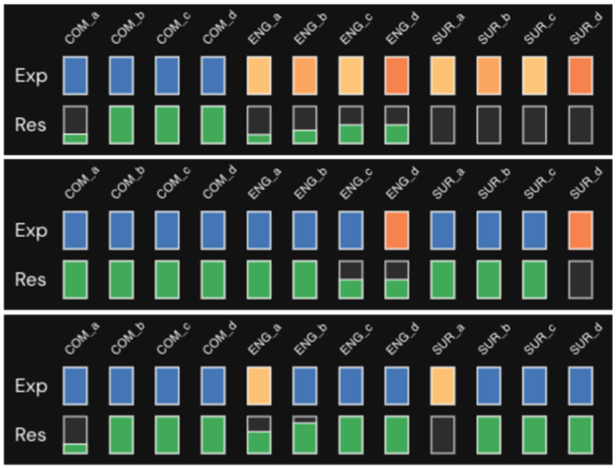


Figure 9: Details of the *Business Pane* showing the functions exposure and resilience levels in the initial scenario (top), after fixing the first 5 vulnerabilities proposed by the attack paths driven strategy (center), and by the resilience-driven strategy (bottom).

The second strategy, resilience-driven, conversely prioritizes the vulnerabilities according to their impact on resilience. By analyzing the first five vulnerabilities, we can see that play an essential role in the functions and their fixing is highly effective in improving the overall exposure and resilience levels (see Figure 9).

By mitigating two vulnerabilities on `M2_d_h21` and one vulnerability on `M1_h1`, `M1_h2`, `M1_h6`, five functions (*ENG_c*, *SUR_b*, *SUR_c*, and the two most exposed, *ENG_d* and *SUR_d*) recover the correct service level and their full resilience capabilities. *ENG_b* recovers the correct service level and its resilience significantly increases. *ENG_a* presents a slight decrease of the exposure and a slight increase of the resilience while *SUR_a* is not impacted.

The proposed fixing strategy may not be directly applicable due to external constraints, e.g., the absence of a patch, or the need to ensure the operation of a device. The analyst explores alternative solutions by selecting sub-optimal choices and evaluating their effectiveness. In this scenario, she may consider not possible to fix `M1_h1` and evaluates the effectiveness of alternative plans fixing `M1_h4`. Also this strategy has a significant impact on the business: it effectively restores the full capabilities of the two most exposed functions with

Fixed	Device	CVE	Priority
☑	M2_d_h20	CVE-2015-0395	0
☑	M2_d_h20	CVE-2015-0412	0
☑	M1_h4	CVE-2007-1858	0
☑	M1_h2	CVE-2007-1858	0
☑	M1_h6	CVE-2007-1858	0
☐	M1_h1	CVE-2007-1858	1
☐	M1_net1_h1	CVE-2007-1858	2
☐	M2_d_h2	CVE-2007-1858	3
☐	M2_d_h1	CVE-2007-1858	4
☐	M2_d_h4	CVE-2007-1858	5

Showing 1 to 10 of 95 entries

Figure 10: Exposure and resilience levels after the application of a sub-optimal strategy driven by the resilience having a slightly lesser increase in the overall security level with respect to the optimal one.

slightly less impact on the others (*ENG_b* and *SUR_b* in particular do not recover the correct service level), see Figure 10.

6 DISCUSSION

This paper explored the possibility of conducting proactive analysis of an organization's network driven by the business functions' service level and their resilience. This approach has the advantage to not only consider the effects that eventual cyber-threats can have on business functions but also introduce the capability to plan what additional actions can "move away" a business function from its possible degraded state, making it more resilient with respect to cyber-exposures. We achieve those analysis capabilities through the conjunction of two models, the classic attack graph for network exposure modeling, and the business dependency model for representing dependencies among business functions, obtaining the mapping of relations between the cyber-exposure status and the business functions. Through the use of Visual Analytics techniques we allow an analyst to explore the results of this new model (see Usage scenario 1), and to construct on top of it a recommender algorithm capable of computing effective planning for mitigating the exposure and raising the resilience and service level of business functions (see Usage scenario 2). This algorithm can be exploited to conduct what-if analysis.

Although the achieved results, some limitations exist that are coped currently or will be coped within the near future:

Comparison and evaluation of used features: As reported in Section 3, we used a classic network attack graph and a classic business dependency model to build the approach developed for `BUCEPHALUS`. Interestingly, using more sophisticated versions of those two models could potentially lead to additional parameters and derived features that could inform the business-centric analysis. More research could be conducted even on correlating those features in different situations and see which of them tend to go in accordance for both cyber-exposure and business-centric views, and which are more biased toward one of those perspectives;

Granularity of mitigation plans: The computed mitigation plans used in the *What-if analysis Pane* are computed at the highest possible granularity, namely a couple $< nodeID, vulnerability >$ according to the classic definition of a network attack graph. While this information is correct and helps in achieving the presented results, during our analysis we discovered that it could exist a second way of modeling this problem based on attack paths (ordered sequences of couples $< nodeID, vulnerability >$). We plan to add this functionality to `BUCEPHALUS`;

Exploration of attack paths based information: Apart from the computation of mitigation plans, even more interesting is the representation of this information in the *Business and Dependencies panes*, allowing the security operator to inspect causes of coupling equivalent configurations for a business function. We coped with this problem in the last part of this work and designed a visual solution integrated with the existing visual encoding, presented in Figure 11. This design can be integrated directly into the *Dependencies pane* , where equivalent configurations (c_i) are represented. It exploits the spaces existing between equivalent configurations to represent the degree of coupling that attack paths model. A column represents an equivalent configuration, while horizontal segments encode the number of attack paths that include devices coming from different configurations, effectively coupling them. The color encodes in both cases the degree of exposure. Looking at the different business functions, it is visible as f_3 is the most resilient function (it does not exist any attack path that includes devices from its equivalent configurations), f_4 is quite resilient but not perfect (it has exposure on its c_1, f_1 has effect from attack paths of length 2 that couples (c_1, c_2) and (c_2, c_3). Finally, for f_2 there exist also attack paths that couple all the equivalent configurations (c_1, c_2, c_3), meaning that if one of those attack paths effectively occurs the business function will be for sure degraded, without any resilience. By interacting with this chart (e.g., selecting one or more horizontal segments), the security operator could obtain the set of attack paths that, if mitigated, decouple two equivalent configurations, making the function more resilient. We are currently implementing this design in the system.

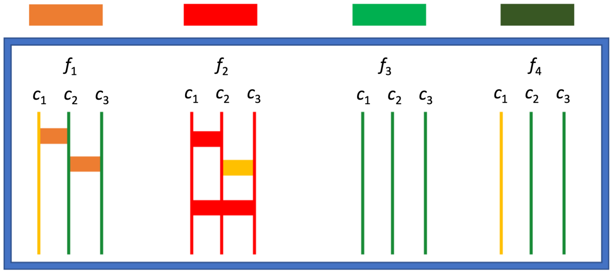


Figure 11: Exploring the relationship between attack paths and equivalent configurations of a function. Vertical lines represent equivalent configurations (c), while horizontal segments encode the number of attack paths that include nodes coming from different equivalent configurations, effectively coupling them. The color encodes in both cases the degree of exposure.

7 CONCLUSIONS AND FUTURE WORK

This paper presented `BUCEPHALUS`, developed within the collaboration between Sapienza University of Rome and the MBDA company. The system eases the analysis of the relationships among business functions, devices, and network vulnerabilities, visually providing an overview of dependencies and weaknesses. Moreover, the system supports the proactive hardening of the network through a what-if analysis scenario, in which the user is presented with an optimized order of vulnerability fixing, exploring the effect of sub-optimal strategies that satisfy business constraints. The system has been implemented through a user-centered design with MBDA professionals, producing eight requirements, whose visual implementation has been validated and tuned by the feedback provided by the experts involved in the process. Moreover, two usage scenarios provided a step-by-step validation of the implemented functionalities. As future work, we plan to extend this approach to reactive actions, i.e., to model the consequences of suitable mitigation actions in terms of business continuity and quality, and to design an automatic extension of `BUCEPHALUS` able to cope with a real cyber-attack, automatically triggering mitigation actions balancing the continuity, even if degraded, of the business functions with the lowering of the attack surface.

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