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Interactive Visualizations for Management of NFV-Enabled Networks

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"In the long run men only hit what they aim at. Therefore, though they should fail immediately, they had better aim at something high."

— HENRY DAVID THOREAU

ABSTRACT

Network Functions Virtualization (NFV) is driving a paradigm shift in telecommunications networks and computer networks, by fostering new business models and creating innovation opportunities. In NFV-enabled networks, service providers have the opportunity to build a business model where tenants can purchase Virtual Network Functions (VNFs) that provide distinct network services and functions (*e.g.,* Firewall, NAT, and transcoders). However, the amount of managed data grows in a fast pace. The network operator must understand and manipulate many data to effectively manage the network. To tackle this problem, we introduce VISION, a platform based on visualizations techniques to help network operators to determine the cause of not obvious problems. For this, we provide: (*i*) an approach to collect and organize data from the NFV environments; (*ii*) five distinct visualizations that can aid in NFV management tasks, such as in the process of identifying VNFs problems and planning of NFV-enabled businesses; and (*iii*) a template model that supports new visualization applications. To evaluate our work, we implemented a prototype of VISION platform and each of the proposed visualizations. We then conducted distinct case studies to provide evidence of the feasibility of our visualizations. These case studies cover different scenarios, such as the identification of misplacement of VNFs that are generating bottlenecks in a forwarding graph and the investigation of investment priorities to supply tenants demands. Finally, we present a usability evaluation with network operators to indicate the benefits of the VISION platform. The results obtained show that our visualizations allow the operator to access relevant information and have insights to identify not obvious problems in the context of NFV-enabled networks. In addition, we received positive feedback about general usability aspects related to our prototype.

Keywords: Network Functions Virtualization. Network Management. Information Visualization.

Visualizações Interativas para Gerenciamento de Funções de Rede Virtualizadas

RESUMO

A Virtualização de Funções de Rede (Network Functions Virtualization - NFV) está mudando o paradigma das redes de telecomunicações. Esta nova tecnologia permite diversas oportunidades de inovações e possibilita o desenvolvimento de novos modelos de negócio. Em relação às redes NFV, os provedores de serviços têm a oportunidade de criar modelos de negócio que permitam aos clientes contratarem Funções de Rede Virtualizadas (Virtual Network Functions - VNFs) que proveem diferentes serviços de rede (*e.g.,* Firewall, NAT e transcoders). Porém, nestes modelos, a quantidade de informações a serem gerenciadas cresce rapidamente. Baseado nisso, os operadores de rede devem ser capazes de entender e manipular uma grande quantidade de informação para gerenciar, de forma efetiva, as redes NFV. Para enfrentar esse problema, introduzimos uma plataforma de visualização denominada VISION, a qual tem como principal objetivo ajudar os operadores de rede na identificação da causa raiz de problemas em NFV. Para isso, propusemos: (*i*) uma abordagem para coleta e organização de dados do ambiente NFV gerenciado; (*ii*) cinco diferentes visualizações que auxiliam nas tarefas de gerenciamento de NFV como, por exemplo, no processo de identificação de problemas em VNFs e no planejamento de negócios e (*iii*) um modelo baseado em templates que suporta o desenvolvimento e o reuso de visualizações. Para fins de avaliação desta dissertação, foi desenvolvido um protótipo da plataforma VISION e de todas as visualizações propostas. Após, conduzimos um conjunto de casos de estudo para prover evidências sobre a viabilidade e utilidade de nossas visualizações. Os diferentes casos analisados, abordam por exemplo, a identificação de problemas na alocação de VNFs que estão impactando no desempenho do serviço oferecido e também na investigação de prioridades de investimento para suprir as demandas dos clientes da rede. Por fim, apresentamos uma avaliação de usabilidade realizada juntamente a especialistas em redes de computadores para avaliar os recursos e benefícios da plataforma VISION. Os resultados obtidos demonstram que nossas visualizações possibilitam ao operador de rede um rápido e fácil acesso às informações importantes para o gerenciamento de redes NFV, assim facilitando a obtenção de insights para a identificação de problemas complexos no contexto de redes NFV. Além disso, os resultados demonstram uma avaliação positiva por especialistas sobre os aspectos gerais de usabilidade do protótipo desenvolvido.
Keywords: Funções de Rede Virtualizadas. Gerenciamento de Rede. Visualização de Informações.

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LIST OF ABBREVIATIONS AND ACRONYMS

AJAX	*Asynchronous Javascript and XML*
CAPEX	*Capital Expenditure*
COTS	*Commercial Of-The-Shelf*
CPU	*Central Processing Unit*
DHCP	*Dynamic Host Configuration Protocol*
DPI	*Deep Packet Inspection*
ETSI	*European Telecommunications Standards Institute*
FG	*Forwarding Graph*
InfoVis	*Information Visualization*
ISG	*Industry Specification Group*
MANO	*NFV Management and Orchestration*
MVT	*Model-View-Template*
NAT	*Network Address Translator*
NetApp	*Network Application*
NFV	*Network Functions Virtualization*
NFVI	*Network Functions Virtualization Infrastructure*
NFVO	*Network Functions Virtualization Orchestration*
NGN	*Next Generation Networks*
NS	*Network Service*
NSD	*Network Service Descriptor*
OPEX	*Operational Expenditure*
PVN	*Programmable Virtual Networks*
SDN	*Software-Defined Networking*
SLA	*Service Level Agreement*
SP	*Service Provider*
VDU	*Virtual Deployment Unit*

VIM	*Virtual Infrastructure Manager*
VNF	*Virtual Network Function*
VNFM	*Virtual Network Function Manager*
VNF-FG	*VNF Forwarding Graph*
VNFaaS	*Virtual Network Function as a Service*
VNFD	*Virtual Network Function Descriptor*
XML	*Extensible Markup Language*

CONTENTS

1 INTRODUCTION

For many years, the service provision in the telecommunications industry has traditionally been based on deploying physical proprietary equipment. Network Functions Virtualization (NFV) has emerged as a part of an overall shift in the industry that has changed the networking landscape by fostering new business models and creating opportunities for innovation (LU et al., 2015). NFV moves packet processing from dedicated hardware middleboxes for Virtual Network Functions (VNFs) running on virtual machines hosted on commercial off-the-shelf servers (ETSI, 2012). NFV benefits include the ability to speed up service delivery and simplified network operations while reducing Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). By adopting this concept, network operators can readily deploy and configure network services to offer solutions for different customers profiles, and thus support the requirements of multiple tenants. This means that the operator can scale network services according to tenants' requirements by ensuring technical feasibility and business opportunities while making network innovations.

In NFV-enabled networks, Service Providers (SPs) have the opportunity to design a business model where tenants can purchase VNFs that provide distinct network services and functions (XILOURIS et al., 2015). For example, one tenant purchases VNFs (*e.g.,* a firewall and load balancer) that provide different services that meet dynamic customer demands. This model benefits tenants (*e.g.,* by reducing capital/operational expenditures and easing the contract of new services) while increasing the revenue of the SPs. In addition, NFV allows a simplified service chaining to ensure the chaining of different VNFs to supply network demands. This chainning is defined by the European Telecommunications Standards Institute (ETSI) as a forwarding graph (FG) for VNFs that are interconnected within the virtual network infrastructure (ETSI GS NFV, 2013). This forwarding graph simplifies the representation of the service chaining, and allows the operator to carry out daily tasks quickly, such as creating and modifying packets flows along VNFs, deploying new VNFs, and undertaking maintenance tasks.

1.1 Problem and Motivation

Despite all the benefits outlined above, the management of NFV-enabled networks requires operators to have a broad understanding of the environment. In fact, the management of NFV environments is a challenging task in itself because of the huge amount of data available, which includes several VNFs migrations that occur in the environment, dynamic resource allocation, and information about VNFs and the requirements of tenants. As well as this, there is key information from the physical infrastructure that requires attention (*e.g.,* memory, CPU core, and available bandwidth). As a result, the operator must take account of a great deal of information so as to be able to effectively address disguised problems that may occur while a VNF is running. In summary, the operator has to understand four important aspects of NFV management:

- Service infrastructure requirements, which rely on the available virtual and physical resources;
- The consumer profiles of tenants, which make it possible to understand and predict network usage;
- Affinities and conflicts resolutions between VNFs and the choice of hardwares to determine the best place to run a service; and
- The inherent features of VNFs, such as resources contracted by tenants and the number of packets being processed.

This information is hard to understand by using traditional management tools (*e.g.,* SNMP-based solutions) because they cannot deal with all aspects of NFV, such as providing information to enable the network operator to appreciate the need to change VNFs configurations, invest in infrastructure, and carry out migrations policies. In addition, networks with most complex technologies (*e.g.,* NFV and SDN) tend to be more disruptive than traditional networks. For this reason, NFV-enabled networks require specific tools and strategies to ensure high-quality services for customers and the business health of the SP.

When tackling this network complexity, Information Visualization can be a viable tool for network operators to investigate not so obvious problems in NFV-enabled networks. The benefits of Information Visualization for NFV management are (*i*) it provides a clarification of tenant demands, (*ii*) a rapid way of detecting bottlenecks in forwarding graphs, and (*iii*) a simplified analysis of resources usage. Visualization techniques are likely to help the operator to make decisions that avoid service degradation as well as adapting services to market trends. However, despite these potential applications and benefits, there is still a lack of visualization solutions in the context of NFV (GUIMARAES et al., 2016). In our view, this lack of mature studies in the area reduces the capacity of network operators to make appropriate decisions, and may even hinder the adoption of new technologies (MIJUMBI et al., 2016a).

1.2 Main Goals and Contributions

In this dissertation, we investigate a visualization solution that can assist network operators and vendors in the management of NFV-enabled networks. We believe that visualization can be a powerful tool for the purposes of this work. For this reason, as our main contribution we propose a platform that support and implements a set of interactive visualization techniques. These visualizations assist network operators in identifying the cause of disguised VNF problems and enables them to plan NFV business strategies that can be adopted in a competitive market. Moreover, our visualization platform is designed to obtain data from a wide range of sources (*e.g.,* management frameworks and environmental monitoring systems). To sum up, the contributions of this research can be outlined as follows:

- The collection, processing, and storage of useful information from the NFV environment;

- Visualizations to identify problems that have an adverse effect on the VNF's performance;
- Visualizations that make it possible to look for behavioral patterns, which can assist, for example, in determining affinity problems among VNFs; and
- Visualizations for SPs that, on the basis of NFV, can enable a business to be planned more effectively.

Another contribution of this work is to provide a solution that supports new visualization applications. The network operator can reuse the modules and visualizations available on VISION to create new visualizations. For example, a developer can implement visualizations on the Web-based interface of VISION and use the data layer modules to obtain and access information. Accordingly, the platform is responsible for collecting and processing the data from the environment, and hence allows the developer to build new visualizations techniques for NFV management. In addition, the modular implementation of VISION allows operators to offer their own version of the data collector and supply VISION with new information from sources that were not initially mapped.

1.3 Document Outline

This dissertation is organized as follows. In Chapter II, we review related works and outline the background of this work. In Chapter III, we introduce the VISION platform and describe all of its modules. In Chapter IV, we present five visualization techniques, which are employed to address the question of NFV management. In Chapter V, six case studies are conducted together with a usability evaluation to provide evidence of the effectiveness and feasibility of our visualizations. Finally, in Section VI, we conclude the work and make suggestions for future work.

2 BACKGROUND AND STATE-OF-THE-ART

This chapter provides an overview of the main elements and concepts involved in our visualization solution for NFV management. In Section 2.1, we set out the main concepts of NFV and describe its architecture. Subsection 2.1.1 provides an overview of the NFV service chaining and introduces the concept of a forwarding graph. Next, in Subsection 2.1.2, we establish the framework (MANO framework) that is needed to manage and orchestrate NFV environments. Subsection 2.1.3 examines two file descriptors which contain relevant information for the deployment and management of VNFs. In Section 2.2, there is a brief overview of Information Visualization techniques and a discussion of typical visualization applications for network management. Finally, in Section 2.3, we review the studies that are most relevant to the management and planning of new technologies, mainly focus on those that make use of Information Visualization to assist the network operators in their daily tasks.

2.1 Network Functions Virtualization

In 2012, the Industry Specification Group (ISG), under the auspices of the European Telecommunications Standards Institute (ETSI), published the Network Functions Virtualization (NFV) architectural framework. The aim of this new paradigm was to transform the way that network operators design and manage networks by employing virtualization technology to consolidate a good deal of traditional network equipment onto industry standard servers (ETSI NFV ISG, 2012). By decoupling packet processing from dedicated hardware middleboxes for Virtual Network Functions (VNFs) running on commercial off-the-shelf (COTS) servers, NFV enhances the flexibility of network service provisioning and reduces the time needed for service deployment. Thus, NFV seeks to introduce innovation in the network core, and hence transform the carrier networks.

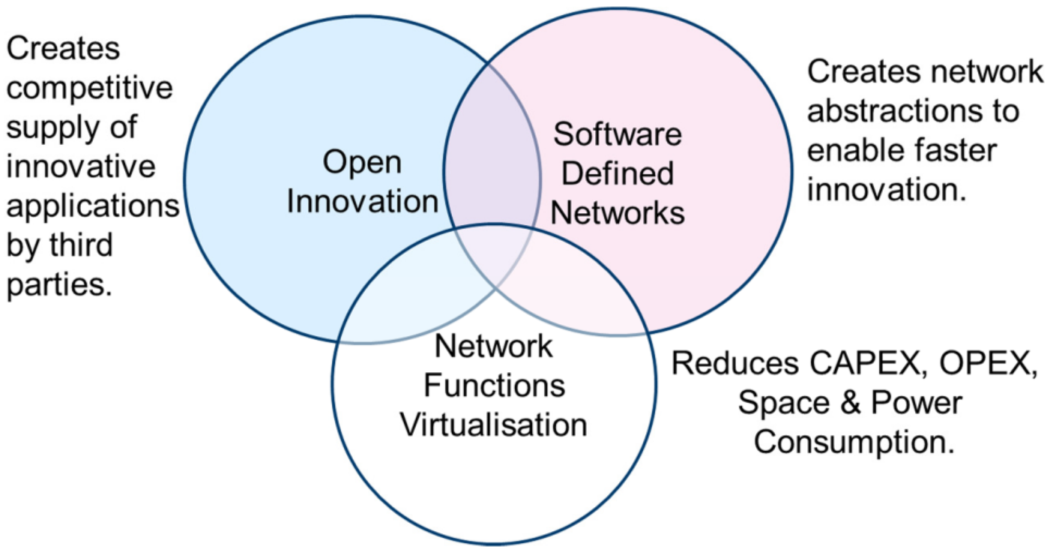
One of the most important features of NFV environment is the Virtual Network Function (VNF), which represents the implementation of a network function (*e.g.,* firewall, NAT, and transcoders) by means of software that is decoupled from the underlying hardware. These VNFs can be chained in a forwarding graph (as explained in Subsection 2.1.1) to define end-to-end network services consisting of distinct network functions. In summary, the main benefits of NFV is that it can virtualize network services and thus enable operators to:

- **Deliver Agility and Flexibility:** NFV allows an easy and quickly method to scale up and scale out services that can meet high dynamic demands; it can thus offer technical feasibility and potential opportunities while increasing the amount of network innovation.
- **Accelerate Time-To-Market:** by reducing the time needed to deploy new networking services, NFV offers new business opportunities and improve return on investment of new services.
- **Reduce costs:** NFV influences capital expenditure (CAPEX) by reducing the need to pur-

chase purpose-built hardware and supporting adaptive models to contract more resources. Another factor is that, the operational expenditure (OPEX) is low because it is possible to reduce the physical requirements of equipment (*e.g.,* space, power, and cooling) and simplify the management of network services.

Furthermore, NFV can be applicable in any data plane for packet processing and control plane function since it can provide different services and solutions, such as traffic analysis, virus scanners, SLA monitoring, and Cache Servers. In addition, by supporting multi-tenancy, NFV allows the network operators to provide customized services which can meet the requirements of different tenants. According to the description given by ETSI, NFV is closely linked to (but not dependent on) Software Defined Networking (SDN). The two concepts can be combined to improve its capacity to create competitive and innovative applications. The network community understands that NFV goals can be achieved by means of non-SDN mechanisms, but the approaches that seek to separate the control from the data forwarding plane (*i.e.,* SDN) can provide a better performance with simplified deployments, and help in the operation and maintenance tasks. Figure 2.1 shows a diagram that gives examples of the relationship and collaboration between SDN and NFV.

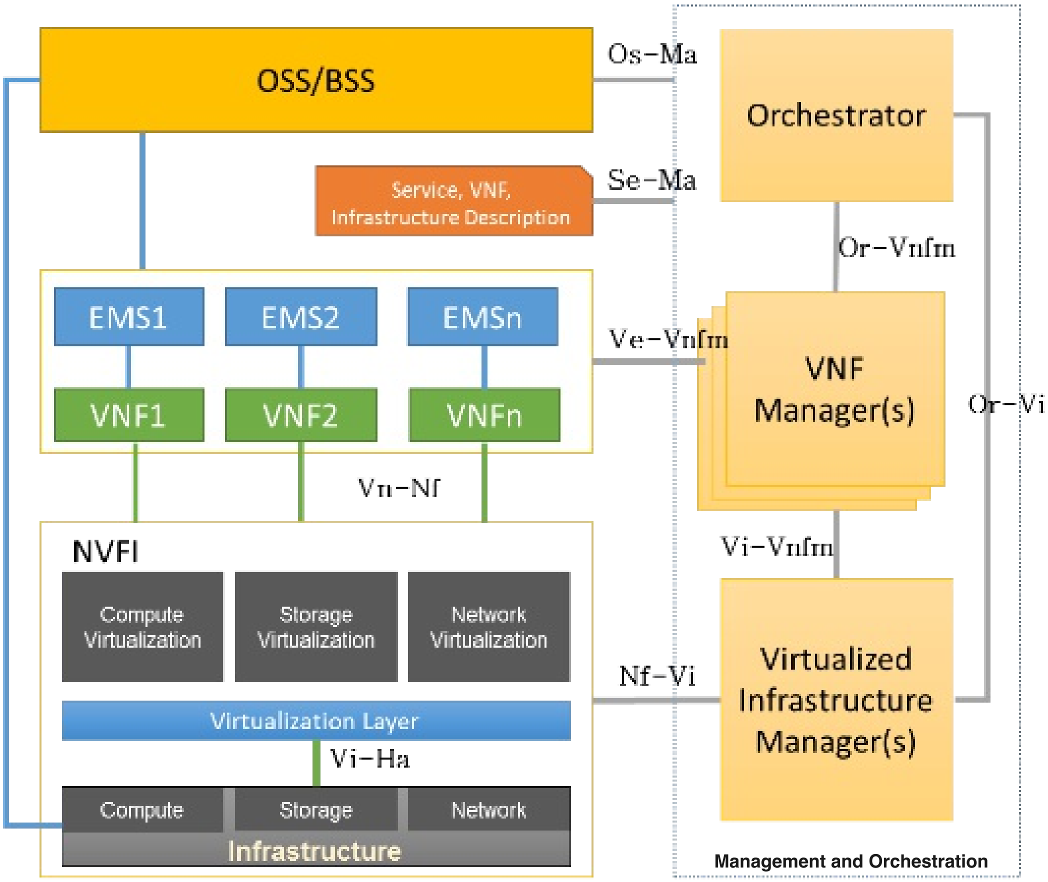
Figure 2.1: Relationship between Network Functions Virtualization and Software-Defined Networking



Source: ETSI NFV ISG (2012).

The NFV framework allows the dynamic construction and management of VNF instances and established relationships between data, dependencies, and management. This architectural framework is employed for the changes that occur in network management and operation due to the network function virtualization process. For this reason, the framework highlights new functional blocks and features which include computing, networking, storage, and virtual machine resources. Figure 2.2 shows the NFV architectural framework that includes the functional blocks and reference points. As can been seen, a generic NFV environment contains the following components: *(i)* Network Function Virtualization Infrastructure (NFVI), which enables the software to run independently of the hardware, *(ii)* Virtualized Network Functions (VNFs) that move network functions from dedicated hardware devices to software hosted on COTS servers; and *(iii)* NFV Management & Orchestration (MANO), which has three components to monitor and configure the NFV environment: Virtualized Infrastructure Manager (VIM), VNF Manager, and Orchestrator.

Figure 2.2: The NFV architectural framework



Source: ETSI NFV ISG (2012).

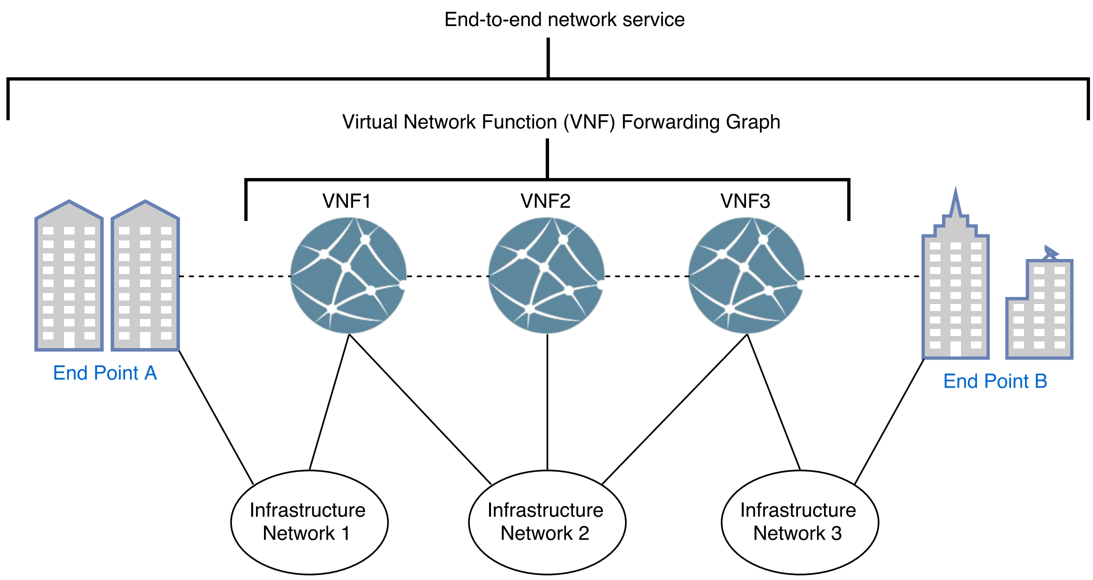
The NFVI represents all of hardware and software components that build up the environment in which the VNFs are deployed, managed and executed. The virtualization layer is responsible for abstracting the hardware resources and decouples the VNF software from the underlying hardware, and hence ensures an independent life-cycle for the VNFs. In addition, the Element Management System (EMS) performs the common management functionality for each VNF. All of these components are combined with existing Operations Support Systems and Business Support Systems (OSS/BSS). The rest of the management components (*i.e.,* VIM, VNF Manager, and Orchestrator) will be described in Subsection 2.1.2 as a part of the MANO Framework.

Although NFV is a promising solution for telecommunications service providers, it faces particular challenges that involve key factors such as security, computing performance, service chaining, and efficient management. To address these challenges, there are several IT organizations (*e.g.,* Telefónica and Red Hat) and academic researchers working together to improve the capacity to deploy and manage NFV environments (BARI et al., 2015). One example of this joint endeavor is the Open Source MANO (OSM), which is an ETSI-hosted project aimed at providing an open-source approach to management and orchestration of NFV (ETSI OSM, 2016). Currently, the OSM project contains 23 members and 24 participants from different countries and sectors of industry.

2.1.1 VNF Forwarding Graph

The VNF Forwarding Graph (VNF-FG) represents the chaining of different VNFs to provide a service where network connectivity really matters. In other words, a VNF-FG provides the logical connectivity between VNFs. On this basis, the SPs can take advantage of forwarding graphs to chain VNFs and provide customized network services to meet individual client demands. For instance, the SP can offer a web server tier that contains three VNFs to deal with the customer traffic: a firewall, NAT and load balancer. Figure 2.3 shows a forwarding graph that contains three VNFs to provide a service between two end points.

Figure 2.3: Graphic representation of an end-to-end network service



Source: the author (2017).

In Figure 2.3, there is an end point A that communicates with an endpoint B through a network connectivity. The network functions VNF1, VNF2 and VNF3 are virtualized into the available infrastructure and compound the forwarding graph between end point A and B. This means that the VNF-FG ensures that all of the traffic from A to B must be forwarded and processed first by the VNF1 followed by VNF2 and then VNF3. Three main benefits of the VNF-FG are worth highlighting: ease project of VNFs, an improved capacity to share resources between VNFs, and reduced period of time to deploy and configure new VNFs. Thus, this simplified representation of service chaining enables network operators and SPs to deal with the dynamic demands of tenants and provide customized services.

2.1.2 NFV Management and Orchestration (MANO) Framework

The MANO framework is described by ETSI as a standard for management and orchestration of NFV (ETSI GS NFV-MAN, 2014) and consists of three components: Virtual Infrastructure Manager (VIM), NFV Orchestrator (NFVO), and VNF Manager (VNFM). As well as this, there are four data repositories available: NS catalog, VNF catalog, NFV instances, and NFVI resources. In this subsection, we examine each of these components in detail and provide an overview of the data repositories together with the main projects that are related to the NFV MANO framework.

- **VIM:** This component monitors and controls the computing, storage, and networking resources of a single NFVI domain. According to the ETSI specifications, an NFV architecture may contain more than one VIM, which each of them monitoring and controlling resources from a given infrastructure provider.
- **VNFM:** Each VNF instance is associated with a VNFM which is responsible for the management of the life-cycle of VNFs. A VNFM performs several VNFs operations, such as the deployment and migrations of VNFs. In addition, this manager stores information about configuration and VNFs events in data repositories (*e.g.,* warnings of SLA disruptions).
- **NFVO:** The NFVO is responsible for the resource and service orchestration. The orchestrator carries out the global resource management, validation, and authorization of NFVI resource requests. As well as this, this component addresses the problem of creating end-to-end services by composing different VNFs (service chaining) and managing the topology of the network service instances.
- **Data Repositories:** The NFV MANO has databases to store different types of information. The NS catalog defines how services may be created and deployed. The VNF catalog describes the deployment and operational features of each VNF. The repository of NFV instances contains information about the lifetime of the VNF. Finally, The NFVI resources repository stores information about NFVI resource allocation.

There are a number of projects that implements the NFV MANO framework. Some of the key projects can be listed as follows: *(i)* OpenMANO, which is a part of OSM project that aims to implement the MANO; *(ii)* OpenNFV, which is an NFV platform developed by HP enterprise and leverages open-source technology to provide an end-to-end NFV and SDN infrastructure;

(iii) OPNFV, which is hosted by Linux Foundation and seeks to establish a platform that allows multi-vendor interoperable NFV solutions; *(iv)* Cisco's Open Network (OPN), a solution that aims at providing implementations for some of the components of the MANO framework; and *(v)* ZOOM, a platform that enables the deployment of services by automating the provisioning process. The main features of these projects that are related to NFV MANO are shown in Table 2.1. This makes clear which MANO components are covered by each project.

Table 2.1: Projects related to the NFV MANO framework

-	General Information			MANO Components			
Project	**Developer**	**Provides API**	**Product Dependency**	**VIM**	**VNFM**	**NFVO**	**Data Repositories**
OpenMANO	Telefónica	Yes	Doest not require a specific product to work	Yes	No	Yes	No
OpenNFV	HPE	Yes	HP Helion OpenStack Carrier Grade and HP NFV director	Yes	Yes	Yes	Yes
OPNFV	Linux Foundation	Yes	Does not require a specific product to work	Yes	No	No	No
OPN	Cisco	Yes	SDN Overly Controller	Yes	Yes	Yes	No
ZOOM	TM Forum	Yes	Does not require a specific product to work	Yes	Yes	Yes	Yes

Source: the author (2017).

Table 2.1 shows that some projects do not provide all of the MANO components. For example, the OpenMANO does not implement the VNFM and the OPNFV does not provide an NFVO. However, this should not be regarded as a limitation because projects are not dependent on specific implementations or products. This means that service providers can combine other solutions to obtain a complete implementation of NFV MANO (*e.g.,* by integrating a commercial NFVO with the OPNFV). On the other hand, some of the available implementations are dependent on products, such as the OpenNFV which require an HP NFV Director (implementation for NFVO) and HP Helion Open-Stack Carrier Grade (correspond to VIM) to be implanted. It can also be noted that all of the projects provides well-defined APIs that describe northbound interfaces that can provide communication with MANO components. These APIs assist in the integration of new management tools and NFV solutions.

The MANO framework is of crucial importance to understand and manage the NFV environment. The vast amount of information managed by MANO, for example, can be accessed by management tools via API to obtain information from the NFV environment that supports network operator activities. Moreover, the MANO components carry out critical operations for the health of an NFV environment, for example, the orchestrator makes dynamic migrations of VNFs and VNFM can issue an alert when an operational problem is detected in a particular VNF. Thus, MANO increases the capacity to deploy and configure VNFs, by allowing new solutions to be found that can help service providers to adopt NFV and explore the opportunities offered by NFV-enabled networks.

2.1.3 Network Function Descriptors

The ETSI defines two structures containing information about how to describe the network services and VNFs: Network Service Descriptor (NSD) and VNF Descriptor (VNFD). These structures (*i.e.,* descriptors) are used to stipulate the main properties that define VNFs and how they will be deployed in the network.

The NSD consists of static information that is used by the NFVO to instantiate a service. This descriptor contains information about the network service vendor and specific information used to deploy VNFs, such as a textual representation of a VNF-FG and the dependencies between VNFs. In addition, the NSD also describes the deployment flavors of a network service (*e.g.,* gold flavors will have more memory available).

The VNFD describes a VNF with regard to its deployment and operational requirements. This descriptor is used by NFV MANO to establish appropriate virtual links within the NFVI. In addition, it describes VNF behavior over a period of time and provides information about VNF management, such as the parameters that need to be monitored and the flavors that describe the resource requirements and performance that is predicted by contracting a single VNF. Table 2.2 shows a list of the basic elements that comprise the VNFD. Note that this information is only the minimum subset needed to describe the VNFD.

Table 2.2: VNFD base information elements

Information	**Description**
Id	ID of this VNFD
vendor	The vendor generating this VNFD
descriptor_version	Version of the VNF Descriptor
version	Version of VNF software
vdu	Describes a set of elements related to a particular VDU
virtual_link	Represents the type of connectivity between Connection Points
connection_point	Describes an external interface
lifecycle_event	Defines VNF functional scripts/workflows for specific life-cycle events
dependency	Describes the dependencies between VDUs
monitoring_parameter	Monitoring parameters which can be tracked for this VNF
deployment_flavour	Represents the assurance parameters and its requirements for each VNF
auto_scale_policy	Represents the metadata policy
manifest_file	The VNF package may contain a file that lists all the files in the package
manifest_file_security	Contains a digest of each file that it lists as part of the package

Source: ETSI GS NFV-MAN (2014).

These descriptors are often used to define templates that describe how to deploy and run VNFs. All the information provided by each of the descriptors is stored in the MANO data repositories. The NSDs, which describe network services, form a part of the NS Catalog and a VNFD for each type of VNF is stored in the VNF Catalog. This stored information contains valuable information about configurations and the expected behavior of VNFs that compound the services in the NFV environment.

2.2 Information Visualization and Typical Applications for Network Management

Information Visualization (InfoVis) is the communication of abstract data via the use of interactive visual interfaces, and is based on interactive visual representations to reinforce human cognition, and hence enable people to acquire knowledge about the data and its relationships (KEIM et al., 2006). The main goal of InfoVis is to design applications which can help people to carry out cognitive work more efficiently. One of the greatest benefits of this is that it simplifies the representation of data and thus allows it to be interpreted quickly by people. This means that they can use visualizations because these techniques help them to solve problems faster and more effectively. With regard to the primary goals and benefits, Information Visualization (WARE, 2013):

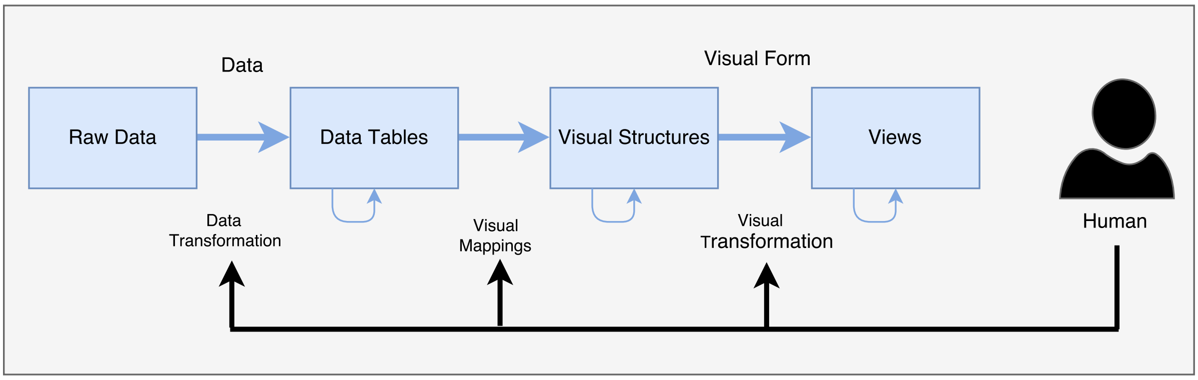
- Makes it possible to understand huge amounts of data;
- Allows people to be aware of emerging properties that were not anticipated;
- Enables problems regarding the data to become immediately apparent;
- Makes both large-scale and small-scale features of the data more comprehensible; and
- Makes it easier to theorize

The process of data visualization follows some basic stages, which are combined with some feedback loops. First, there is the stage that involves collection and storage of data. Second, a preprocessing stage is designed to transform the data into something easier to manipulate. Next, the computer algorithms map the selected data to a visual representation displayed on the screen. Finally, the human perceptual and cognitive system is able to interpret the visualization. This visualization process flow can be viewed in Figure 2.4.

In recent years, Information Visualization has been applied in diverse areas of knowledge (ISENBERG et al., 2017) to help humans understand data and, hence, solve problems. There are several visualization techniques in the literature that deal with different types of data, for example, graph visualization (HERMAN; MELANCON; MARSHALL, 2000) that is applicable when there is an inherent relationship between the data elements that need to be visualized, and highlighting techniques (LIANG; HUANG, 2010) which are often employed to attract the attention of users when reading visualizations (*e.g.,* making changes in light, shape and size of objects).

InfoVis has also been able to cooperate with network operators, particularly, when monitor-

Figure 2.4: Flow of visualization process



Source: CARD; MACKINLAY; SHNEIDERMAN (1999).

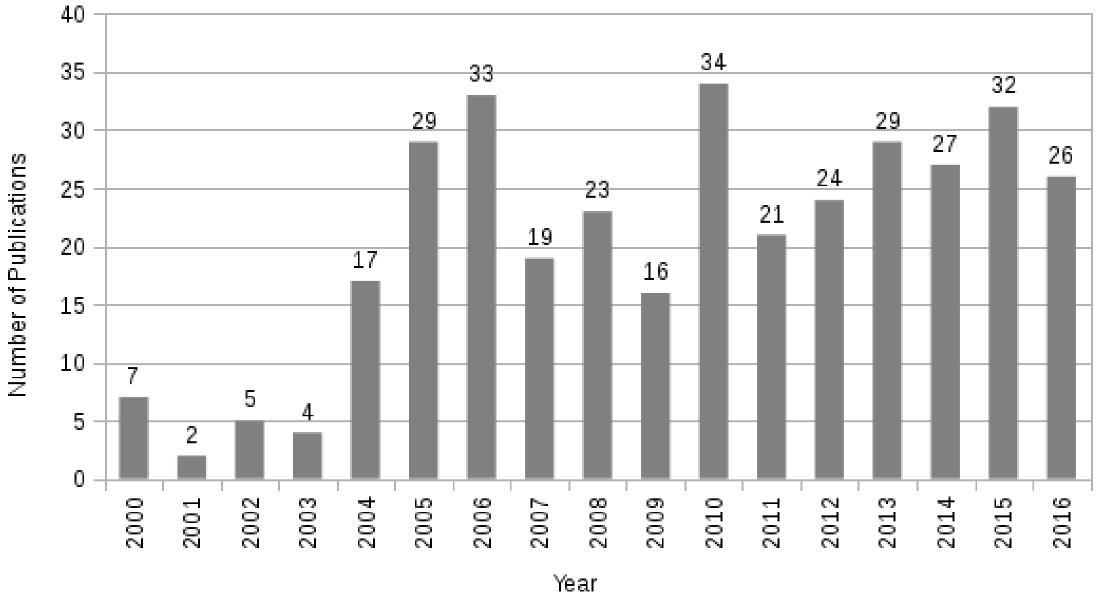
ing and analyzing the data so as to understand the network behavior and make correct decisions. For example, the operators can use visualizations to investigate network topologies, analyze a significant amount of measured data, and understand the reason for a high-volume of traffic flows. This collaboration between areas increases as the technology evolves and adds to the complexity of network management by introducing a huge amount of new data from several end-users and services. The traditional management tools are unable to deal with the nuances and data introduced by the adoption of new network technologies (*e.g.,* SDN and NFV); in view of this, there is a need for an upgrading of current solutions and adoption of new approaches to meet the requirements of management. Figure 2.5 shows a timeline with the number of publications that address network management problems using visualizations in the past few years.

It is clear that the number of visualizations in the field of network management are more evident from 2004 onwards. This increase in the number of publications is a result of efforts by local communities to use visualizations for a better understanding of security issues in heterogeneous scenarios. Most of the current works focus on network security management, which is a current research area where there is a large amount of data (*e.g.,* log files from distinct services and applications) and relationships undergoing analysis. If we analyze the papers about network management published in the main visualization conferences (*e.g.,* IEEE InfoVis and ACM SIGGRAPH) in recent years, nearly 78% are about security management (GUIMARAES et al., 2016).

Despite the large amount of contributions by the security community, there are other useful applications in all of the network management functional areas. In the area of industry, for example, there are some players in the cloud computing market (*e.g.,* Amazon Web Services (AWS)[1] and Microsoft Azure[2]) that use Information Visualization to help customers configure and monitor the contracted services related to the network. In Table 2.3, there is a summary

[1]https://aws.amazon.com
[2]https://azure.microsoft.com

Figure 2.5: Timeline of visualization publications in network management area



Source: GUIMARAES et al. (2016).

of the typical applications of InfoVis for network management. This includes an overview of the main InfoVis applications in functional areas and indicates the existence of works in the literature. In addition, we provide examples of visualizations that are related to each of the functional areas of network management.

	General Information		Typical Applications	
Functional Area	Frequency of Publications	Current Technologies	Example	Visualization Overview
Accounting	Rare	IP networks	(MINARIK; DYMACEK, 2008) proposes a visualization tool to display network traffic in a way that helps operators to undertand and define accounting policies	Graph-based visualization that supports the data overview, with on-demand details, and filters
Accounting	Rare	IP networks	(MINARIK; DYMACEK, 2008) proposes a visualization tool to display network traffic in a way that help operators to undertand and define accounting policies	Graph-based visualization that supports the data overview, on-demand details, and filters
Configuration	Few	IP and mobile networks	(HIMURA; YASUDA, 2013) uses visualization techniques to validate configurations of network devices before deployment in multi-tenant datacenters	Graph-based visualization that only supports the data overview
Event	Few	IP networks	(T. Takada and H. Koike, 2002) provides a tool that integrates the statistical analysis and visualizations to inspect log messages of events	Customized visualizations that support overview, on-demand details, and filters
Fault	High	IP and mobile networks	(RIGGIO et al., 2011) introduces a distributed network monitoring and visualization toolkit for wireless multi-hop networks	Maps and charts visualization that supports data overview, on-demand details, and filters
Performance	High	IP and mobile networks	(SEDLAR et al., 2012) proposes a data visualization solution for problemas about performance and root cause discovery in IPTV systems	Link-node visualization that supports data overview and filters
Security	Extremely High	IP and mobile networks	(PAPADOPOULOS, 2013) proposes a scheme for visualizing and exploring BGP path changes anomalies	Graph-based visualization that provides data overview, on-demand details, and filters
SLA	Rare	IP networks	(MCLACHLAN et al., 2008) provides a visualization solution to analyze large datasets and parameters of network devices to explore SLA issues	Chart-based visualization that supports data overview, on-demand datails, and filters

Table 2.3: Typical Applications of Information Visualization for Network Management

Source: GUIMARAES et al. (2016).

As can be seen in Table 2.3, researchers have been applying visualizations to address several complex problems in network management. The main benefits of these visualizations are that they define a clear way for operators to understand a significant amount of data as well as the behaviors of different technologies and networks. As a result, this makes it easier to analyze and mitigate disguised problems. However, most of the studies are limited to exploring certain techniques and their supported technologies. For example, a lot of works mainly focus on IP and mobile networks, without covering the management of new paradigms and technologies.

In view of this, despite these initial efforts and popular applications, it can be noted that there is an apparent lack of advanced visualizations that can cope with particular areas of network management and corresponding needs. In our view, the study and applications of Information Visualization provides an excellent opportunity for simplifying the management of complex networks, and thus can lead to a broad adoption of new technologies and paradigms by network operators.

2.3 Related Work

2.3.1 Network Management and Problem Identification

There are management challenges with regard to management that cover several aspects of NFV networks, such as orchestration (MIJUMBI et al., 2016a), resource management (HERRERA; BOTERO, 2016), and security issues (YANG; FUNG, 2016). Both companies and academia are actively seeking to find solutions that can address these challenges, and thus help the network operators to deal with issues inherent in NFV environments.

Attention should be drawn to three examples of well-known implementations that were carried out to support the management of NFV: *(i)* CloudNFV, which is an open platform for implementing NFV and is based on cloud computing and SDN; *(ii)* OSM that seeks to develop an Open Source NFV MANO software stack aligned with ETSI NFV; and *(iii)* Planet Orchestrate, which is an SDN and NFV platform aimed at service orchestration, automation, and multi-vendor management. Although these solutions are designed to assist the management of NFV, they do not provide sufficient tools to identify and overcome all the problems that arise when VNFs are running. Hence, there is an urgent need for the scientific community to address the open problems and to explore opportunities in NFV (MIJUMBI et al., 2016b).

In an attempt to tackle the problems of VNFs, Jacobs et. al. designed a mathematic model to measure affinity between pairs of VNFs, given weighted set of affinity criteria (JACOBS et al., 2017). The authors defined a function that helps network operators identify the root cause problems in NFV-enabled networks by analyzing affinity measures between VNFs. This model allows the operators to provide weights according to the relevance of each criterion, thus supporting the creation of more concise and improved affinity rules. Although this model was able to present an affinity number for a pair of VNFs, it is still complex for operators analyzes and compares affinities in scenarios with a lot of VNFs.

Scheid et al. found a solution based on Intent-Based Networking to translate intents into a set of configurations to perform the desired service chaining in both homogeneous and heterogeneous environments (SCHEID et al., 2017). This solution applies a refinement process to decompose intents and to calculate values that are utilized as selection criteria for the choice of middleboxes that will compose the service chain. However, the authors are disregard, for example, the question of affinities among VNFs and hardware; they are thus only concerned with a solution that applies some of the underlying features of NFV management, such as quality of services and security.

QU et al. employed a genetic algorithm based method to reduce the latency of the overall VNF schedule (QU; ASSI; SHABAN, 2016). The reduction of the scheduling latency enables cloud operators to accept more customers, and thus increases the revenue obtained from SPs. In offering this solution, the authors are mainly concerned with the dynamic bandwidth allocation. However, their response to the problem does not provide the features that are needed by the network operator to deal with the high demands of an NFV environment where several VNFs contracted by tenants are running.

With regard to the management of Next Generation Networks (NGN), Information Visualization has attracted considerable attention from the scientific community. Several visualization solutions support the discovery and analysis of information through visual exploration (GUIMARAES et al., 2016). These solutions enable human operators to explore subsidiary network problems, such as conflicting firewall rules (MANSMANN; GOBEL; CHESWICK, 2012), network device failures (KUMATA; KOYAMA, 2013), and malicious attacks (NUNNALLY et al., 2013). Hence, operators can recognize patterns, anomalies, and incompatibility issues in a fast and efficient way.

Liao and Striegel designed a visual analytical tool based on a graph differential anomaly visualization model to find the root causes of anomalies in dynamic graphs (LIAO; STRIEGEL, 2012). This tool combines human and computer intelligence for a smarter network operation and, more effective management. Several agents collect local context information (*e.g.*, running applications and connections). This information supplies a tool that applies the proposed model and provides different graphs to the network operator. However, although it detects changes in the behavior of users and applications, which can occur as a result of malicious intent or misconfiguration, this tool fails to provide information about conflicting applications or include data from network services.

In another study, Isolani et al. conducted an analysis of the traffic control in OpenFlow networks to determine the impact of specific parameters and their influence on the overall consumption of resources and network performance (ISOLANI et al., 2015). On the basis of this analysis, the authors proposed a tool that integrates Software-Defined Networking (SDN) monitoring, visualization, and configuration activities. This tool allows operators to configure SDN-related parameters and reduce the impact, in terms of resource consumption and performance, of the network management. However, this tool only provides simple statistical visualizations, which not allows operators to customize neither the monitored data nor the visualizations generated.

In the area of the industry, the Real Status company (Real Status, 2015) designed the HyperGlance platform to dynamically aggregate key resource data, relationships, and control functions in a unified, full-scale, interactive visualization for simplified, efficient, cross-platform monitoring and management within a single screen. This platform integrates data from various platforms (e.g., OpenStack, Open Daylight, and Nagios) to generate several visualizations, and allow operators to make decisions about the whole network. Nevertheless, HyperGlance seeks to support the NFV environment in the future. Thus, this general solution does not cover all the issues that concern the NFV management.

Despite attracting a significant amount of attention from the Information Visualization and network management areas in companies and universities/research centers, none of the solutions explore visualization techniques in NFV-enabled networks. As a result, these solutions do not assist human operators to have a full understanding of particular problems, because they ignore important NFV features (*e.g.*, forwarding graphs, migrations, and questions of affinity).

2.3.2 Planning of New Business and Opportunities

Designing a computer network to meet every business requirement is a hard task and involves several decisions that affect service levels, profits, and the question of competitive advantage. These decisions are even more challenging when the network technologies in place tend to be more disruptive than traditional wired networks, such as SDN, NFV, and wireless communications. These new technologies require specific planning tools and strategies to ensure high-quality services for customers and SP profits.

The current literature on network planning includes works that address topics as diverse as optimizing energy efficiency in data centers (YANG; LEE; ZOMAYA, 2016), analyzing the data of mobile applications (LAHMADI et al., 2015), and improving security in future networks (KHYAVI; RAHIMI, 2016). In this subsection, we review some key studies on network planning, particularly those related to new technologies and challenges in networking.

El-Beaino et al. investigated wireless network planning for the upcoming 5G networks (EL-BEAINO; EL-HAJJ; DAWY, 2015). The planning process is focused on the deployment of wireless networks and its requirements with regard to coverage, capacity, and quality of service (QoS). The authors were able to reduce the number of base stations and improve their location in a selected geographical area using a heuristic algorithm. In another study, Plets et. al. conducted an evaluation of two wireless network planning approaches for a very large industrial site (PLETS et al., 2016). However, the inconclusive results suggest that more studies for network planning in large environments are required to fill the gap in the area. Moreover, the authors stressed the fact that there are no wireless network planners available so far who are able to overcome the problem of intra-network interference.

Pavon-Marino and Izquierdo-Zaragoza proposed the Net2Plan, a visual solution designed for the planning, optimization, and evaluation of communication networks (PAVON-MARINO; IZQUIERDO-ZARAGOZA, 2015). Net2Plan can also assist in the development of different planning tools. In another study, the authors discussed the opportunities and challenges of interactions between SDN controllers and current network planning tools (IZQUIERDO-ZARAGOZA et al., 2014). The authors recommend a Net2Plan tool and investigate its capacity to orchestrate an OpenFlow-based network on top of the OpenDaylight controller. However, although the Net2Plan solution can be adapted for planning networks of any technology, it is limited to the tasks of network design, traffic evaluation, and the generation of reports. Moreover, the original features of Net2Plan do not provide visualizations to support planning decisions in a business model based on NFV-enabled networks.

Velasco et al. put forward a novel network planning framework, which allows the network operator to plan and reconfigure the network dynamically according to traffic changes (VELASCO et al., 2014). The authors describe two case studies that are concerned with transport networks, and show that both the resource overprovisioning and overall network costs can be reduced. However, this framework does not provide the network operator with a fuller understanding of business strategies or customers profiles.

None of the current solutions exploits the planning capacity of NFV-enabled networks either. As a result, there is a lack of tools for dealing with NFV features and its business opportunities. It should also be emphasized that Information Visualization techniques are generally underutilized as a resource for assisting network operators to carry out NFV planning tasks. To fill this gap, in the next sections, we introduce the VISION platform and visualizations designed to support NFV management.

3 VISION PLATFORM

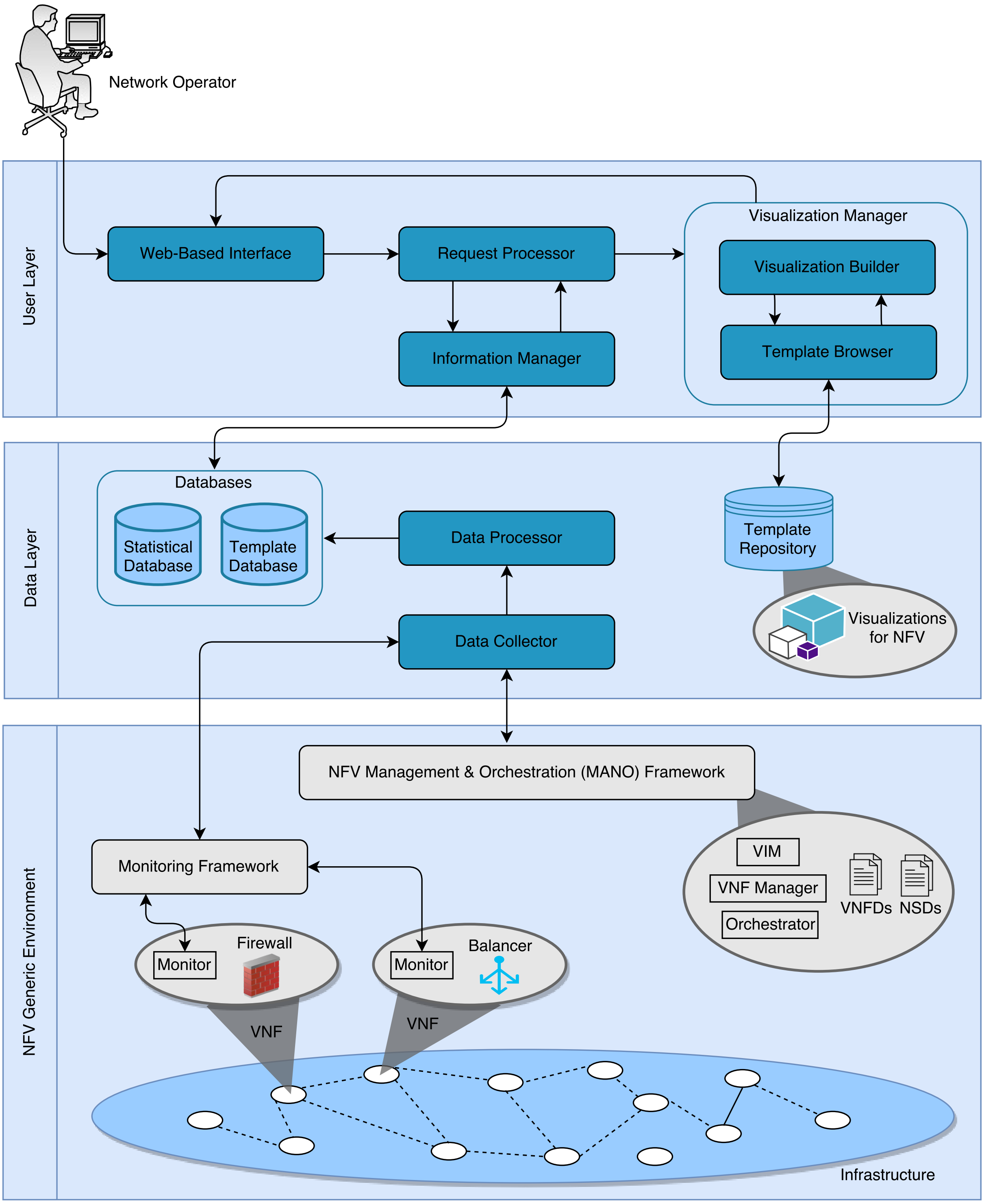
In this chapter, we present VISION (**Vis**ualizat**i**on **on** **N**FV), a visualization platform that collects information from the NFV environment and provides visualizations to help the human operator in the management and planning of NFV-enabled networks. We will introduce the conceptual architecture of VISION and describe all of the components that comprise the platform. We also provide details of the prototype and implementation.

VISION sets out two key goals to simplify NFV management and assist in the problem of identification. First, we provide a means of communicating with a generic NFV platform (*e.g.,* openMANO and OPNFV) and a monitoring system to collect, compile, and store a vast amount of data from different sources. Following this, we provide an interactive way of defining which data must be visualized and how this data should be displayed. Hence, the network operator can choose the information that will compound the visualizations. For example, the operator can select a set of statistics to generate a useful chart that represents only the VNFs in the same forwarding graph that need to be analyzed. These features provide ease of access to crucial information and allow operators to take benefit from exploring this information through visualization techniques.

A visualization template concept is proposed to facilitate the implementation and reuse of our visualizations. Visualization templates are files containing the specifications and implementations of visualizations (*e.g.,* documentation and javascript files), which support dynamic input data, thus ensuring that a single visualization can be reused to display a different set of data. In addition, the templates can be integrated to support other visualizations, such as a specific visualization that can access and display other visualizations with data that is determined by human interactions (*e.g.,* mouse clicks and mouse rollover can show statistical visualizations). Moreover, each template provides a file descriptor which contains the following requirements and specifications for visualization: description, type of data supported, minimum and maximum elements recommended to create a visualization, and details of the implementation. When a new template is created, this information is stored in the Template database and can be accessed by other modules (*e.g.,* in the verification and validation stages) or by new templates developers.

Our focus is on designing an architecture composed of separate modules which are interconnected, and hence provide a modularization mechanism that allows operators to replace and add any module without affecting the rest of the platform. The VISION conceptual architecture is shown in Figure 3.1. The main modules are highlighted against a dark blue background. As can been seen, a generic NFV environment contains the following components: (*i*) the Network Function Virtualization Infrastructure (NFVI), which enables the software to run independently of the hardware; (*ii*) Virtualized Network Functions (VNFs) that allow network functions from dedicated hardware devices to be operated by software hosted on COTS servers; and (*iii*) NFV Management & Orchestration (MANO) (ETSI GS NFV-MAN, 2014), which has three components to monitor and configure the NFV environment: Virtualized Infrastructure Manager (VIM), VNF Manager, and Orchestrator. In addition, the MANO framework contains two network function descriptors: Network Service Descriptor (NSD) and VNF Descriptor (VNFD).

Figure 3.1: Conceptual Architecture of VISION



Source: the author (2017).

In MANO, VIM monitors and controls the computing, storage, and networking resources of the NFVI domain. The VNF Manager carries out several VNF operations (*e.g.*, deployment and migrations). In addition, this manager stores data about configuration and VNF events (*e.g.,* alarm to SLAs disruptions). Finally, the Orchestrator is responsible for the global resource management, validation, and authorization of NFVI resource requests. Moreover, this component includes performance measurements and policy management for VNFs. This means that these components have a significant amount of meaningful information for management, such as the textual representation of forwarding graphs and information about the migrations that occur. As such, information from the MANO framework is of crucial importance to supply information to the VISION statistical database. The Data Collector module can collect this information, and also a set of specific statistics (*e.g.*, CPU usage and memory diagnostics) that are available in the custom monitoring services installed in the VNFs (PFITSCHER et al., 2016).

VISION architecture (Figure 3.1) is separated into three distinct layers so that the modules can be isolated and abstracted with regard to their functions. These include the following: (*i*) the User Layer which contains modules that implement the user interface, processes requests, and creates visualizations; (*ii*) the Data Layer that incorporates the modules responsible for collecting, processing, and arranging the data from the NFV environment and monitors; and (*iii*) the Generic NFV environment layer that represents the infrastructure and the corresponding NFV features. As is suggested by the architectural flow, three key stages must be followed to build the proposed visualizations. First, the Data Collector communicates with the MANO framework, VNF monitors, and file descriptors to supply the statistical database with relevant information. Next, the Data Processor prepares this information so that it can be available for the Information Manager requests. Finally, the Visualization Manager selects the templates and creates the visualizations in accordance with the requests of the operator. All of these modules will be examined in detail in the rest of this chapter.

3.1 Data Layer

The modules displayed in the Data Layer are responsible for carrying out several tasks that involve data management, collecting, and processing. This layer directly interacts with the infrastructure layer to obtain data which can be requested by the upper layers. Thus, in addition to playing a crucial role in data management, the Data Layer facilitates the communication between the user interfaces and underlying infrastructure. Each of these layer modules is described as follows.

3.1.1 Data Collector

The Data Collector module obtains data (*e.g.,* VNF events and textual forwarding graph representation) from the MANO framework. In carrying this out, the Data Collector can send GETs messages via API REST (Representational State Transfer) to MANO. This module can also access the NFV files descriptors directly so as to extract information. In addition, this module can collect data from customized monitors installed in the VNFs. The network operator only needs to configure the monitor's parameters in the VISION platform (*e.g.,* correspondent VNF, hardware, and IP address from the monitor) to allow the data collection. Each of these data collection mechanisms is listed above.

Many of the implementations of the MANO framework for industry and society, include well-defined northbound interfaces based on REST that allow activities to be carried out in the environment. These APIs enable useful information to be obtained from VNFs, MANO components (*e.g.,* VIM, VNF Manager, and orchestrator), and tenants. Our platform can deal with different MANO implementations that provide a northbound interface. This only requires the operator to define the API methods in the Data Collector and specify what kind of information should be obtained that can be mapped in the database.

The Data Collector can get data from another source to enhance the VISION statistical database. This involves the module requesting data from customized monitors that are strategically placed in the NFV environment. The network operator can create and configure these monitors to obtain additional statistical information from VNFs, such as CPU usage and memory diagnostic. As well as this, these monitors can collect specific information (*e.g.,* data about firewall rules and errors in packet processing). We provide a visual interface to enable network operators to indicate and configure new real-time monitors. The communication between VISION and the monitors occurs via a socket connection or API that is previously defined by the monitor developer.

As explained in Chapter 2, the NFV files descriptors (NSD and VNFD) contain relevant information for the VISION statistical database. The Data Collector obtains this information by directly accessing the respective files for each VNF and handling them by means of a predefined parser. Thus, this module is able to extract the information that is required by VISION. The operator can implement a custom parser to deal with other forms of file descriptors and add/remove information during this process.

After collecting the data from the MANO and monitors, this module sends them to the Data Processor, which will separate, arrange, and classify the information. Following this, the Data Processor stores the information in the VISION statistical database, and thus completes the process of acquiring and handling the data.

3.1.2 Data Processor

The Data Processor inspects, transforms, and models the data to discover meaningful information. This component manipulates the data to obtain information that is readable for the other modules. This kind of manipulation includes extracting and sorting out the relevant information while removing any non-usable data. This component is divided into three phases: (*i*) Parsing, (*ii*) Classification; and (*iii*) Storage.

The parsing phase is the first phase of the Data Processor. Its main function is to build a data structure on the basis of the input data to give a structural representation of the data; for example by arranging the data in tables where the columns and lines represent information from the VNFs. Moreover, this module checks whether there is any incorrect syntax (*e.g.,* information that is below the acceptable standards) and detects failures in the process of acquiring data. The network operators can create new custom parsers and upload them in the platform so that the available information can be handled in different ways.

In the classification phase the data is tagged and classified in accordance with shared features (*e.g.*, by creating a data structure that represents the VNFs hosted by the same hardware). These features define the groups of VNFs that can provide ease of access to information. The operators can also define the custom groups that should be taken into account during this process. The classification of data allows other VISION modules to have rapid access and filter the information needed to create customized visualizations, such as those that are only shown by the statistics obtained from the VNFs contracted by a specific tenant. After this stage, the data is stored in the statistical database (storage phase) by the Data Processor and made available on request by the VISION platform.

3.2 User Layer

In this layer, we aggregate all the modules and components that allow human-computer interactions. The modules are responsible for processing the operators' requests, providing visual interfaces, and communicating with the other layers to prepare visualizations. All modules and their respective attributions are described below.

3.2.1 Web-Based Interface

The VISION architecture specifies a Web-based interface module which provides an easy way for network operators to access visualizations, customize their settings (*e.g.,* by selecting the information that will be available and configuring new monitors), and interacting with other layers (*e.g.,* defining a new parser model for the Data Processor). The goal of this module is to produce a user interface which can provide an easy and user-friendly mechanism to control and access the VISION platform. This interface is the only way in which interactions between the operators and VISION modules can occur.

As well as providing a way to access and configure visualizations, this interface can, for example, make a dashboard available that gives an overview of the NFV environment, such as the number of VNFs available, resource usage, and migration alerts. In addition, the Web-based interface can provide significant information about the network traffic, by showing how much traffic is generated by the tenants. As well as this, logs from key events (*e.g.*, migrations and failures of VNFs) can be made available on the dashboard.

3.2.2 Request Processor

This module is the main way to establish communication between the Web-based interface and others modules of VISION. For this reason, all of the interactions, settings, and commands executed by the network operator that require actions from other modules will be processed and forwarded by the Request Processor module.

The Request Processor module sent the operator's requests via the Web-based interface or API and transforms them into actions to be executed in other modules (*e.g.,* Information Manager and Visualization Builder). For instance, the operator can interact with VISION and define a set of parameters to obtain a visualization that contains information from a particular group of VNFs. The Request Processor must analyze the parameters settings and the group of VNFs required to ask data for the Information Manager and must then send the specifications of this visualization, in a clear way, to the Visualization Manager so that the required visualization can be formed in accordance with the operator's preferences and requirements.

Another important task that is carried out by the Request Processor is the verification of conflicts between the data and visualizations. This requires the Request Processor to ask the Information Manager for details about what is needed for the visualizations and whether there are any restrictions (*e.g.,* what is the type of data that can offer support and what is the min/max amount of data that can be visualized in a visualization template). Following this, this module checks and validates the users' requests before proceeding to carry out the task in the other modules. Thus, if an operator selects data that is not supported by a visualization template, the Request Processor will return an error notification, and hence ensure the quality of the visualizations.

3.2.3 Information Manager

The Information Manager module acts as an intermediary between the user and data layers. On the basis of the requests from the plataform, this module executes queries into the databases (*i.e.,* the statistical database and template database) to obtain information that meets the demands of the user layer. These queries return a set of data that will be forwarded for processing by the user layer modules and applied to meet the platform requests, such as providing information and creating visualizations for network operators.

Given the fact that the Information Manager has full access to the stored data, when implementating this module, attention must be paid to key security issues, so that secure and reliable communication between the user and data layers can be ensured. This means that the developers must adopt security policies and programming techniques that provide integrity, confidentiality, and availability of data. An admissible level of security can be achieved by applying cryptography and hash algorithms (*e.g.,* RSA and SHA) to establish and validate the communication between the layers.

3.2.4 Visualization Manager

The Visualization Manager builds visualizations based on the information available in the VISION databases. This component explores visualization techniques that are available in a repository of templates, such as forwarding graphs and statistical visualizations, to provide an interactive view of the NFV environment. These visualizations help the network operator to identify the cause of problems. In addition, this component receives the data and processes the parameters so that it is able to customize the visualization modules, for instance, by deciding which information will be displayed and how the visualization will take place. This component is divided into two modules, which are responsible for loading the visualization templates and building the visualizations in accordance with the operators requests so that they can shown in the Web-based interface. Each of modules is described below.

The Visualization Builder is the module responsible for combining the data and visualization templates into a single element that represents the visualization requested by an operator. First, this module receives a message from the Request Processor that contains the operator's requests and the information available that needs to be displayed. Second, a request to obtain the necessary visualization templates is sent to Template Browser. Next, the Template Browser obtains access to a repository of templates and provides the requested template to the Builder. Finally, the Visualization Builder provides the visualization requested so that it can be displayed in the Web-based interface.

3.3 Prototype and Implementation

We implemented the VISION prototype as a modular application with independent functionalities that can support useful visualizations for NFV management.We chose Python 2.7[1] with Django 1.9[2] as the design framework. This prototype was implemented by taking account of the Model-View-Template (MVT) design patterns, which is an adaption, provided by the Django framework, of the Model-View-Controller approach. The database used for storing the information from the NFV environment and template records is a PostgreeSQL 9.6[3] implemented as a Django Model. The VISION modules were developed as Django Views and the visualization as Django Templates. Some of the functional requirements underlying the implementation of our prototype can be listed as follows:

- The implementation should allow data to be collected from the NFV environment and custom monitors;
- The implementation should store statistics and information about VNFs, tenants, file descriptors, and visualization templates in a database;

[1] https://www.python.org
[2] https://www.djangoproject.com
[3] https://www.postgresql.org

- The implementation should allow the operator to make custom settings and requests via a web-based interface;
- The implementation should provide an overview about the NFV enviroment (*e.g.,* total consumption of resources and number of VNFs that are running);
- The implementation should generate visualizations in accordance with the to operators' requests;
- The implementation should enable an interaction to occur between the operators and visualizations;
- The implementation should support new visualizations; and
- The implementation should update the database by determining polling interval

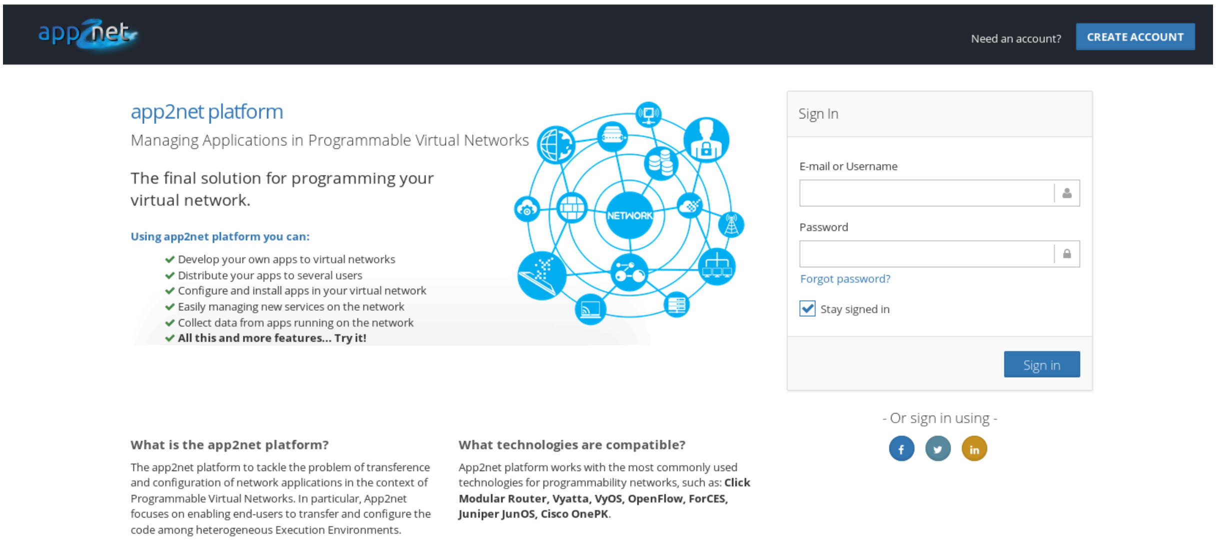
To facilitate the integration and distribution of our solution, we developed the VISION platform as a branch under App2Net[4], which is a platform to enable network applications (NetApps) to be transferred to, and configured in Programmable Virtual Networks (PVNs) that use heterogeneous execution environments (SANTOS et al., 2015). By reaching our solution through an App2Net branch, we derived a number of benefits such as a rapid deployment and installation of our visualizations in NFV environments, authentication, permissions management, and a better integration with other NFV management applications (SANTOS et al., 2017). Figure 3.2 shows the login page for accessing VISION platform.

Figure 3.3 shows the Web-based interface of VISION. On the left-hand side, there is a menu which allows network operators to access our visualizations and customize their VISION settings (*e.g.,* by configuring the pooling interval and custom monitors). We have also implemented a dashboard which gives an overview of the NFV environment. First, at the top of the dashboard, we display the number of customers that contract the services (*i.e.,* tenants), the number of VNFs available (active VNFs), tenant notifications, and alerts of events that have occurred in the environment (*e.g.,* VNF migrations and hardware saturation). Next, on the right-hand side, there is a panel which shows recent events that require attention. In addition, we have created a line chart to allow a historical analysis to be conducted of the number of packets per hour that are being processed by active VNFs.

Currently, the VISION platform is able to acquire data from the openMANO framework (Telefonica Research and Development, 2015). We chose this framework because it is the first open source project that provides a practical implementation of the NFV MANO framework. The openMANO offers a northbound API that allows information to be obtained from the NFV environment, such as resource allocation and VNF events. The process of collecting data is based on REST requests. The response of each request is a JSON with information from the object. For example, the request *GET /openvim/hosts/{host_id}* returns information about each of the interfaces attached on the *host_id*. We define an initial polling time as five minutes to update the databases.

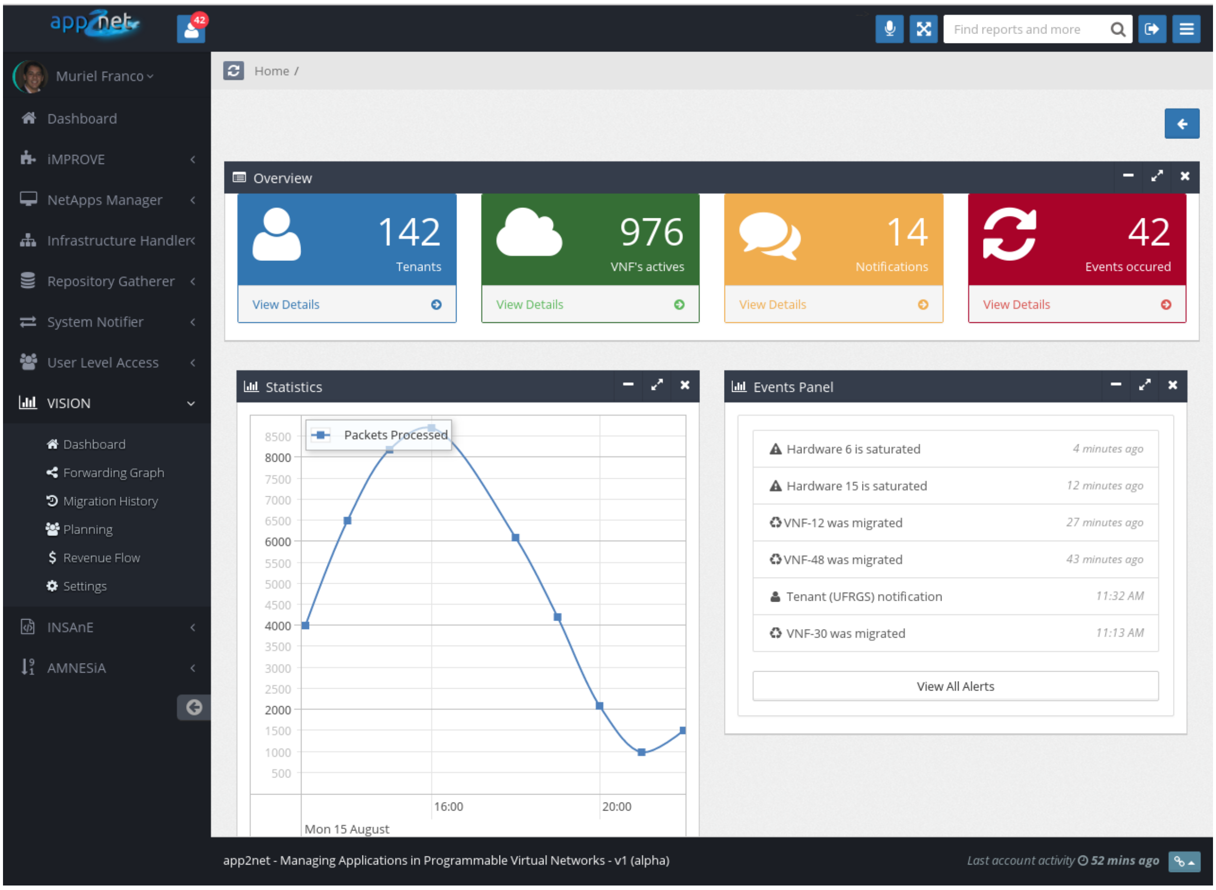
[4]http://www.app2net.com.br

Figure 3.2: App2Net login page



Source: the author (2017).

Figure 3.3: VISION Web-based Interface



Source: the author (2017).

The Data Collector can also get data from another source to populate the VISION database. This involves the component requesting data from customized monitors that are strategically placed in the NFV environment. The network operator can configure the Data Collector to obtain additional statistics that are in accordance with the API provided by the monitor developers, such as metrics to define the NFV service quality or information about specific services (*e.g.,* configurations of firewalls and caches servers). Our implementation requests and receives data from monitors via DReAM Python API[5], which defines the commands that have to be executed in monitors to obtain a JSON with the information monitored. For instance, the request *GET monitor/IPaddress/api/vnfs/{name}* returns a JSON with information from the specific VNF monitor (*e.g.,* latency and memory usage). All of the other VISION modules were implemented as a Python script for carrying out specific tasks inside the platform.

[5]https://github.com/ricardopfitscher/genic

4 VISUALIZATIONS FOR NFV MANAGEMENT

We propose a set of interactive visualizations based on techniques that are adapted to deal with the nuances inherent to the NFV context. These visualizations can make it possible to address different problems in NFV management, such as identifying bottlenecks in forwarding graphs and making it easier to understand types of behavior that are incompatible with the business strategy (*e.g.,* the overprovision of resources for unprofitable VNFs).

We implemented all visualizations in Django Template language to facilitate the integration with the VISION platform and enable the visualizations to use the power of Python language to handle the data. On the basis of this integration, our visualizations can be regarded as NetApps running over the VISION platform, which operate as a visualization branch of App2Net. The descriptors of the visualization templates are XML files that contain tags to represent the description, type of data, and amount of information supported by the respective visualization. These descriptors are necessary for some further validation stages and future developers, as shown in Chapter 3.

The JavaScript programming language was chosen to implement our visualizations and their respective interactions, and two libraries were selected for handling the documents and dynamic data: D3js 4.0[1] and VISjs 4.17[2]. These libraries provide powerful visualization components to handle significant amounts of dynamic data, and allow it to be manipulated or used for interactions. Hence, by means of these libraries, we were able to create the visualizations proposed in this work. We also employed jQuery User Interface 1.12[3] to simplify the interaction between the client-side and Django Templates, thus enabling our visualizations to manipulate events and use AJAX (Asynchronous Javascript and XML) applications.

It should be emphasized that although the proposed visualizations use the VISION architecture to obtain and manage information, they are not restricted to it. In fact, these visualizations can be applied in any other solution that provides and supports the information required. In the remainder of this chapter, we will introduce each of our visualizations, by describing their main features and giving examples of applications.

4.1 Graph Visualization

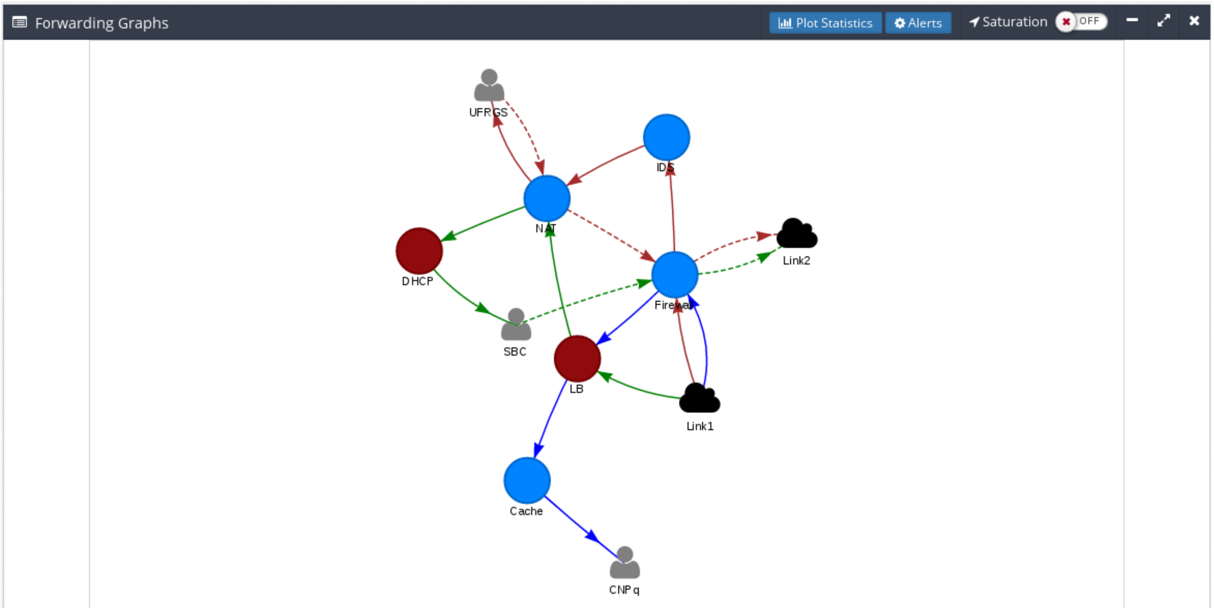
The purpose of Graph theory is to study the structures that model the relationship between objects (TAMASSIA, 2014). On this basis, we propose a Graph visualization template that provides a way for network operators to explore the relations between VNFs and tenants. This visualization offers a meaningful view of the forwarding graph, and thus makes it easier to analyze service chaining and the performance of the VNFs, such as determining when an incorrect VNF placement has a negative impact on the performance of another VNF and identifying

[1] https://d3js.org
[2] https://visjs.org
[3] https://jqueryui.com/

bottlenecks in the service chaining.

In Figure 4.1, there is an example of this visualization, which includes three hypothetical tenants (UFRGS, CNPq, and SBC) and their respective forwarding graphs. In this visualization, the solid lines represent the flow that comes in the respective network while the dashed lines show the flow leaving the network. The red lines describe the service chaining of Tenant 1 (UFRGS), the blue lines describe the chaining of CNPq, and green lines the chaining of SBC. As well as this, in this example, each node describes one VNF and the color of nodes represent the hardware that is hosting determined VNF (*e.g.,* the blue nodes are hosted in hardware A and the red nodes in hardware B).

Figure 4.1: Example of Graph visualization



Source: the author (2017).

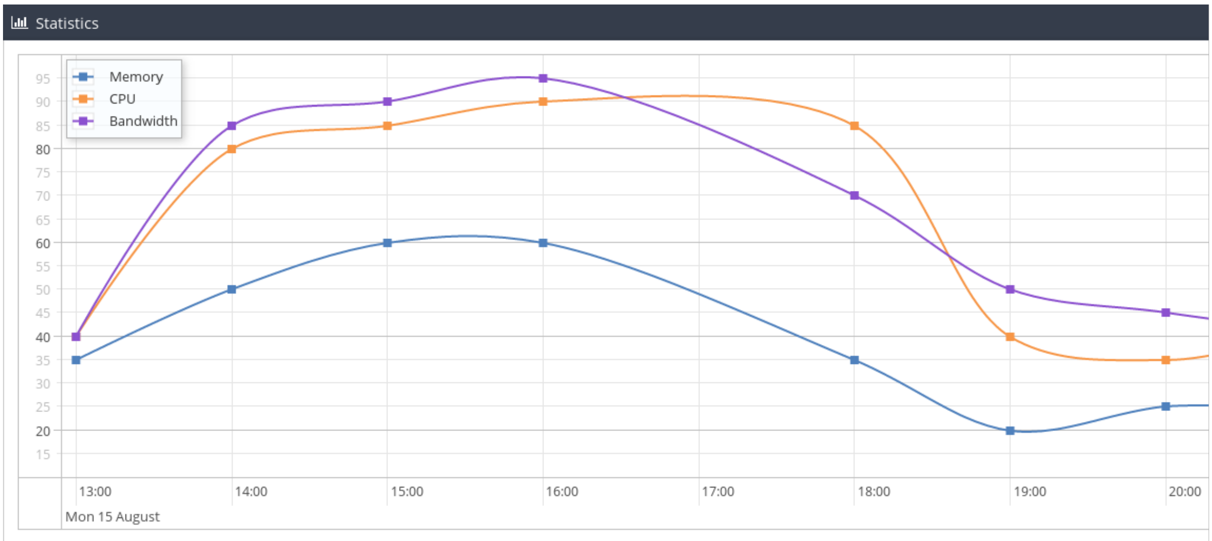
The Graph visualization template contains other features that can help in the process of detecting different problems, such as achieving an integration through statistical visualizations and highlighting for saturated VNFs. Moreover, this template has several optional settings which can help to improve human perception and the flexibility of the visualizations. The operator can configure visualization attributes to represent different information such as color, and the size of nodes can be adjusted with the level of CPU usage and packets being processed. The operator, for example, can determine that the nodes with a large size are processing many packets while nodes with high CPU usage are represented with distinct shapes (*e.g.,* triangles or squares).

4.2 Statistical Visualization

The statistics about VNFs are important to alert the network operator when a problem is occurring. For example, the operator may analyze event messages that suggest a VNF that is saturated. With this information, the operator can conduct a more in-depth analysis to have a fuller understanding of the cause of the problem that affects the VNF performance. The Statistical visualization template provides intuitive visualizations that can improve our understanding of the behavior of the VNFs. The operator can select the available statistics from VNFs (*e.g.*, latency and CPU usage) and any specific statistics collected by customized monitors so that they can be displayed in a useful visualization.

In Figure 4.2, there is an example of this visualization. In this example, we have created a line chart that displays three items of information about a single VNF over a period of time: physical host CPU, memory, and bandwidth usage. On this basis, the operator can easily find out that, for example, in some periods of a day, the large amount of traffic revealed by bandwidth usage is directly affecting the total amount of physical host CPU usage. This visualization can help the operator to understand some kinds of behavior, such as the fluctuations in resource usage during the day and how the VNF behaves when it is processing a large number of packets.

Figure 4.2: Example of a Statistical Visualization



Source: the author (2017).

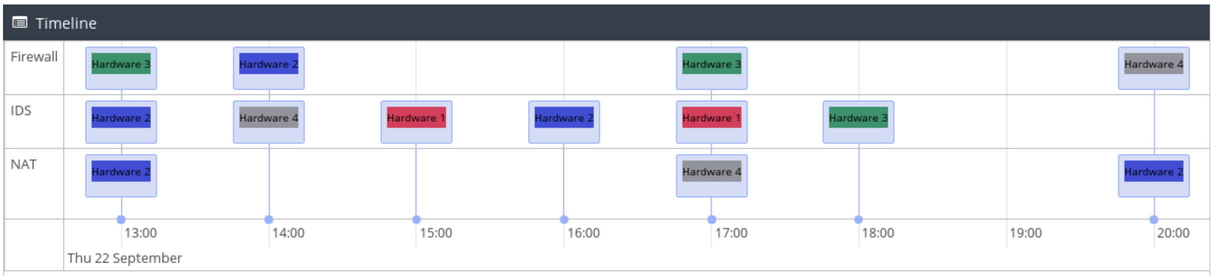
An essential feature of the Statistical visualization template is that it allows a comparison to be made between different statistics from several VNFs (*e.g.,* the difference in the latency of VNF-A and VNF-B during the monitoring time). This visualization provides real-time information for each monitored VNF, such as the number of packets processed and the resource usage. Moreover, the network operator can use the Statistical visualization template to improve other visualizations. For instance, the VISION platform can provide a visualization of the history of VNF migrations, and enhance it with meaningful statistics. Thus, when the operator clicks on the determined VNF, the Statistical visualization is invoked to provide information about the selected VNF (*e.g.,* by creating a line chart that shows the history of CPU usage).

4.3 Visualization of Migrations

VNFs can be dynamically migrated, and this increase the complexity for the network operator to know where a given VNF is hosted (*i.e.,* the VNF placement). Moreover, migrations can have several effects on the NFV environment, such as affecting the performance of VNFs when affinity issues are not respected and it is difficult for the operator to know where a VNF is hosted. In our view, an analysis of historical behavior provides a better understanding of the present. In the light of this, we store information about all of the migration events in the database. With the aid of this information, we have provided a visualization that can assist the operator in identifying the nature of the hardware and exact time when a VNF experienced misbehavior (*e.g.,* finding out what VNFs were sharing the same physical resources when a problem occurred).

VNF Migration visualization provides a complete overview of migrations. The operator selects the VNFs that need to be analyzed, and the visualization makes clear the kinds of hardware that hosted these VNFs. In addition, this visualization interacts with the Statistical template to enhance the visualization with charts and statistics about each VNF (*e.g.,* it displays in a chart the latency of the VNFs during the time). Moreover, the network operator can customize these visualizations to obtain useful information, for example by highlighting the VNFs and comparing their statistics. This means that, several issues can be explored with this visualization. For example, if two or more VNFs are not running properly when sharing the same physical hardware, the operator identifies the problem and may create anti-affinity rules among these VNFs, to prevent this unwanted behavior from taking place in the network.

Figure 4.3: Example of Migrations Visualization



Source: the author (2017).

In Figure 4.3, there is an example of this visualization. In this example, it can be seen where three VNFs (firewall, IDS, and NAT) are hosted during the period 13:00 - 22:00 on a particular day. Each item of hardware has a color that distinguishes it from others, thus making it easier for the operators to conduct the analysis. It should be noted, for example, that IDS has several migrations until it is hosted in the Hardware 3, which may throw light on the need for optimization in the migration algorithm.

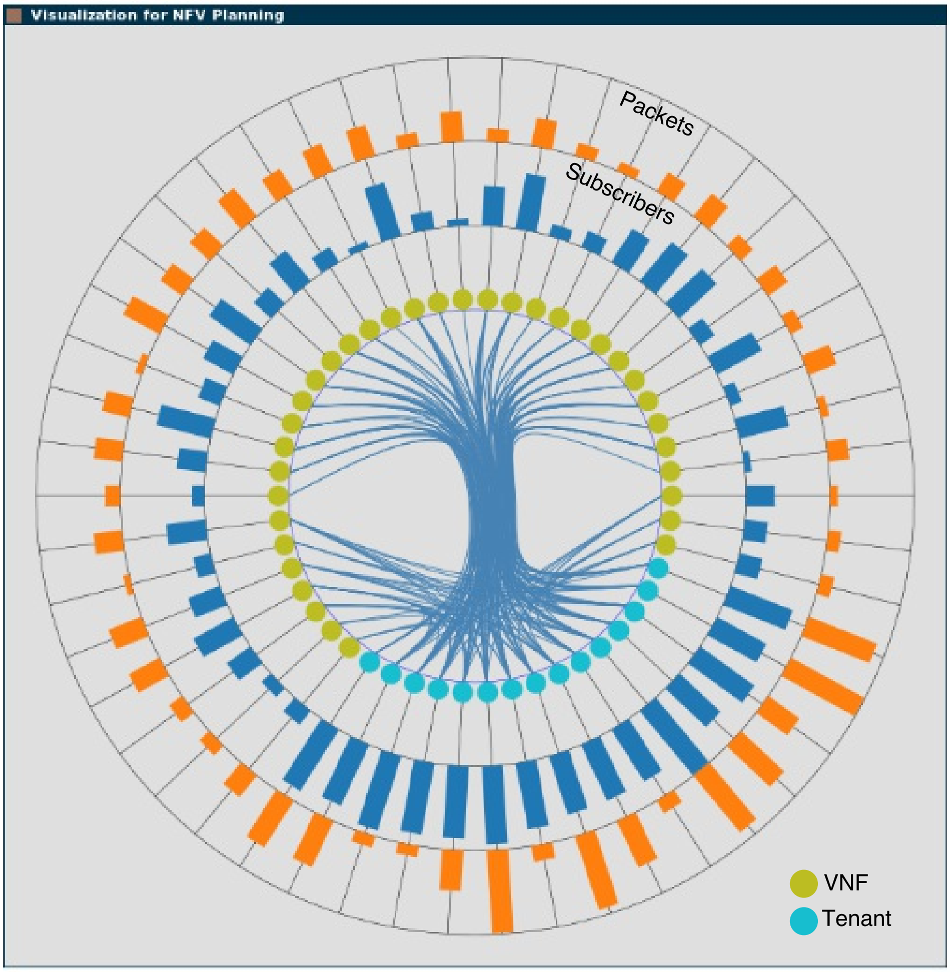
4.4 Visualization of Relationships and Business Demands

There are some VNFs from the service provider's application and several tenants of the service in NFV-enabled networks. The operator must have extensive knowledge of the information about relationships and requirements related to the business players (*i.e.,* tenants and VNFs) to efficiently plan the NFV business. In fact, understanding this information is a challenging task in itself because of the amount of data involved. As a means of simplifying the planning tasks, we propose a visualization of relationships and business demands. Our visualization is an adaptation of the ClusterVis technique (CAVA; WINCKLER; FREITAS, 2017), which is an interactive visualization to represent relationships between entities along with multiple attributes. ClusterVis borrows ideas from the Hierarchical Edge Bundling technique (HOLTEN, 2006). With this visualization (Fig. 4.4), we are able to provide information about the NFV environment in a useful way that can make the planning of tasks easier. The network operator, for instance, can analyze and compare statistics (*e.g.,* how many resources are allocated for each VNF or tenant) to have an understanding of how to improve or maintain the health service.

Visualization consists of a central circle that contains nodes representing the business players. The blue and yellow nodes are the tenants and VNFs that comprise the business respectively. The blue lines inside the main circle show the relationship between the nodes. For instance, a tenant node is represented with connections (blue lines) to contract the VNF nodes. In addition, the rings around the inner circle contain bar charts; each bar has a size proportional to the value of the corresponding node attribute that the ring represents. The first ring shows the number of subscribers for each node while the outer ring indicates the number of packets per second that are linked to each node. A settings menu allows all the rings to be customized so that they can represent any information collected by the Data Collector module, such as calls per second, CPU cores, and allocated memory. Moreover, the network operator can select a ring to sort out the visualization. For example, the operator can sort out the nodes by packets per second and the nodes will be arranged in increasing order of importance (see Case Study 5.1.4). Thus, the nodes with more packets associated will be displayed first, followed by the nodes with fewer packets, and hence make it easier for them to be interpreted by operators.

In summary, our visualization is based on representations of three key subsets of data about the NFV environment: *(i)* tenants and VNFs that comprise the business; *(ii)* resources allocated to operate the business (*e.g.,* resources assigned to each VNF and flavors contracted by tenants); and *(iii)* relationships between the business players involved (*i.e.,* tenants and VNFs). In addition, other relevant information (*e.g.,* number of packets being processed and latency time) can be collected by custom monitors installed inside the VNFs (PFITSCHER et al., 2016). By using our visualization, the network operator can detect questions involving planning, such as deter-

Figure 4.4: Visualization of Relationships and Business Requirements



Source: the author (2017).

mining when a virtual firewall that is processing a huge number of packets has less memory and CPU cores than other VNFs that are idle.

Other features that we propose allow network operators to interact and customize the visualization according to their needs. These features include, for example: (*i*) the information about nodes and rings that is displayed by the hovering mouse; (*ii*) new rings that can be removed or added either to simplify the visualization or obtain details about a node; and (*iii*) color attributes that can be defined for the nodes by different to categories (*e.g.,* red for firewalls and green for load balancers). In Chapter 5, we discuss these features through two case studies.

4.5 Visualization of Allocated Resources and Revenue Generation

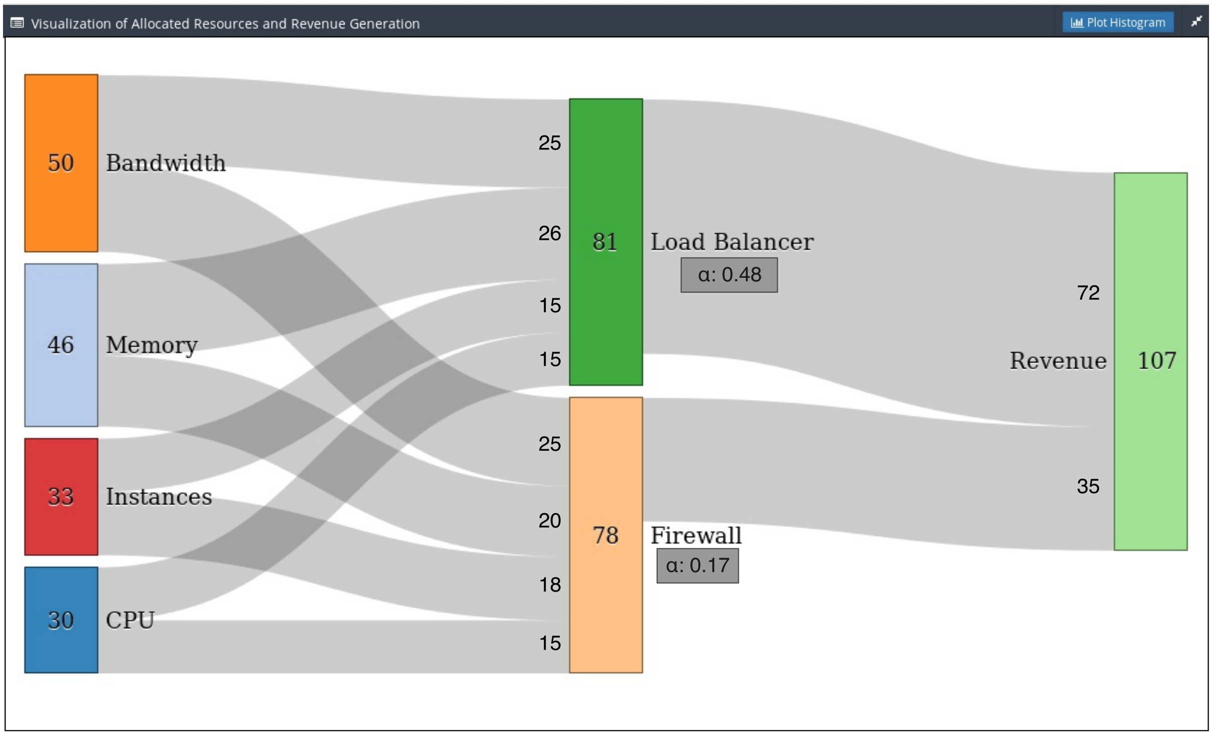
Resource Planning (*e.g.,* resource allocation policies and financial investment in infrastructure) is an essential task to estimate the amount of resources needed to offer a computing service (CANDEIA; SANTOS; LOPES, 2015). This task requires continuous planning to ensure it can be run in a flexible environment with high dynamic demands. Furthermore, incorrect planning for resources allocation can reduce its potential ability to obtain profits in an NFV-enabled business. For instance, the provisioning of resources to run services that generate little revenue requires attention to ensure it does not seriously affect the health of the business. To aid the network operator, we put forward the idea of a flow-based visualization that shows the amount of financial resources that need to be allocated to run a determined group of VNFs, as well the total revenue obtained by all groups of VNFs. Hence, this visualization can help the operator to estimate the profit-making potential of each service, which is important when making decisions to improve the business strategy.

Our visualization of allocated resources and revenue generation is based on a Sankey Diagram (RIEHMANN; HANFLER; FROEHLICH, 2005). This shows a flow chart to clarify the amount of expenditure needed to generate the business revenue. Figure 4.5 shows this visualization and its main features. The beginning of the flow chart (left-to-right) represents the resources available inside the rectangles. The connecting lines show the amount of resources made available to a group of VNFs (*i.e.,* services). Next, in the middle of the flow chart, there is a representation of the total amount of allocated resources, which means the sum of all the allocated resources needed to run the services. Finally, it is possible to note the total revenue obtained by each group. For example, in this case, there is a group with 15 load balancers, which are consuming 25 units of bandwidth, 26 units of memory, and 15 units of CPU. The total amount of resources allocated to this group is 81 units of resources, and this generates a revenue of 72 units.

For the purpose of making it easier to interpret our visualization, we have defined the general values that are used as a reference point for resources and revenue units: *(i)* one unit of memory is equal to 1GB, *(ii)* each unit of bandwidth corresponds to 10Mbps, *(iii)* one unit of CPU Core is equal to one instance of CPU, and *(iv)* each unit of revenue represents the amount of $100. Thus, for example, the group of load balancers is allocated 26GB of memory, 250Mbps of bandwidth and 15 CPU cores, thus resulting in a revenue of $7200 (72 units). Moreover, the network operator can set any value to define one unit of each resource. For instance, 2GB of memory can represent one unit of memory, and $50 can be the reference value of one unit of revenue.

Figure 4.5 also shows a revenue coefficient (α). This value is related to each group of VNFs, and represents a trade-off between the cost of running the VNFs and the revenue that they provide. The objective of showing this coefficient is to help network operators identify groups of VNFs that are profitable for the businesses. Thus, the service with the highest α is the most profitable for the business. The revenue coefficient is obtained individually for each category of VNF. For example, in Figure 4.5 there are two values for the potential revenue: one for firewalls and another for load balancers. We calculate the average cost C to run a VNF of a given type (*e.g.,* cost of one firewall) by means of Equation 1. The rationale behind this is: for each resource i allocated to a VNF j of a group, we add a specific weight (W_i). The weighted

Figure 4.5: Visualization of Allocated Resources and Revenue Generation



Source: the author (2017).

sum of resources allocated to each VNF, divided by the number of VNFs in the group (n), results in the average cost to run one VNF in the group. We assume that the network operator is responsible for determining the resource weights (*i.e.,* resources hard to obtain will have a higher W than others that are in abundance). Next (Equation 4.2), we calculate the average revenue of one VNF (R), which is the result of a division between the total revenue (Rt) and the number of running VNFs (n). Finally (Equation 4.3), we obtain the revenue coefficient (α) by dividing the average cost (C) per the average revenue (R).

$$C = \frac{\sum_{j=1}^{n} [\sum_{i=1}^{r} A_i * W_i]}{n} \tag{4.1}$$

$$R = \frac{Rt}{n} \tag{4.2}$$

$$\alpha = \frac{C}{R} \tag{4.3}$$

In addition, our visualization allows the network operator to include elements that will be visible in the flow chart, such as which resources and what group of VNFs will be used as the basis for the visualization. Moreover, the operator can access a supplementary visualization that represents an overview of the revenue of the VNFs being analyzed. These visualizations can be combined to provide valuable resources to help network operators to perform different tasks for

NFV planning, and hence improving the capacity of the operators to understand the business. For instance, the operator can identify any abnormal behavior that leads to a wrong conclusion about the revenue of the group; for example, a single VNF with high revenue may incorrectly suggest that an entire group is attractive to the business.

5 EVALUATION AND DISCUSSION

In this chapter, we focus on the present and discuss case studies that reveal the key contributions and benefits of our work. In addition, we conduct an experimental evaluation with real network operators to measure usability factors related to our platform and visualizations.

5.1 Case Studies

Our case studies consist of six scenarios that make use of the distinct features and visualizations set out in our work. First, we provide a complete forwarding graph visualization, which allows the network operator to detect if there is an incorrect VNF placement and the VNFs are overloaded. Second, we transform migration logs into a meaningful visualization that can help the operator to deal with affinities. Third, we provide a helpful force-directed graph visualization to understand the service priority of each tenant. Next, in Case Study #4, we outline a scenario where the network operator has to identify failures in resource allocation policies and the flavors available in the business. In Case Study #5, the service provider has a large amount of capital to invest in infrastructure and wants to know the best way to improve the business. Finally, in Case Study #6, there is an in-depth investigation of business profits.

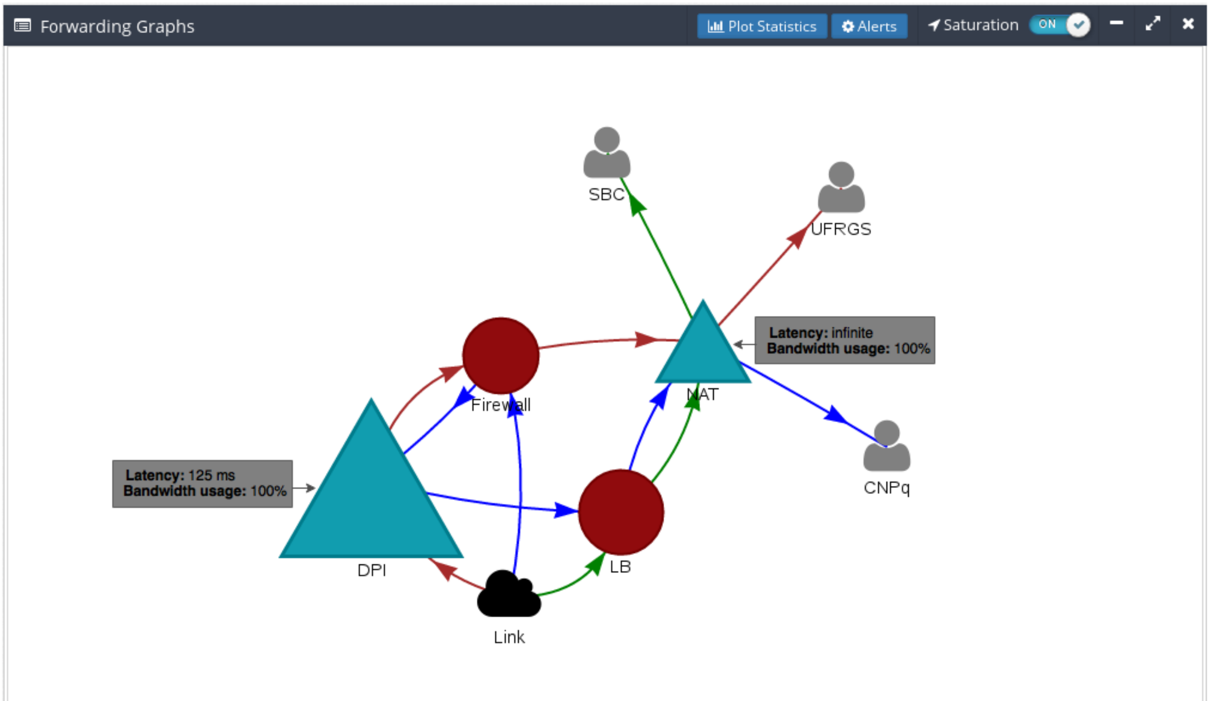
5.1.1 #1 - Identifying bottlenecks by using forwarding graph visualization

Let us suppose a scenario where there are four VNFs (Deep Packet Inspection – DPI, firewall, load balancer, and Network Address Translation – NAT) and three distinct tenants (UFRGS, SBC, and CNPq) sharing these VNFs, but with different forwarding graphs. In this situation, the network operator receives several complaints from the tenants about the performance of the contracted service. In a preliminary analysis, the operator does not have sufficient information to determine the cause of the problem, although the NAT performance has an abnormal behavior (saturated network bandwidth). Thus, a more in-depth analysis is required to determine the cause of the problem.

Another way of dealing with the problem mentioned above, is to analyze all the VNFs that form the service chaining of tenant 1 one by one. However, this poses several challenges (*e.g.*, checking a lot of statistics), and adds to the time needed to find out the cause of the problem. Moreover, the operator must access the information about each forwarding graph to understand how the VNFs are shared among the tenants. For this reason, a traditional management procedure without visualization is not an effective way of addressing the problem because it is not trivial for people to be able to grasp textual information which involves a lot of statistics.

Our platform improves the capacity of the operator to understand the misbehavior of a VNF when it causes problems in another VNF. This involves the operator interacting with the Visualization Manager to obtain a global view of the forwarding graphs. In this visualization, each node represents a VNF and its size is defined by the number of packets that are processed. In addition, the nodes are represented by a triangular shape when an observed statistic is saturated (*i.e.*, the network bandwidth usage is higher than 90%). In addition, the color of the edges represents the forwarding graphs of each tenant (the red lines represent the UFRGS service chaining, the blue lines the CNPq, and green lines the SBC). In addition, the color of the nodes represents the hardware where a VNF is hosted (the blue nodes are hosted on one type of hardware and the red nodes are in another). In the Web-based interface, the network operator defines the saturation thresholds and chooses the statistics that will form the visualization. With the aid of this visualization, the operator can identify VNFs with abnormal behavior, and analyze individual statistics (*e.g.,* latency and network bandwidth) to find bottlenecks.

Figure 5.1: Forwarding graphs and statistics visualizations



Source: the author (2017).

In Figure 5.1, the visualization is shown that helps the operator to find the cause of the problem. As can be observed, the NAT and DPI are saturated. However, it is not sufficient to understand the problem, since it can be noted that the DPI is receiving more packets from the Internet than it can process. On the basis of this visualization, it can be seen that the bandwidth of the hardware that hosts both the DPI and NAT is saturated. As a result, the NAT cannot receive and deliver the packets to the next hop, because of the congestion caused by this saturation. Thus, it can be concluded that the forwarding graph of the UFRGS, SBC, and CNPq have crashed due to the incorrect placement of the VNFs.

The network operator must make a decision about how the DPI is running. For example, the firewall performs fewer in-depth analyses than DPI. This means that the operator must change the forwarding graph, and make the firewall process the packets prior to the DPI. In another solution, the network operator can maintain the original forwarding graph, by making changes directly in the DPI, such as creating affinity rules to host the DPI in a hardware with more resources and a greater capacity to support the high demands.

5.1.2 #2 - Detecting failures in migrations policies

The placement of VNFs entails finding a physical host that has the resources available to run the service properly. However, the placement of a set of VNFs in relation to each other is not considered to be feasible, even though affinity and anti-affinity rules are recognized (OECHSNER; RIPKE, 2015). An affinity rule stipulates that VNFs must be hosted in the same hardware, whereas anti-affinity requires that VNFs be instantiated on distinct physical machines. If these rules are not well defined, VNFs with anti-affinity might be placed on the same host. As a result, one VNF will experience misbehavior and have a negative impact on the service provided.

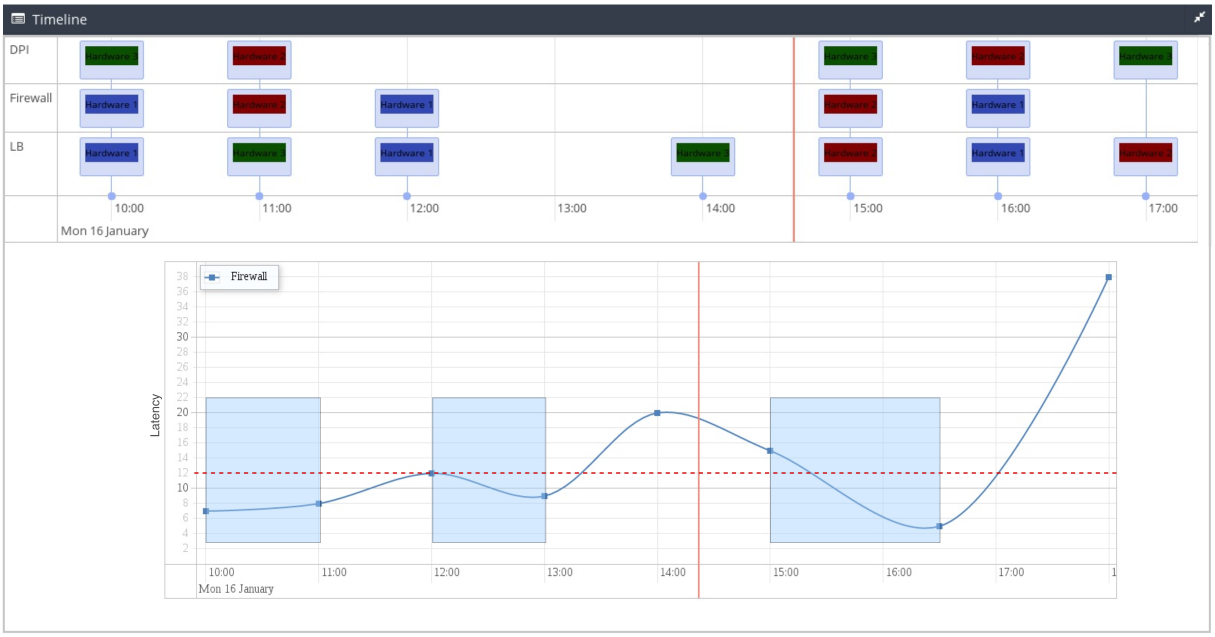
The identification of affinities among VNFs is a very complex task and this complexity increases when the operator does not have the appropriate resources. For example, if operators try to understand the question of affinities by just using traditional management tools, they will only access the available event logs and spend a great deal of time analyzing textual information about the migrations of each VNF. Despite this, the problem of affinities will still be not clarified.

Let us suppose the following scenario: on the basis of previous reports, the network operator observes that a virtual instance of a firewall is undergoing sudden changes in its performance during the day. The first analysis suggests that this has had a considerable impact on the service provided, such as increasing the propagation delay and spoiling the packet processing. In response to this, the operator adopts the VISION platform to identify and mitigate this problem. Initially, the visualizations provide information which leads to the conclusion that the VNF performance worsens when migration events occur and hence the network operator must analyze the VNF migrations to understand the problem.

In Figure 5.2, there is a visualization of the migration history and statistics from VNFs. In this visualization, the operator can select what statistical data will be available about VNFs, and show them in a line chart to understand the behavior of VNFs during the period. At the same time, another visualization provides a view of what physical structure hosts these VNFs. Thus, the operator uses both visualizations to understand the nature of the problem in the NFV network. In this visualization, a red dotted line can be moved to define what is the threshold of the observed statistic. This provides the operator with a clearer view when the statistical value is high (*e.g.*, when the latency is high). Hence, the interval where the values are apparently fine can be highlighted.

On the basis of this visualization, the network operator can determine that the Firewall is

Figure 5.2: Visualization of the VNF's migration history



Source: the author (2017).

working fine when it shares the same physical host with that of the Load Balancer. This can be viewed in Figure 5.2 where there is an analysis of the times 10:00 to 11:00, 12:00 to 13:00, and 15:00 to 16:00. Based on this, the operator can have a clear view of the problem: the affinity between the firewall and the load balancer are not respected. Thus, to mitigate the problem, the operator must create an affinity rule to host both the VNFs in the same physical hardware.

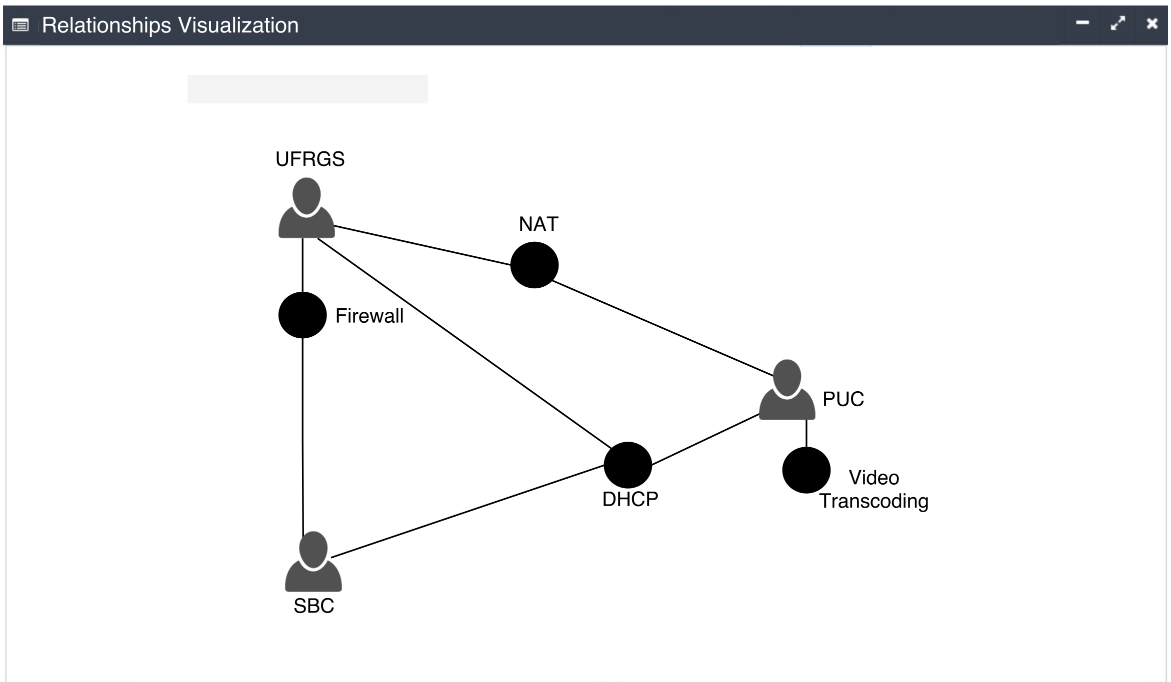
5.1.3 #3 - Analyzing tenants usage profile with force-directed graph

The network operator manages the VNFs to provide a good service for the tenants. This requires the operator to have a view of the distribution of VNFs and the consumption profile of each tenant to meet all the performance requirements. The available information is essential to identify the specific demands and foresee what impact the maintenance activities will have on the service. The current solutions for NFV management do not provide features that help the operator to manage this information and thus it is impossible to assist in planning network management. For example, the maintenance of a determined VNF may have a significant impact on a high priority tenant (based on a policy of priorities). Thus, the operator repairs the VNFs when there is minor traffic for this tenant, and thus avoids severe consequences of the service contracted. In addition, visualizations allows the operator to analyze the demands, and, thus, offers special services for each tenant, such as instantiating a dedicated firewall for one tenant or increasing the resources available for a VNF.

In an supposed NFV environment, there are four shared VNFs (NAT, DHCP, firewall, and video transcoding) among three tenants (UFRGS, SBC, and CNPq). The UFRGS contracts the firewall, DHCP, and NAT services, whereas the SBC only uses the firewall and DHCP. The VNFs corresponding to DHCP, NAT, and a particular Video Transcoding, meet the demands of the CNPq (Figure 5.3). In this environment, the network operator receives a performance service complaint from a high priority tenant (UFRGS). On the basis of this, the operator must reassure the high priority tenant that its demands will be satisfied, in view of the fact that one or more VNFs are shared. Before this can be achieved, the information about the network and specific demands of each tenant must be analyzed so that the distribution of VNFs can be rearranged. Examples of this information are: *i)* what VNFs are being shared by two or more tenants, *ii)* which tenant uses a more determined VNF; and *iii)* what are the performance requirements for each tenant.

A technique known as the force-directed graph is employed to provide ways for the operator to understand the information from the network. This technique defines the forces needed to attract or repel a pair of nodes. Thus, the proximity between the VNFs and tenants can be represented on the basis of the pre-defined statistic (*e.g.,* the VNFs are near to the tenants that send more packets through the process). Using VISION interface, the operator can choose another statistic to create the force-directed graph, such as the use of physical resources and geographic location. This visualization provides an overview of the different relationships between nodes, and assists in some NFV management issues (*e.g.,* the operator can perceive when the geographic location of the physical hosts is having an impact on the VNFs' performance).

Figure 5.3: Force-directed graph based on the consumption of each tenant



Source: the author (2017).

Figure 5.3 shows the relationships between the VNFs and tenants (*i.e.,* which VNF is available to each tenant). The number of packets processed defines the distance between two nodes. For example, this visualization suggests that, although shared by both UFRGS and SBC, an instance of a firewall is more requested (in terms of packets processed) for the UFRGS. Hence, this visualization provides a better view of the utilization profiles, and helps the network operators to provide services that will meet the tenants' demands. Thus, the operator can offer the UFRGS a dedicated firewall that gives priority to its high demands.

5.1.4 #4 - Investigating failures in resource allocation policies and the flavors available

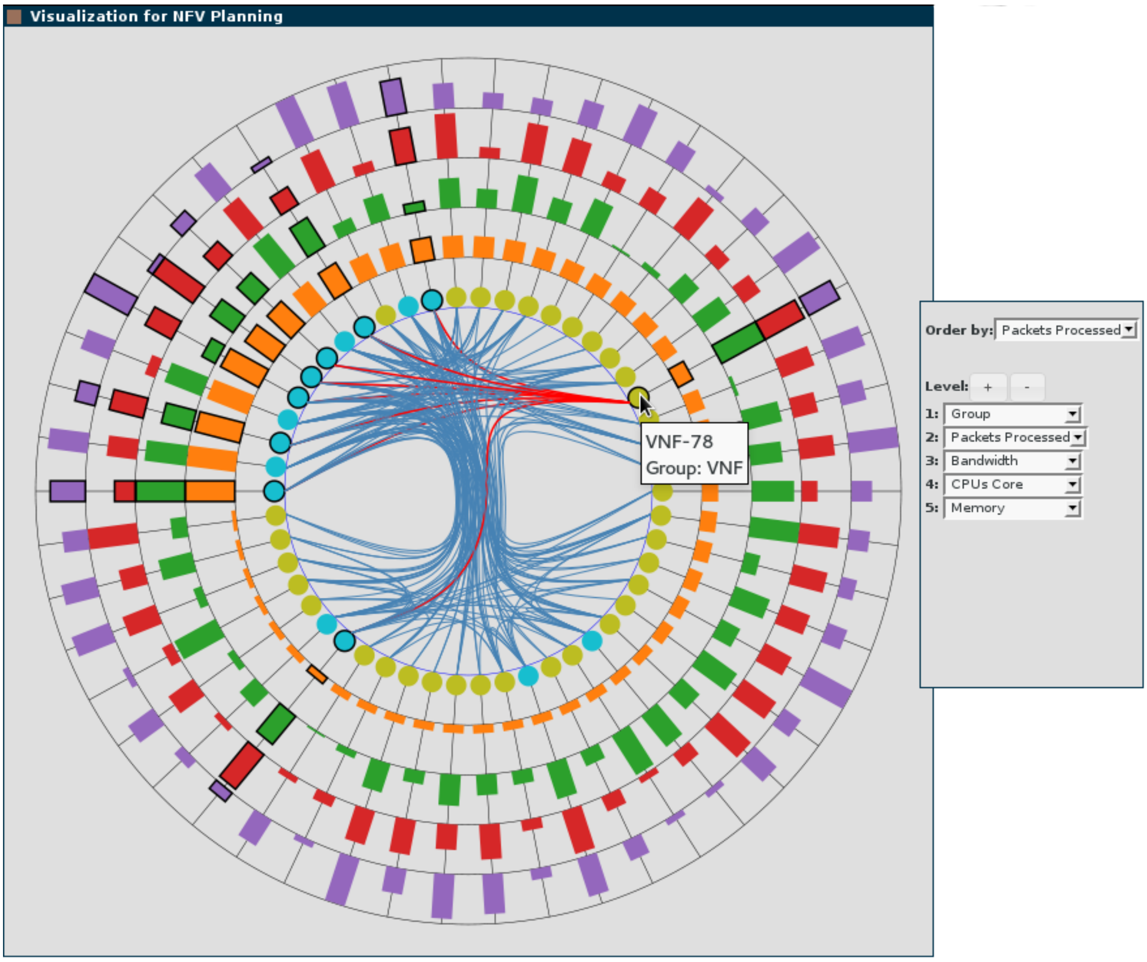
Let us suppose the following scenario: the network operator notices a considerable increase in complaints by the tenants about service performance. In an initial analysis, the monitoring tools inside the NFV environment, report an overload of packets being processed in a particular period of the day, which is having an impact on the latency of some VNFs and, hence, the service performance. Based on this information, the operator seeks to examine the situation and then, conducts a deeper investigation to make decisions that can help avoid further problems.

Initially, there is no obvious factor that indicates a problem in the NFV-enabled business. Thus the operator investigates the business by accessing our visualization of relationships and business demands. Figure 5.4 displays the operator customization: the VNFs and tenants are shown as yellow and blue nodes, respectively, and located in the first ring; the number of packets processed are shown in the second ring; the allocated bandwidth in the third ring; the number of CPU cores in the fourth ring; and the available memory in the fifth ring. Moreover, in this visualization, the network operator decided to sort the visualization into the number of packets processed. Thus, the visualization shows first the nodes that process the larger number of packets followed by nodes that are processing a smaller number of packets (*i.e.,* in increasing order).

By using our visualization, the operator is able to discover the following: there are some VNFs with few allocated resources that are handling many packets per second, while others have idle resources. This problem is highlighted when we analyze the rings of allocated resources and note that there are several resources allocated to VNFs that are processing few packets. The operator can discover this, for example, by noticing that VNF-78 (see Fig. 5.1) has a small second level bar graph (*i.e.,* the orange bar that represents the number of packets being processed) while having a full bar for bandwidth (green bar) and CPU cores (purple bar). In addition, it should be noted that other VNFs share the same behavior. This problem can occur because the network operator has failed to take account of the business demands when defining the initial business structure, thus resulting in bad policies for resource allocation and incompatible VNF flavors.

To tackle this problem, the network operator must plan a new strategy for resource allocation, thus changing the allocation policies so that they can address the dynamic demands of the business. As another solution, the operator can decide to make changes in the way the tenants

Figure 5.4: Investigation of failures in resource allocation policies and the flavors available



Source: the author (2017).

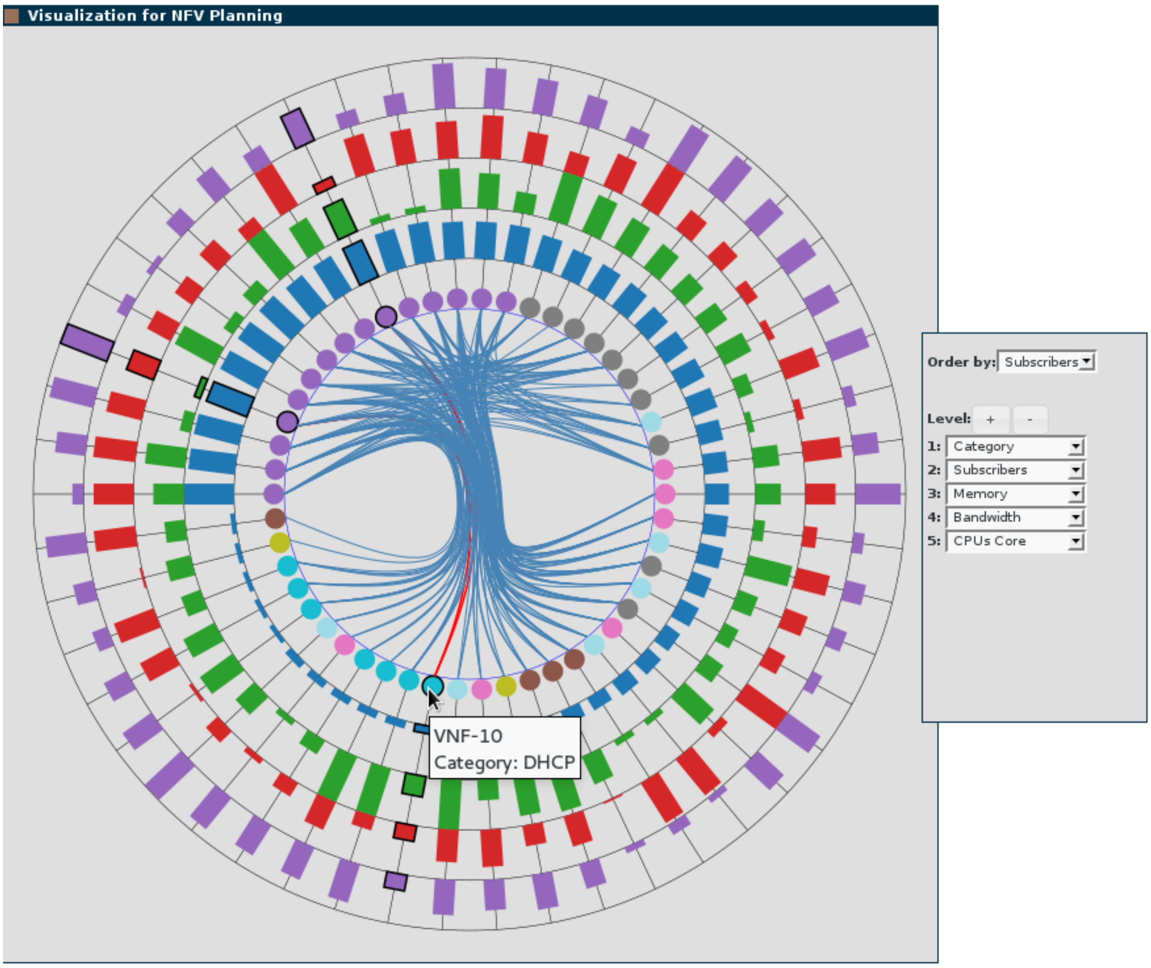
are charged for the use of one VNF. Thus, tenants that consume more packets will pay more to use flavors that provide a high availability of resources. In addition, the network operator can structure the business to support flexible flavors in which tenants will pay an appropriate amount for their demands.

5.1.5 #5 - Identifying priorities of capital investment

In traditional business scenarios, competition between companies leads to a continuous increase in the quality and range of products available to customers. It is not different in an NFV-enabled business, where the service providers have to implement a better service performance and change reasonable costs according to the tenants' wishes and the market landscape. This means that the SPs must have a broad knowledge of the tenants' profiles and their demands so that they can make strategic investments and introduce changes to be more competitive.

In this case study, we have created a scenario where a service provider has a substantial amount of capital to invest in business infrastructure. The network operator has to understand the business demands to plan how to expand the business in the best way. For instance, if the tenants are contracting a lot of VNFs that are firewalls with flavors that provide a greater capacity to process packets, this might suggest that an investment in firewalls with sufficient resources available is a good planning decision. Hence, the operator can use our visualization to plan the next stages of the business expansion.

Figure 5.5: Visualization for planning a business investment



Source: the author (2017).

Figure 5.5 shows a visualization that provides resources for identifying which category of VNFs (*e.g.,* load balancer and firewall) are the most contracted and what resources are more requested by the tenants. In this visualization, the operator sets an option to display the category of each node in the inner ring. Hence, the colors are defined according to the services that each node represents. For example, the gray and yellow nodes are firewalls and DPIs respectively. The purple nodes represent the tenants of the business. The second ring shows how many tenants are contracting each VNF or - when only analyzing tenants' nodes - the number of VNFs contracted by tenants. The last three rings represent information about the resources allocated to each node (*e.g.,* memory, bandwidth and CPU cores). Moreover, the operator defines the visualization which must be arranged in accordance with the number of subscribers. Thus, the nodes with the largest number of subscribers are presented first, followed by the other nodes.

In a first analysis, the operator observes that VNFs with more subscribers are firewalls (gray nodes). Moreover, it is clear that the tenants have a preference for firewalls with more memory allocated, and by observing this, it can be concluded that the VNFs with more subscribers (largest blue bar) are firewalls that have more memory allocated (largest green bar) than others. Moreover, the operator can find out something else: there are many DHCPs (blue nodes) with few or no subscribers (*e.g.,* VNF-10). This suggests an incorrect investment in a service that does not comply with the tenants' interests.

The network operator must make a decision to mitigate this behavior, and thus adapt the business to market trends and the requirements of the tenants. To achieve this, the operator could invest capital in running firewalls with flavors that provide a large amount of memory. Furthermore, some DHCPs could be removed from the business, and hence release resources for other services. The tenants that need an individual DHCP, for example, should pay to contract a special flavor. Thus, on the basis of these decisions, the operator can obtain a profitable business model, which provides both high-performance VNFs that meet the tenants' demands (*e.g.,* firewalls and other useful services) and VNFs that supply the needs of individual requirements (*e.g.,* DHCPs with a low demand but that are attractive to some tenants).

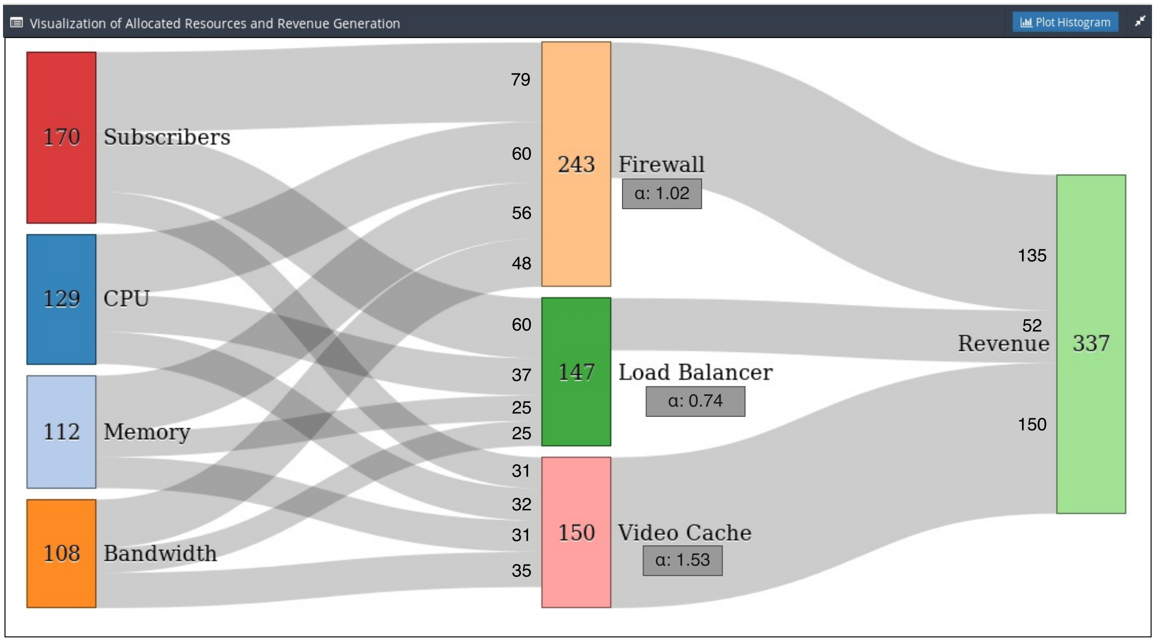
5.1.6 #6 - Determining the most profitable group of VNFs and top business priorities

This case study is based on a situation where, in a previous investigation, the network operator defined three categories of VNFs which may be useful for improving the business. The operator has the following key information: *(i)* firewalls and load balancers are the VNFs with more subscribers in the business; and *(ii)* some video caches have few subscribers but high demand (*i.e.,* many packets being processed and calls-per-second). Even though load balancers have more subscribers than video caches, this is no obvious sign to suggest which of them is more profitable. This information implies that the network operator must understand how profitable each service is to the business.

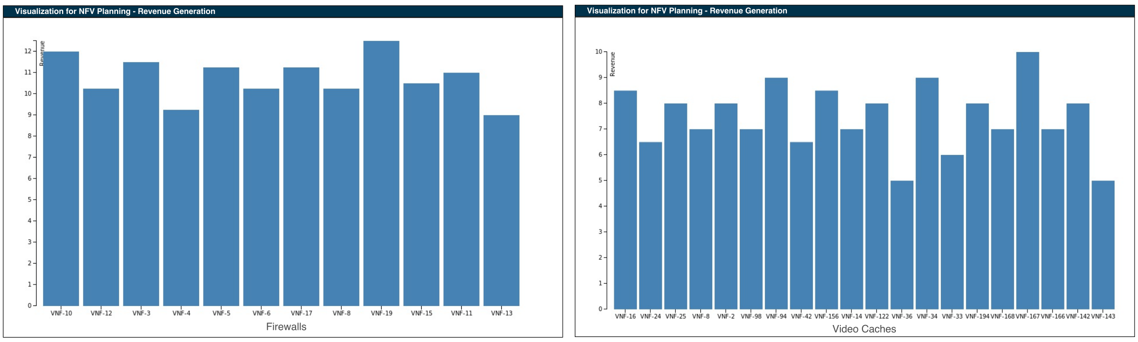
The operator accesses our visualization of allocated resources and revenue generation to obtain ideas that can help in planning new business strategies and investment. Figure 5.6 shows the amount of resources allocated and subscribers for each group of VNFs being analyzed. The visualization contains the following: at the start of the flow (left), the amount of allocated resources (*e.g.,* CPU cores, memory, and bandwidth) to run a group of VNFs and the number of tenants contracting it). The middle of the flow represents the sum of all the allocated resources. Finally, the revenue of each group of VNFs is also provided, together with the revenue coefficient (α) which highlights the services that are being the most profitable to the business.

For this case study, we defined the following values as benchmarks for the allocated resources and revenue: (*i*) one unit of memory is equal to 1GB, (*ii*) each unit of bandwidth represent 10Mbps, (*iii*) one CPU unit is equal to one CPU core; and (*iv*) each unit of revenue is equal to $500 (five hundred American dollars). Thus, the operator should use these reference-points when converting the visualization values to real outgoing expenses and incomes.

Figure 5.6: Determining the most profitable group of VNFs and top business priorities



(a) Flow visualization to understand amount of resources spent on each service to generate the business revenue and profits



(b) Supplementary visualization with an overview of the revenue of each video cache and firewall available

Source: the author (2017).

By analyzing the flow visualization (Fig. 5.6(a)), the operator can determine that even though there are only a few subscribers to the video caches, this service is very profitable for the business. This estimate can be made by comparing the amount of revenue ($75000) and the α of video caches with others. Thus, this service should be maintained in future planning. Moreover, the firewalls demonstrate that they are also attractive to the business. Many tenants are subscribing firewalls (79 subscribers), and there is a significant revenue ($67500) and α value. On the other hand, the load balancers, which have a good number of subscribers and allocated resources, provided a revenue below what was expected. In view of this, the network operator must plan a strategy to make VNFs available that correspond to the business goals, such as new load balancer pricing and flavors to meet the tenants' demands and, also, ensure a profitable service.

Moreover, the supplementary visualization (Fig. 5.6(b)) provides information which makes it possible to conclude that there are more video caches (20 VNFs) than firewalls (12 VNFs); it also suggests that, on average, one firewall generates more revenue than one video cache. However, the video caches obtain a better result for α because one instance of a video cache is less expensive to implement than other services. On the basis of this analysis, it should be noted that another attractive approach to business might to define a new strategy that reduces the cost to run a firewall, and thus increases the potential profit of this service.

5.2 Usability Evaluation

A remote survey was conducted[1] to measure the usability of our visualizations. This survey aimed at measuring the users' understanding of the overall flow of the platform and their ability to carry out management tasks and obtain results according to need. In addition, we obtained feedbacks about the general aspects of the platform's usability, such as how useful and easy it was to obtain the information by using our visualizations.

5.2.1 Participants

The test involved 12 participants, between the age of 19 and 31. All of these participants are from the area of computer science, 80% from the field of network management while 20% are from mobile and wireless networks. The level of education of the participants varied considerably, with 33.3% being graduates, 42% with an MSc degree and 24.7% with a PhD degree. In addition, all of these participants had at least one year's experience of the management of computer networks. 85% of the participants knew what NFV and its basic concepts are.

5.2.2 Tasks and Initial Setup

In conducting this evaluation, we followed five stages: First, the operators were presented with a brief description of the purpose of the platform. Following this, each operator navigated for ten minutes until they had become familiar with the platform. Finally, there was a survey with questions about the user profile, usability issues, and the specific tasks. The first part of the survey contained some personal information about the operator, such as age, experience, and involvement in the area.

[1] http://inf.ufrgs.br/m̃ffranco/survey/

After the personal information had been collected from the operators, we asked ten questions to measure the operators understanding of the features of this work and also ensure that they really interacted with the platform before answering the usability questions. Each question required the operators to interact with several visualization features before being answered. These questions and their description were as follows:

- **T1: How many tenants are available in the platform?**
  The correct answer is 14. This value can be found in the dashboard of the platform. The aim of this question is to check if the operator can access and understand the overview of the managed environment.
- **T2: How many VNFs are available in the platform?**
  The correct answer is 35. Like the previous question, the aim of this question is to check the capacity of the operator to understand the overview information of the managed environment.
- **T3: What is the VNF that is processing more packets?**
  The correct answer is Firewall-9. This value can be found by analyzing the size of the nodes in the Forwarding Graph visualization. The purpose of this question is to check the capacity of the operator to explore the visual resources available for having insights.
- **T4: Which tenants have their network traffic processed by Firewall-9?**
  The correct answer is SBC and UFRGS. This value is obtained in the Forwarding Graph visualization. The aim of this question is to evaluate if the operator can identify the service chaining by using our visualizations for FG.
- **T5: How many VNFs are there with saturated bandwidth (higher than 90%)?**
  The correct answer is Firewall-5, Firewall-9 and Load Balancer. To answer this question, the operator must interact with the Forwarding Graph visualization to enable saturation alerts. The purpose of this question is to check if the operator can identify saturated VNFs by using highlighting techniques.
- **T6: Which VNF was migrated more often in the analyzed period?**
  The correct answer is Firewall-5. In this question, the operator must access the Migration History visualization. The purpose of this question is to analyze the capacity of the operator to identify migrations during a given period.
- **T7: Based on the last available information, which hardware is running Firewall-5?**
  The correct answer is Hardware 4. To arrive at this answer, the operator has to analyze the migrations that have occurred. This question evaluates if the operator is able to distinguish between the types of hardware that are hosting VNFs during the day
- **T8: What is the VNF that has most subscribers?**
  The correct answer is VNF-10. In this question, the operator must access the Planning visualization. The purpose of this question is to check the capacity of the operator to interpret and filter the information about VNFs and tenants that are active in the business.

- **T9: Is it true that the VNF with more subscribers is the VNF that is processing more packets?**
  The correct answer is No. To answer this question, the operator must analyze the Planning visualization. Through this question, it is possible to determine if the operator is able to understand each ring that contains relevant information.
- **T10: What VNF type generates most revenue for the business?**
  The correct answer is Load Balancer. In this question, we hope that the operators access the Revenue Flow visualization. The aim of this question is to check if the operator can understand the amount of resources allocated for VNFs and how profitable each type of VNF is for the business.

The final part of the survey was designed to measure the usability of the system by means of the System Usability Scale (SUS), a reliable, low-cost usability scale that can be used for global assessments of system usability (Brooke, John et al., 1996). This scale consists of ten questions the purpose of which is to provide an overview of subjective assessments of usability. These items were very carefully selected to ensure that a half of them had the most preferred response being "strongly agree" and the other half "strongly disagree". On the basis of this analysis, it is possible to detect response biases caused by operators not fully reading and understanding each statement. The items that form the SUS survey are given below.

- S1 - I think that I would like to use this system frequently.
- S2 - I found the system unnecessarily complex.
- S3 - I thought the system was easy to use.
- S4 - I think that I would need the support of a technical person to be able to use this system.
- S5 - I found the various functions in this system were well integrated.
- S6 - I thought there was too much inconsistency in this system.
- S7 - I would imagine that most people would learn to use this system very quickly.
- S8 - I found the system very cumbersome to use.
- S9 - I felt very confident using the system.
- S10 - I needed to learn a lot of things before I could get going with this system.

5.2.3 Results

In general, the participants provided correct answers to most of the questions. Even the questions with more complexity have a greater success rate. The results of the success rate from the specific tasks are presented in Table 5.1. The questions that involves the dashboard (T1 and T2) and migrations history (T6 and T7) achieved 100% of success rate. These questions have less complexity because of the operator do not need to make many operations to obtain the result. However, it prove that the visualizations provide in an intuitive way the relevant information. Another task that had high success rate (100%) was the T10, which make available an overview (in a flow format) of the business revenue.

The visualizations that require more attention and interactions from the network operator also obtain a great result. The tasks T3, T4, and T5 (both related to the Forwarding Graph visualization) was executed almost perfectly. We emphatize that all of the operators that enable the saturation alerts was able to solve with sucess the task T5. However, some operators do not find this option, thus resulting in some errors. Although the visualization for planning obtain a great result as well, we understand that the ausence of a subtitle have difficulted the interpretation for the question T8 and T9. The operators make some confusion about the nodes that represent tenants and VNFs.

Based on the results obtained by the objective answers, we can conclude that our platform achieved the key objectives of providing insights by using interactive visualizations for the NFV management. In all of the tasks, the absolute majority find the correct answers in a fast way. In addition, in average, each participant demands 8 minutes to solve all of the tasks. We advocate that this time can be reduced when the operator acquires more experience with the platform.

Table 5.1: Summary of the success rate achieved in the tasks with objective answers that were asked in the survey

Task	Question	Sucess Rate
T1	How many tenants are available in the platform?	100%
T2	How many VNFs are available in the platform?	100%
T3	What is the VNF that is processing more packets?	92%
T4	Which tenants have their network traffic processed by Firewall-9?	100%
T5	How many VNFs are there with saturated bandwidth (higher than 90%)?	83%
T6	Which VNF was migrated more often in the analyzed period?	100%
T7	Which hardware is running Firewall-5?	100%
T8	What is the VNF with most subscribers?	75%
T9	Is it true that the VNF with more subscribers is the VNF that is processing more packets?	92%
T10	What VNF type generates most revenue for the business?	100%

Source: the author (2017).

The results with regard to user satisfaction were obtained from the decisions about the interface design that are included in the questionnaire based on the System Usability Scale (SUS) and are summarized in Table 5.2. In general, the users liked and understood the proposed visualizations and the layout of the tool. They particularly felt very confident when using the platform and would like to use the platform often. In addition, the platform was considered easy to use and well-integrated by the most of the participants.

To conclude, the SUS feedback was mostly positive, especially regarding the consistency and effectiveness of the platform. The only controversial sentence was S4, which received a 58.4% level of satisfaction. This result can be explained by the fact that a significant number of participants did not read the preliminary instructions, which prevented them from the understanding important features of how to use the platform. Thus, the learning curve for the respondents who did not read the instructions was greater than among the participants that paid attention to it. This lack of attention was also found in the answers to other statements (S2 and S3) that were also designed to check the capacity to learn how to use the platform.

Table 5.2: Summary of results from the SUS survey

ID	Statement	Disagree	Neutral	Agree
S1	I think that I would like to use this system frequently.	8.3%	8.3%	83.3%
S2	I found the system unnecessarily complex.	75%	0%	25%
S3	I thought the system was easy to use.	16%	8.3%	75%
S4	I think that I would need the support of a technical person to be able to use this system.	58.4%	8.3%	33.3%
S5	I found the various functions in this system were well integrated.	8.3%	8.3%	83.4%
S6	I thought there was too much inconsistency in this system.	83.3%	16.7%	0%
S7	I would imagine that most people would learn to use this system very quickly.	8.3%	8.3%	83.4%
S8	I found the system very cumbersome to use.	83.3%	0%	16.7%
S9	I felt very confident using the system.	16.6%	0%	83.4%
S10	I needed to learn a lot of things before I could get going with this system.	75%	8.3%	16.7%

Source: the author (2017).

The analysis of additional comments made by five participants allowed us to understand how they felt about the visualizations, and what alterations they regarded as important. One participant with a color vision problem (called color blindness) suggested that an option to see the visualizations with shades of gray would improve the usability for this group of people. In addition, some operators suggested some modifications to facilitate the navigation in the dashboard. Also, distinct kinds of subtitles were suggested to improve the interpretation of some of the visualizations.

6 CONCLUDING REMARKS

Despite the benefits of NFV, the operator must have an extensive knowledge of the enormous amount of data available to efficiently manage the NFV environment. In fact, understanding these data is a challenging task in itself because of the amount of data involved. To tackle this problem, information visualization can be a viable tool for enabling network operators to investigate tenant demands and improve the performance of VNFs. The benefits of information visualization for NFV planning include the following: it makes it easy to understand the pattern of tenant consumption, the root cause of problems can be quickly discovered, and it simplifies the analysis of resource usage. Moreover, visualization techniques are likely to help the operator in making decisions that avoid service degradation as well as adapting services to market trends. However, despite these potential applications and benefits, visualization solutions are still scarce in the context of NFV. The lack of advanced studies in the area reduces the capacity of network operators to make appropriate decisions, which may hinder the adoption of new technologies such as NFV and SDN.

In this context, we argue that a visualization solution is a powerful tool for the management of NFV. Visualization techniques can be used to facilitate the analysis of complex NFV scenarios, thus enabling network operators to become aware of issues that previously went unnoticed. For instance, a network operator can access the visualization of the history of VNFs to detect recurrent problems and find out what tasks must be carried out to avoid future problems, such as creating affinity rules among VNFs and different types of hardware.

6.1 Summary of Contributions and Results Obtained

In this dissertation, a visualization solution has been outlined to assist in the management of NFV-enabled networks. Our aim was to help network operators to identify and mitigate the cause of problems in NFV that are not obvious, such as the misconfiguration and misplacement of VNFs. VISION was implemented for this, which is, a platform that collects and organizes relevant data from NFV environments, thus enabling us to build interactive visualizations that could simplify the procedure of detecting problems. In addition, our platform provides a well-defined Web-based interface to support the interactions between the operators and proposed visualizations. It should be emphasized that our platform was designed to facilitate the implementation and reuse of visualizations.

Five distinct visualizations were examined that help the operator find out about several issues regarding the management of NFV-enabled networks, such as discovering mistakes in the business strategy and which VNFs require attention. First, a visualization provided a way for network operators to explore the relations between VNFs and tenants through a forwarding graph view. Next, was employed to analyze the behavior of VNFs and events (*e.g.,* SLA disruptions and saturation alerts) by using statistical plots. A further visualization provided a complete overview of the VNFs migrations, thus helping the network operator to know where a given VNF is hosted and how the migration policies work. Finally, we introduced two interactive visualizations to help network operators make strategic planning decisions in an NFV-enabled business.

The case studies provided evidence of the effectiveness and feasibility of these visualizations. We provided a complete forwarding graph visualization, which allows the network operator to see whether there is an incorrect VNF placement and check whether VNFs are overloaded. Without this, the operator has to identify the corresponding forwarding graph and conduct an exhaustive analysis of each VNF to understand the problem. In Case Study #2, the migration logs are transformed into a meaningful visualization that can help the operator discover affinity issues, on the basis of the physical hardware that hosts VNFs. Following this, there are some graph visualizations that can help understand the demands of each tenant, and allow operators to offer services to meet their requirements. In Case Study #4, there is a detailed examination of a scenario where the network operator has to detect failures in resource allocation policies and the flavors available in the business. The operator uses the visualization of relationships and business demands to find out whether there are some VNFs with few resources allocated, which are handling many packets per second, while some VNFs have idle resources. In Case Study #5, the service provider has a substantial amount of capital to invest in infrastructure and has to know the best way to improve the business. Thus, the operator can access our visualization to discover which VNFs and services are most useful for tenants. Finally, we carried out an in-depth investigation of business profits. The operator can use our visualization of allocated resources and generated revenue to determine which is the most profitable group of VNFs, and hence find out which service is more lucrative for the business.

We also conducted an evaluation to measure the usability of VISION. This involved conducting a remote survey aimed to measure the operators' understanding of the overall flow of the platform and their ability to perform objective tasks. We obtained a highly successful rate of correct answers during the survey, and also received excellent feedback on the usability and general aspects of the platform, which was regarded as useful and easy to operate.

6.2 Future Work

In future work, we plan to extend VISION with novel visualizations to address other problems related to NFV (*e.g.,* conflicting policies, incorrect service chaining, and Service Level Agreement issues). In addition, we plan to explore human-centric evaluation techniques to increase the benefits of the VISION platform. We also intend to extend our visualizations to deal with other issues, such as affinities between the parameters of VNFs and security issues. Moreover, we plan to find a collaborative solution that can enable operators to share information and thus help other operators in the area of NFV management. Finally, we seek to support different implementations of NFV (*e.g.,* ClickOS and openNFV) and MANO framework.

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AppendixA PUBLISHED PAPER – AINA 2016

Muriel Figueredo Franco, Ricardo Luis dos Santos, Alberto Egon Schaeffer-Filho, Lisandro Zambenedetti Granville. **VISION - Interactive and Selective Visualization for Management of NFV-Enabled Networks**. The 30th IEEE International Conference on Advanced Information Networking and Applications (AINA-2016), pp. 274 - 281, March 23 - March 25, 2016, Le Régent Congress Centre, Crans-Montana, Switzerland. ISSN 1550-445X. DOI 10.1109/AINA.2016.26.

- **Title:** *VISION - Interactive and Selective Visualization for Management of NFV-Enabled Networks.*
- **Contribution:** Visualization platform to help network operators to have insights about the cause of problems in NFV-enabled networks.
- **Abstract:** Network Functions Virtualization (NFV) enhances the flexibility of network service provisioning and reduces the time to services deployment. NFV and SDN promises transform the carrier networks, introducing innovation in the network core. NFV moves packet processing from dedicated hardware middleboxes to Virtualized Network Functions (VNFs), which run on virtual machines hosted on commercial off-the-shelf servers. However, in NFV-enabled networks, the amount of data managed grows in a fast way. Based on this, the network operator must understand and manipulate a lot of information to effectively manage the network. In this paper, we introduce the VISION, a platform to help the network operator to determine the cause of problems based on visualizations techniques. Our platform implements a set of interactive and selective visualizations to assist in the NFV management. Finally, we conducted three cases studies to provide evidences of the feasibility of our platform.
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VISION - Interactive and Selective Visualization for Management of NFV-Enabled Networks

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***Abstract*—Network Functions Virtualization (NFV) enhances the flexibility of network service provisioning and reduces the time to services deployment. NFV and SDN promises transform the carrier networks, introducing innovation in the network core. NFV moves packet processing from dedicated hardware middleboxes to Virtualized Network Functions (VNFs), which run on virtual machines hosted on commercial off-the-shelf servers. However, in NFV-enabled networks, the amount of data managed grows in a fast way. Based on this, the network operator must understand and manipulate a lot of information to effectively manage the network. In this paper, we introduce the VISION, a platform to help the network operator to determine the cause of problems based on visualizations techniques. Our platform implements a set of interactive and selective visualizations to assist in the NFV management. Finally, we conducted three cases studies to provide evidences of the feasibility of our platform.**

I. Introduction

Network Functions Virtualization (NFV) enhances the flexibility of network service provisioning and reduces the time to services deployment [1]. NFV moves packet processing from dedicated hardware middleboxes to network functions, hereinafter referred to as Virtualized Network Functions (VNFs), running on virtual machines hosted on commercial off-the-shelf (COTS) servers. The benefits offered by NFV allows network operators to create innovative services, reducing the capital expenditure (CAPEX) and operational expenditure (OPEX) [2]. Also, by using NFV, the operator can easily scale network services according to the multiple client-organizations (tenants) demands, offering technical feasibility and potential business opportunities while increases the network innovation.

In NFV-enabled networks, one tenant purchases VNFs that implement different services, such as a firewall and load balancer. The operator must chain these VNFs (*i.e.*, service chaining) in order to comply with the tenant's demands. The European Telecommunications Standards Institute (ETSI) defines such service chaining as a forwarding graph of VNFs interconnected by the virtual network infrastructure [3]. This forwarding graph simplifies the representation of the service chaining, allowing the operator realize daily tasks quickly, such as creating and modifying packets flows along VNFs, deployment of new VNFs, and maintenance tasks.

Although the aforementioned service chaining enables the quick deployment and maintenance of a vast number of VNFs, the operator needs to have extensive knowledge of the enormous amount of data available to efficiently manage the NFV environment. In fact, understanding these data is a challenging task itself because of the previously mentioned amount of data involved. Today, there are several visualization solutions to help in the network management [4] and ease the process of a human have insights into a large dataset, such as identifying policy violations [5] and analysis of security issues in large-scale computer networks [6]. However, none visualization solutions consider the NFV features (*e.g.*, forwarding graph and dynamic migration). As a consequence, solutions based on visualization techniques not support directly the daily tasks related to NFV management (*e.g.*, identifying misplacement and misconfigurations in the VNFs).

Visualization solutions provide several benefits for the network operator tackling problems that arise while VNFs are running. Such benefits include a quickly understanding of the information about the environment [7], identification of VNFs behavior patterns [8], and easy maintenance of VNFs. Today, none of the traditional tools to NFV management explore visualization techniques to help in the process of having insights into the cause of VNFs problems. Thus, we advocate that visualization solutions are powerful tools to assist network operator into problem identification that are not obvious in NFV-enabled networks. For instance, a network operator can access the visualization of a history of VNFs migration to identify recurrent problems and have insights about what rules must be created to avoid problems, such as affinities among VNFs and hardwares.

In this paper, we present VISION (**Vis**ual**i**zation **O**n **N**FV), a platform that implements a set of interactive and selective visualization techniques. Such visualizations assist network operators to identify and mitigate the cause of not obvious VNF problems, such as misconfiguration or misplacement. Besides, our platform: *i*) helps in the identification of problems that impact negatively on the VNF performance, *ii*) provides distinct perspectives about the NFV-enabled networks that allow planning and offering a better service for tenants; and *iii*) provides visualizations that allow looking for behavior standards, which determine affinities issues among VNFs. Finally, we conducted three case studies in a Virtualized Network Function as a Service (VNFaaS) scenario to demonstrate evidence of the feasibility of our platform.

The remaining of this paper is organized as follows. In Section II, we present the related work. In Section III, we introduce our platform and describe each of components and modules. In Section IV, we present three case studies to prove the concept of the platform proposed and realize discussion. Finally, in Section V, we conclude the paper and list future work.

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II. Related Work

Both information visualization and network management areas have received considerable attention from the scientific community. Several visualization solutions support the discovery and analysis of information through visual exploration [4]. These solutions enable human operators to explore and have insights about not obvious network problems, such as conflicting firewall rules [9], network device failures [10], and malicious attacks [11]. Hence, operators can recognize patterns, anomalies, and incompatibility issues in a fast and efficient way. Below, we discuss some of the most important studies in the information visualization area mainly related to the network management.

Liao and Striegel [12] proposed a visual analytic tool based on graph differential anomaly visualization model to find the root causes of anomalies in dynamic graphs. The tool combines both human and computer intelligence for a smarter network operation and management. Several agents collect local context information (*e.g.*, running applications and connections). Such information fed a tool that applies the proposed model and provides different graphs to the network operator. Despite identifying behavior changes of users and applications, which can occur by malicious intention or misconfiguration, this tool neither provides information about conflicting applications and nor considers data from network services.

In another study, Isolani *et. al.* [13] perform an analysis of the control traffic in OpenFlow networks to verify the impact of specific parameters and their influence on the overall resource consumption and network performance. Based on this analysis, the authors proposed a tool that integrates Software-Defined Networking (SDN) monitoring, visualization, and configuration activities. Such tool allows operators to configure and control SDN-related parameters, minimizing the impact, in terms of resource consumption and performance, of the network management. However, this tool only focuses on statistics visualizations and operators customize neither the monitors and nor the generated visualizations.

The Real Status company [14] developed the HyperGlance platform to dynamically aggregates key resource data, relationships, and control functions into a unified, full-scale, interactive visualization for simplified, efficient, cross-platform monitoring and management within a single screen. This platform integrates data from various platforms (e.g., OpenStack, Open Daylight, and Nagios) to generate several visualizations, allowing operators to perform decisions about the whole network. Nevertheless, HyperGlance intends to support NFV environment in the future. Thus, this general solution not covers all issues that concerning the NFV management.

Although the significant attention received by the information visualization and network management areas from companies and academia, none of the solutions explore visualization techniques in NFV-enabled networks. As a consequence, these solutions do not assist human operators to have insights about particular problems, because they ignore important NFV features (*e.g.*, forwarding graph and dynamic migration). To fill this gap, in the next sections, we introduce VISION platform as follows.

III. VISION Platform

In this section, we present VISION (Visualization on NFV), a platform to help the human operator in the problem identification process into NFV-enabled networks. The VISON platform obtains data from the environment and presents it using visualization techniques [15], such as link-node representation, matrix layout, and charts. Our platform provides visual resources that allows network operators to have insights about mitigating the cause of problems in the NFV environment.

VISION considers two main goals to simplify the NFV management and assist in the problem identification process. First, we provide an interactive way to define which data must be visualized and how data are presented. Hence, the network operator can choose the information that will be represented in visualizations. For example, the operator can select statistics to generate a chart that represents only VNFs of the same forwarding graph. Second, our platform collects, organizes, and stores a vast amount of data from distinct sources. VISION communicates with generic NFV platforms (*e.g.*, openMANO) to obtain the available data. Moreover, operators may create and configure their monitors to collect additional statistics in order to enrich VISION database (see Subsection III-B3).

An operator access VISION resources via a Web-based interface that provides details from the collected data, tenants, and configurations. In Figure 1, we show such Web-based interface. This interface contains a dashboard to provide an overview of the NFV environment, such as the amount of VNFs available, resources usage, and migration alerts. Besides, the Web-based interface provides significant information about the network traffic, allowing observe how much traffic is generated by tenants. Also, logs from relevant events (*e.g.*, migrations and failures of VNFs) are available on the dashboard. Such interface was implemented using Django framework 1.8.5 and as database engine PostgreSQL 9.4.5.

In Figure 2, we present VISION conceptual architecture. The main components and modules are, respectively, highlighted with dark gray and white background. As can been seen, a generic NFV environment contains the follows components: *i)* Network Function Virtualization Infrastructure (NFVI), which enables the software to run independently of the hardware, *ii)* Virtualized Network Functions (VNFs) that moves network functions from dedicated hardware devices to software hosted in COTS servers; and *iii)* NFV Management & Orchestration (MANO) [16], which has three components to monitor and configure the NFV environment: Virtualized Infrastructure Manager (VIM), VNF Manager, and Orchestrator.

In MANO, VIM monitors and controls computing, storage, and networking resources of the NFVI domain. VNF Manager performs several VNFs operations (*e.g.*, deployment and migrations). In addition, this manager stores data about configuration and VNFs events (*e.g.,* alarm to SLAs disruptions). Finally, the Orchestrator realizes the global resource management, validation, and authorization of NFVI resource requests. Besides, such component includes performance measurements and policy management for VNFs. These components have a significant amount of meaningful information. For instance, the orchestrator has a textual representation of forwarding graph (service chaining) and perceives when VNFs are migrated. As

Fig. 1: VISION Web-based interface

such, the MANO framework information is crucial to populate VISION platform database. The Data Collector component collects this information and a set of specific statistics (*e.g.*, CPU usage and memory diagnostics) available in the custom monitors.

VISION architecture (Figure 2) contains three main components, which are in charge of collecting, organizing and providing visualizations for the network operator. First, the Data Collector gathers data from the NFV environment. Second, the Data Processor manipulates and stores such data in a database. Finally, the Visualization Manager builds the visualizations. All of VISION components are described in the rest of this section.

A. Data Collector

The Data Collector component obtains data (*e.g.*, VNFs events and textual forwarding graph representation) from MANO implementation. For this, the Data Collector sends GETs messages via API REST (Representational State Transfer) to MANO. Besides, this component may collect data from customized monitors placed into the VNFs. The network operator must configure, in VISION platform, the monitors parameters (*e.g.,* correspondent VNF, hardware, and IP address from the monitor) to allow the data collection.

Currently, VISION platform is able to acquire data from openMANO framework [17]. We choose this framework because it is the first open source project that provides a practical implementation of the NFV Orchestration and Management. The openMANO offers a northbound API that allows getting information from the NFV environment, such as resource allocation and VNFs events. The process of collecting data is based on REST requests. The response of each request is a JSON with information from the object. For example, the request *GET /openvim/hosts/*{*host_id*} returns information about each of interfaces attached on the *host_id*.

Data Collector can get data from another source to enrich VISION database. For this, such component requests data from customized monitors strategically placed in the NFV environment. The network operator can create and configure such monitors to obtain additional statistics from VNFs, such as CPU usage and memory diagnosis. Besides, these monitors can collect specific information (*e.g.,* data about Firewall's rules and packet process errors). Our platform requests and receives data from monitors via a socket connection. For instance, the request *GET* {*monitor_IPaddress*} returns a JSON with information from the specific monitor, *e.g.*, latency and memory usage.

After collecting the data from the MANO and monitors, the component sends such data to the Data Processor component, which separates, organizes, and classifies the information (see Subsection III-B). Then, the Data Processor stores the information in VISION database, thus completing the process of acquiring and manipulating the data.

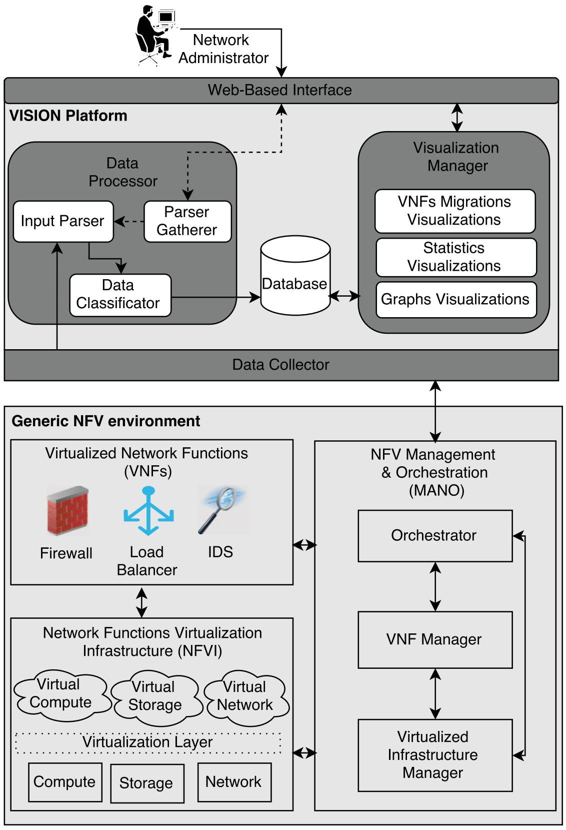

Fig. 2: Conceptual Architecture of VISION

B. Data Processor

Data Processor inspects, transforms, and models the data to discover meaningful information. This component manipulates the data to obtain a readable information for others modules. Such manipulations include extracting and organizing the relevant information while removing not usable data. This component is divided in three modules: *i)* Input Parser, *ii)* Data Classificator; and *iii)* Parser Gatherer.

1) Input Parser: The Input Parser module is the first phase of Data Processor. It main function takes the input data and builds a data structure to giving a structural representation of the data, such as organize the data in tables where the columns and lines are representing information from VNFs. Moreover, this module checking for incorrect syntax (*e.g.*, information outside the accepted standards) and identifying failures in the process of acquiring data.

2) Data Classificator: This module tags and classifies the data based on shared characteristics (*e.g.*, create a data structure that represents the VNFs hosted by the same hardware). Such characteristics define groups of VNFs to ease information access. The classification of data allows other VISION components to access quickly and filter the information in order to create customized visualizations, such as shows only statistics from VNFs contracted by a specific tenant. After this step, the data is stored in the database by Data Classificator and available to be requested by VISION platform.

3) Parser Gatherer: This module allows the operator to upload a new parser, in order to assure the manipulation of data from customized sources and formats. Such customized parser must be a Python script, which creates new rules about how the Input Parser will deal with data received from the Data Collector (*e.g.*, defining a new rule to discard the first five columns). This module takes the input data and manipulates according to rules predefined, ensuring that different data will be recognized. Moreover, the operator can configure and use a new parser for each one of the monitors. For example, considering that the Data Collector sends data from two distinct monitors, which contains the information divided, respectively, by commas and semicolon. The Input Parser must separate both data correctly, for this, the operator uses differents implementations of the parser to deal with such data.

C. Visualization Manager

The Visualization Manager builds visualizations based on the information available in VISION database. This component explores visualization techniques, such as forwarding graphs and statistics charts visualizations, to provide an interactive and selective view of the NFV environment. Such visualizations help the network operator to identify the cause of problems. In addition, this component receives and processes the parameters to customize the visualization modules, such as which information will be presented and how the visualization will occur.

This component is divided in three modules, which allows the human operator having insights about not obvious problems: *i)* Statistics Visualization, *ii)* VNFs Migrations Visualization; and *iii)* Graphs Visualization. Below, we describe each one of the visualization modules individually.

1) Statistics Visualization: The statistics about VNFs are important to alert the network operator when a problem is occurring. For example, the network operator may analyze events messages that suggest a VNF saturated. With this information, the operator can conduct a more in-depth analysis to have insights about the cause of the problem that impacts on the VNF performance. The Statistics Visualization module provides intuitive visualizations to improve the understanding of VNFs behaviors. The operator can select the available statistics from VNFs (*e.g.*, latency, propagation delay, and CPU usage). Moreover, any specific statistics collected by customized monitors can be presented in a useful visualization. In Figure 3, we show an example of this visualization. In this example, we present a line chart that display a physical host CPU usage along the time. Such visualization helps the operator to understand some behaviors, such as the latency oscillation along a day and what is the VNF behavior when is processing a lot of packets.

An essential feature of Statistics Visualization module is the comparison of distinct statistics from several VNFs (*e.g.*, difference in the latency of VNF-A and VNF-B along the monitoring time). This module provides real-time information for each monitored VNF, such as a number of packets processed and the resources usage. Moreover, the network operator can use the Statistics module to improve others

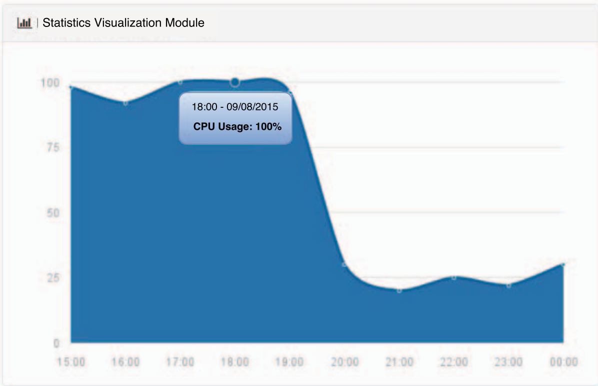

Fig. 3: Example of Statistics Visualization module

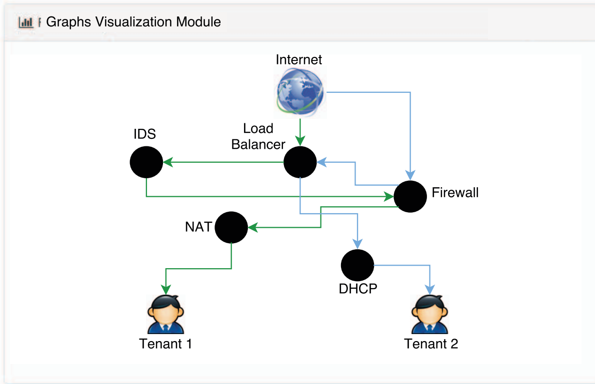

Fig. 4: Example of Graphs Visualization module

visualization modules. For instance, VISION platform can provide a visualization of the VNF migration history, enriching it with novel statistics (see Subsection IV-B). Thus, when the operator clicks in determined VNF, the Statistics module is invoked to provide information about the selected VNF (*e.g.,* build a line chart that shows the CPU usage history).

2) VNFs Migrations Visualization: VNFs can be dynamically migrated, and it brings additional complexity for the network operator know where a given VNF is hosted (*i.e.*, VNF placement). Besides, migrations can have several impacts on the NFV environment, such as affecting VNFs performance when affinities issues are not respected and difficulting for the operator knows where a VNF is hosted. We argue that the analysis of the historical behavior provide a better understanding of the present. Based on this, we store, in the database, information about all of migration events. With such information, we provide a visualization for assisting the operator in identifying the exact time when a VNF presented a misbehavior, textite.g., what VNFs were sharing the same physical resources when a problem occurred.

VNFs Migrations Visualization module provides a full overview of migrations. In this module, the operator selects VNFs to be analyzed, and VISION shows in a clear perspective the hardwares that hosted these VNFs. Also, this module interacts with the Statistics Visualization module to enrich the visualization with charts and statistics about each VNF (*e.g.*, display in a chart the latency of VNFs along the time). Moreover, the network operator can customize these visualizations to obtain useful information, such as highlight VNFs and compare statistics among them. Thus, several issues can be explored with this visualization. For example, if two or more VNFs are not running fine when sharing the same physical hardware, the operator identifies it and may create rules for anti-affinity among these VNFs, preventing that unwanted behaviors arise in the network.

3) Graphs Visualization: Graph theory studies structures to model the relationship among nodes [18]. Based on this, we implemented a module to provide a way for network operators explore the relations between VNFs and tenants. Such module helps humans operators to identify some problems. For example, the network operator can understand the demands of the NFV-enabled network and plans how the VNF instances will be shared among tenants. Besides, this module provides a meaningful view about the forwarding graphs, facilitating the problem identification, such as when a VNF placement incorrect impacts negatively on the performance of another VNF (see Subsection IV-A). In Figure 4, we present a visualization built by VISION that represents two tenants and their respective forwarding graphs. In this visualization, the blue lines represent the service chaining of Tenant 1 and green lines the chaining of Tenant 2.

The Graphs Visualization module provides others visualizations that help in identification process of the distinct problems, such as the consumption resources profile of each tenant and visualization for the relationship between tenants and VNFs. Moreover, such module has several optional settings to improve the human perception and the flexibility of visualizations. For example, the operator can configure attributes, such as color and size of nodes to represent different information (*e.g.*, the level of CPU usage and packets processed). Thus, the human operator can suppose that a VNF node, represented by a big circle, received a lot of packets to be processed, and VNFs, with a red color node, the CPU usage saturated.

IV. Case Studies

We analyze different scenarios to evaluate the technical feasibility of VISION platform. All of this case studies considers a VNFaaS (VNF as a Service) scenario, which contains VNFs from service provider's application and several costumers of the service (tenants). In this section, we detail three case studies focus on distinct problems that can occur in the NFV environment. First, we explore the graphs and the statistical visualizations modules to provide a way for determining VNFs bottlenecks. Second, we investigate affinities among VNFs, using the migration and statistical module. Finally, we present a visualization to understanding the necessities of each tenant. As a result of these analyzes, we observe the effectiveness and the feasibility of VISION.

A. Case Study #1

Let's suppose a scenario with four VNFs (Deep Packet Inspection – DPI, Firewall, Load Balancer, and Network Address

Translation – NAT) and three distinct tenants sharing these VNFs, but with different forwarding graphs. In this scenario, the network operator receives several complaints from the tenant 1 about the performance of the contracted service. In a preliminary analysis, the operator does not have sufficient information to identify the cause of the problem, although the NAT performance presents abnormal behavior (saturated network bandwidth). Thus, a more in-depth analysis is required to determine the cause of the problem.

Another way to deal with the aforementioned problem is to analyze one by one all VNFs that compose the service chaining of tenant 1. However, this imposes several challenges (*e.g.*, verify a lot of statistics), increasing the time to identify the cause of the problem. Moreover, the operator must access the information about each forwarding graph, in order to understand how the VNFs are shared among tenants. In this way, the traditional management without visualization is not efficient to address the problem, because is not trivial for humans have insights into textual information about a lot of statistics.

Our platform improves the capacity of operator have insights about VNFs misbehavior that provoke problems in another VNFs. For this, the operator may interact with the Visualization Manager to access the global view about the forwarding graphs. In this visualization, each node represents a VNF and has the size defined by the number of packets that are processed. In addition, the nodes are represented with a red color border when some observed statistic is saturated (*i.e.*, network bandwidth usage higher than 90%). In addition, the color of edges represents the forwarding graphs of each tenant (black lines represents the tenant 1 service chaining, blue lines the tenant 2, and green lines the tenant 3). Also, the color of nodes represents the hardware where a VNF is hosted (blue nodes are hosted in one hardware and green nodes are in another) In the Web-based interface, the network operator defines saturation thresholds and chooses the statistics that will compound the visualization. Using this visualization, the operator can identify VNFs with abnormal behavior, analyzing individual statistics (*e.g.,* latency and network bandwidth) to find bottlenecks.

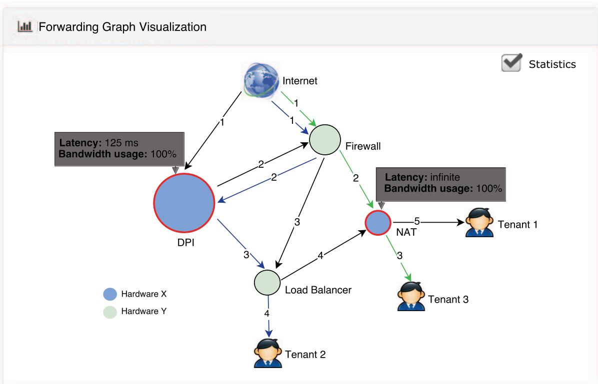

Fig. 5: Forwarding graphs and statistics visualizations

In Figure 5, we present the visualization that helps the operator to identify the cause of the problem. The numbers in the edges represent the sequence of the service chaining. As can be observed, the NAT and DPI are saturated. But, it is not sufficient to understand the problem. However, we can note that the DPI is receiving more packets from the Internet that can process. Based on this visualization, we can see that the hardware that host both DPI and NAT are with the bandwidth saturated. As a consequence, the NAT cannot receive and deliver the packets to the next hop, because of the congestion caused by this saturation. Thus, we can conclude that the forwarding graph of the tenant 1 and 3 are crashed due to incorrect placement of VNFs.

The network operator must take decisions about how the DPI is running. For example, the Firewall perform fewer in-deep analyzes than DPI. Therefore, the operator changes the forwarding graph, putting the firewall to process packets prior to the DPI. In another solution, the network operator can maintain the original forwarding graph, performing changes directly in the DPI, such as create affinity rules to host the DPI in hardwares with more resources and capacities to sustain the high demands.

B. *Case Study #2*

The placement of VNFs focuses on finding a physical host that has the resources available to run properly the service. However, the placement of a set of VNFs in relation to each other is not considered, even though affinity and anti-affinity rules are recognized [19]. An affinity rule expresses that VNFs must be hosted on the same hardware, whereas anti-affinity requires that VNFs are instantiated on distinct physical machines. If these rules are not well defined, VNFs with anti-affinity can be placed on the same host. As a consequence, one VNF will present misbehavior and impact negatively in the service provided.

The identification of affinities among VNFs is a very complex task. Such complexity increases when the operator does not have the appropriate resources. For example, if operators try to understand the affinities issues just using traditional management tools. Thus, they will only access the available events logs and will spend a lot of time to analyze textual information about migrations of each VNF. Nevertheless, the identification of affinities issues will be not evident.

Let's suppose the following scenario: the network operator, based on previous reports, observes that a virtual instance of Firewall is presenting sudden changes in its performance along the day. The first analysis indicates that it caused several impacts in the service provided, such as increasing the propagation delay and spoiling the packet processing. Thus, the operator adopts VISION platform to try identifying and mitigating this problem. Initially, the visualizations provide information to conclude that VNF performance worsens when migrations events occur. Based on this, the network operator must analyze VNFs migrations to understand the problem.

In Figure 6, we present a migration history visualization and statistics from VNFs. In this visualization, the operator can select what statistics data will be available about VNFs, showing them in a line chart to understand the behavior of VNFs along the time. Meanwhile, another visualization provides a view about what physical structure hosts these VNFs. Thus, the operator uses both visualizations to understand the nature

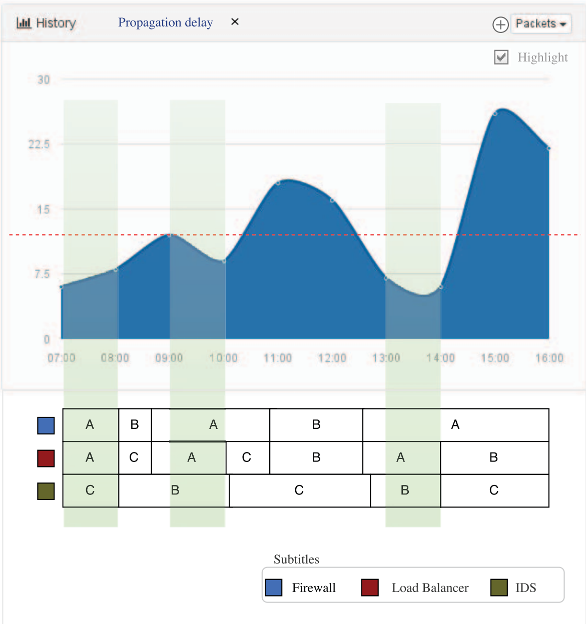

Fig. 6: Visualization for VNFs migration history

of problems in the NFV network. In this visualization, a red dotted line can be moved to define what is the threshold for the observed statistic. With this, the operator has a more clear view when the statistic value is high (*e.g.*, when the latency is high). Besides, we can highlight the interval where the values are apparently fine.

The network operator has identified that the blue VNF (Firewall) is working fine when shares the same physical host that the red VNF (Load Balancer). It can be viewed in Figure 6 analyzing the times 07:00 to 08:00, 09:00 to 10:00, and 13:00 to 14:00. Based on this, the operator has an insight about the problem: the affinity among the Firewall and the Load balancer are not respected. Thus, in order to mitigate the problem, the operator must create one affinity rule to host both VNFs on the same physical hardware.

C. Case Study #3

The network operator manages the VNFs to provide a great service for the tenants. For this, the operator must have a view about the distribution of VNFs and the consumption profile of each tenant to support all performance requirements. The available information is fundamental to identify the specific demands and foresee the impacts of maintenance activities on the service. The current solutions for NFV management do not provide features that help the operator manage this information to have insights, which contribute to planning the network management. For example, the maintenance of determined VNF can have a significant impact on a high priority tenant (based on politics of priorities). Thus, the operator repairs VNFs when there is a minor traffic of such tenant, avoiding several consequences in service contracted. Visualization allows the operator to analyze the demands, and, thus, offering specific services for each tenant, such as instantiating a dedicated Firewall for one tenant or increasing the resources available for a VNF.

In an NFV environment, there are four shared VNFs (NAT, DHCP, Firewall, and Video Transcoding) among three tenants (Tenant 1, 2, and 3). The tenant 1 contracted the Firewall, DHCP, and NAT services, whereas the tenant 2 uses only the Firewall and DHCP. The VNFs correspondent to DHCP, NAT, and a particular Video Transcoding supply the tenant 3 demands (Figure 7). In this environment, the network operator receives a performance service complaint from a high priority tenant (tenant 1). Based on this, the operator must reassure that the hight priority tenant demands will be satisfied, considering that one or more VNFs are shared. For this, the information about the network and specifics demands of each tenant 1 must be analyzed to reorganize the distribution of VNFs. An example of these information are: *i)* what VNFs are being shared by two or more tenants, *ii)* which tenant use more determined VNF; and *iii)* what is the performance requisites for each tenant.

In order to provide ways for operator understanding the information from the network, we use a technique known as the forced-direct graph. This technique defines forces to attract or repulse pair of nodes. Thus, we can represent the proximity between VNFs and tenants based on the pre-defined statistic (*e.g.,* the VNFs are near to the tenants that send more packets to process). Using VISION interface, the operator can choose another statistic to create the forced-direct graph, such as physical resources usage and geographic localization. This visualization presents an overview of the different relationships among nodes, assisting in some NFV management issues, *e.g.,* the operator can perceive when the geographic location of the physical hosts is impacting in the VNFs performance.

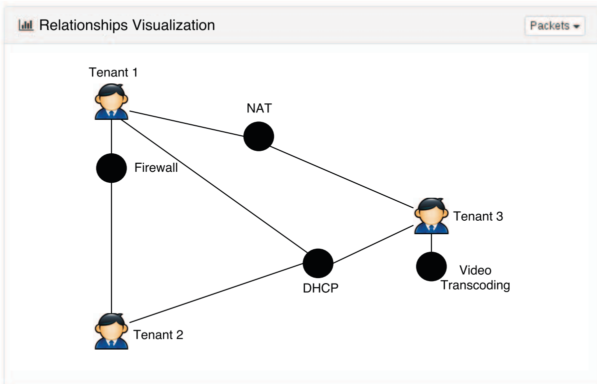

Fig. 7: Forced-direct graph based on the consume of each tenant

Figure 7 shows the relationships between VNFs and tenants (*i.e.,* which VNFs is available to each tenant). The number of packets processed defines the distance among two nodes. For example, this visualization suggests that an instance of Firewall, although shared by both tenant 1 and 2, is more requested (in terms of packets processed) for the tenant 1. Hence, this visualization provides a better view of the utilization profiles, helping the network operators to provide services that will attend the tenants' demands. Thus, the operator can offers for the tenant 1 a dedicated Firewall that prioritize it high demands.

V. Conclusion and Future work

In this paper, we introduced VISION (**Vis**ual**i**zation **O**n **N**FV), a platform that implements a set of interactive and selective visualization techniques. Such visualizations help network operators to identify and mitigate the cause of not obvious VNF problems, such as misconfiguration or misplacement. To sum up, in this paper we: *i)* implement an approach to collect and organize data from NFV environment, *ii)* provide visualization solutions to simplify the identification of the cause of some VNFs problems; and *iii)* help the operator to have insights about several issues related to NFV-enabled networks management.

Case studies reveal that VISION platform provides useful visualizations that simplify the understanding of the information and, as a consequence, the network operator can have insights into the cause of problems. In the Case Study #1, VISION provides a complete forwarding graph visualization, which allows the network operator to perceive incorrect VNF placement and VNFs overloaded. Otherwise, the operator needs to identify the correspondent forwarding graph and exhaustively analyze each VNF to understand the problem. In the Case Study #2, we transform migrations logs in a meaningful visualization that helps the operator to identify affinity/anti-affinity issues, based on the physical hardware that hosts a VNFs. Finally, in the Case Study #3 are presented helpful graphs visualizations to understand the demands of each tenant, allowing operators offer services to supply their demands.

As future work, we plan to extend VISION with novel visualizations to support another VNFs problems (*e.g.*, conflicting policies, incorrect service chaining, and Service Level Agreement issues). In addition, we plan to investigate about human-centric evaluation techniques to quantify the benefits of VISION platform. Also, we intend to extend our visualizations to support other issues, such as affinities among VNFs running parameters and security issues. Finally, we aim to support another implementation of NFV (*e.g.*, ClickOS and openNFV).

Acknowledgements

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AppendixB PUBLISHED PAPER – AINA 2017

Muriel Figueredo Franco, Ricardo Luis dos Santos, Ricardo Cava, Eder John Scheid, Ricardo Jose Pfitscher, Carla Dal Sasso Freitas, Lisandro Zambenedetti Granville. **Interactive Visualizations for Planning and Strategic Business Decisions in NFV-Enabled Networks**. The 31st IEEE International Conference on Advanced Information Networking and Applications (AINA-2017), Taipei, Taiwan. (to appear)

- **Title:** *Interactive Visualizations for Planning and Strategic Business Decisions in NFV-Enabled Networks*.
- **Contribution:** A couple of interactive visualizations to support planning and strategic decisions into NFV-enabled business.
- **Abstract:** Network Functions Virtualization (NFV) is driving a paradigm shift in telecommunications networks, fostering new business models and creating innovation opportunities. In NFV-enabled networks, Service Providers (SPs) have the opportunity to build a business model where tenants can purchase Virtual Network Functions (VNFs) that provide distinct network services and functions. However, the chance to negotiate VNFs requires a change in traditional network planning strategies to accommodate tenants demands. In this context, the planning tasks perform a critical role in the introducing of business strategies that encompass both profit and health of services, which requires operators to have a broad understanding of the environment. In this paper, we propose the usage of two interactive visualization techniques to help NFV network operators in planning and strategic decisions. We advocate that our visualizations can aid in NFV planning tasks, such as infrastructure investment, resources allocation, and service pricing. We present three case studies to provide evidence of the feasibility and effectiveness of our visualizations.
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Interactive Visualizations for Planning and Strategic Business Decisions in NFV-Enabled Networks

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***Abstract*—Network Functions Virtualization (NFV) is driving a paradigm shift in telecommunications networks, fostering new business models and creating innovation opportunities. In NFV-enabled networks, Service Providers (SPs) have the opportunity to build a business model where tenants can purchase Virtual Network Functions (VNFs) that provide distinct network services and functions. However, the chance to negotiate VNFs requires a change in traditional network planning strategies to accommodate tenants demands. In this context, the planning tasks perform a critical role in the introducing of business strategies that encompass both profit and health of services, which requires operators to have a broad understanding of the environment. In this paper, we propose the usage of two interactive visualization techniques to help NFV network operators in planning and strategic decisions. We advocate that our visualizations can aid in NFV planning tasks, such as infrastructure investment, resources allocation, and service pricing. We present three case studies to provide evidence of the feasibility and effectiveness of our visualizations.**

Keywords – Network Functions Virtualization; Network Management; Network Planning; Information Visualization.

I. INTRODUCTION

Network Functions Virtualization (NFV) decouples packet processing from dedicated hardware middleboxes to Virtual Network Functions (VNFs) running on commercial off-the-shelf servers [1]. NFV itself and the fact that it changes service provisioning have attracted many interests from industry and academia [2]. The NFV benefits include the potential to speed up service delivery, simplified network operations, and reduced costs. Today, NFV concept is driving a paradigm shift in telecommunications networks, fostering new business models and creating innovation opportunities. By adopting this concept, network operators can readily deploy and configure network services to offer solutions for distinct customers profiles, supporting multiple tenants demands.

Service Providers (SPs) have the opportunity to migrate their legacy networks to networks based on NFV and Software-Defined Networking (SDN). In NFV, SPs have the opportunity to build a business model where tenants can purchase VNFs that provide distinct network services and functions [3]. That model benefits tenants (*e.g.,* by reducing capital/operational expenditures and easing the contract of new services) while increasing SP's revenue. However, the ability to negotiate VNFs requires a change in traditional network planning strategies to accommodate tenants demands, such as changing the strategy to offer VNFs with high performance and trustful operation according to tenant's interests. Thus, planning strategies for such networks not only are based on cost minimization but also require the maximization of flexibility to support the market's competitive landscape.

Planning tasks in NFV-enabled networks require operators to have a broad understanding of the environment to propose business strategies that encompass both profit and health of services. In summary, the operator must consider three key aspects of NFV planning: *(i)* service infrastructure requirements, which represent the virtual and physical available resources; *(ii)* tenants consumption profiles, which allows the understanding and prediction of the network usage; and *(iii)* characteristics inherent to VNFs, such as resources contracted by tenants and packets processed. This information leads SPs to drive the direction of the business, providing adequate information for the network operator to create a strategy to increase the business competitiveness. Also, planning helps operators to improve the capacity of the business (*i.e.,* number of tenants allowed and VNFs available), the service performance, and consequently, the SPs revenue.

Relevant information and relationships between VNFs and tenants are complex to understand by using traditional planning tools because they cannot deal with all key aspects of NFV planning, such as providing information for the network operator to have insights about the necessity of changing VNFs configurations and investments priorities. To tackle this issue, information visualization can be a viable tool for network operators to investigate tenant demands and improve business strategies. The benefits of information visualization for NFV planning include the easy understanding of the tenant consumption profile, fast identification of VNFs that generate more revenue, and simplified analysis of resources usage. Visualization techniques are likely to help the operator in making decisions that avoid service degradation as well as adapting services according to market trends. However, despite these potential applications and benefits, visualization solutions are still scarce in the context of NFV [4]. The lack of mature work in the area reduces the capacity of network operators of making appropriate decisions, which may event inhibit the adoption of new technologies such as NFV and SDN [5].

In this paper, we present a solution to aid network operators and vendors in the planning on NFV business models. We extend the VISION platform [6] to provide an interactive visualization based on Hierarchical Edge Bundling technique [7] that helps operators understand the behavior of the environment where VNFs run, such as easily identifying the most common tenant's requests and how the available VNFs supply it. This visualization provides insights for a better planning of infrastructure investment, resources allocation policies, and service prices. We also present a visualization using the Sankey diagram technique [8] to correlate resources allocation, VNF usage, and profits. Thus, the operator can identify behaviors that are incompatible with the business strategy (*e.g.,* overprovision of resources for not profitable VNFs) to have insights about how to improve the business. Finally, we conducted three case studies in different scenarios to show the application and feasibility of our visualizations.

The remaining of this paper is organized as follows. In Section II, we review related work. In Section III, we introduce our visualizations and give details about them. In Section IV, we present three case studies to demonstrate the feasibility of our visualization solution. Finally, in Section V, we conclude the paper and comment on future work.

II. Related Work

Designing a computer network to support all business requirements is a hard task and involves several decisions that impact on service levels, profits, and competitive advantage. Such decisions are even more challenging when network technologies in place tend to be more disruptive than traditional wired networks, such as SDN, NFV, and wireless communications. These new technologies require specific planning tools and strategies to both guarantee high-quality services for customers and assure SP's profits. The current literature on network planning include works that address topics as diverse as optimizing energy efficiency in data centers [9], analyzing data of mobile applications [10], and improving security in future networks [11]. In this Section, we review some relevant studies on network planning, mainly those related to new technologies and challenges in networking.

EI-Beaino et al. [12] investigate wireless network planning for the upcoming 5G networks. The planning process is focused on the deployment of wireless networks with requirements with regard to coverage, capacity, and quality of service (QoS). The authors were able to minimize the number and optimize the location of base stations in a selected geographical area using a heuristic algorithm. In another study, Plets et al. [13] perform an evaluation of two wireless network planning approaches for a very large industrial hall. The inconclusive results indicate that more studies for network planning in large environments are required for filling the gap in the area. Moreover, the authors highlighted that no wireless network planners available so far could deal with intra-network interference.

Pavon-Marino and Izquierdo-Zaragoza [14] propose the Net2Plan, a visual solution devoted to planning, optimization, and evaluation of communication networks. Net2Plan can also support the development of distinct planning tools. Izquierdo-Zaragoza et al. [15] discuss the opportunities and challenges of interactions between SDN controllers and current network planning tools. The authors propose a Net2Plan tool and investigate the capacity to orchestrate an OpenFlow-based network on top of the OpenDaylight controller. However, although the Net2Plan solution can be adapted for planning networks of any technology, it is limited to the tasks of network design, traffic evaluation, and generation of reports. Moreover, the original features of Net2Plan do not provide visualizations to support planning decisions in a business model based on NFV-enabled networks.

Velasco et al. [16] propose a novel network planning framework, which allows the network operator to plan and reconfigure the network dynamically according to traffic changes. The authors report two case studies regarding transport networks, showing that resource overprovisioning can be minimized and that overall network costs can be reduced. However, as was not their focus, such framework does not provide ways for the network operator to have insights about business strategies or customers profile.

At the industry side, the Real Status company [17] maintains the HyperGlance platform to aggregate resources data and relationships into a unified and interactive visualization. HyperGlance integrates data from various sources (*e.g.,* OpenStack, OpenDaylight, and Nagios) to generate useful visualizations, hence improving the network operators capacity for planning and managing complex networks. Nonetheless, HyperGlance neither supports NFV technology nor covers particular issues concerning NFV planning.

Although network planning has received significant attention from researchers and companies, none of the existing solutions exploits planning of NFV-enabled networks. As a consequence, there is a lack of tools that deal with NFV features and its business opportunities. We also emphasize that information visualization techniques be generally underused as a resource to assist network operators in NFV planning tasks. To address this situation, in the next sections, we introduce our visualization techniques designed to support NFV planning.

III. Visualization Solution for NFV Planning

In this section, we present a set of visualizations to assist network operator in NFV planning tasks (*e.g.,* capital investment and resources allocation). Our solution is composed by visualizations that consider static and dynamic information from NFV environment to allow operators to understand the business strategy and tenant's demands in a clear way. Hence, the operator can have insights to make strategic decisions about the NFV business, such as determining how to invest correctly in infrastructure and performing actions that avoid future problems in service performance. In essence, our visualizations are based on two main visualization techniques: *(i)* Hierarchical Edge Bundling technique [7] to visualize the relationships and the edges adjacency in complex graphs; and *(ii)* Sankey Diagram [8] that implements a technique to explore complex flows scenarios. These techniques were found as valuable for this study and have been adapted to meet the specific needs of NFV-enabled networks planning.

We have implemented the proposed visualizations as templates on VISION platform, which was developed in a previous work [6] aiming at simplifying the management of NFV-enabled networks and assisting in problem identification process. VISION obtains and manipulates data from an NFV environment and presents it using visualization techniques, thus helping human operators understand and avoid recurrent VNF problems. One of the richest features of VISION is the capacity to integrate new visualization solutions; it allows the reuse of modules of the platform in the implementation of new visualizations. For example, an operator can implement visualizations on the web-based interface and use the data layer module to obtain and access information. Therefore, VISION is responsible for collecting and processing the data from the NFV environment, hence allowing us to focus in proposing novel visualizations techniques for NFV planning.

Although VISION collects several data from the NFV environment, it does not consider the information from the VNF Descriptor (VNFD) and Network Service Descriptor (NSD). The European Telecommunications Standards Institute (ETSI) specifies the VNFD file as a template which describes a VNF in terms of deployment and operational behavior requirements [18]. Also, the NSD file is defined to present the network service in an XML notation, including the virtual hardware requirements, dependencies, and conflicts. These descriptors files define important details about how the VNFs will run, such as the amount of required resources for each VNF, distinct flavors available (*i.e.,* contractable plans that define how much resources will be allocated for each VNF), and capacity of the network. Thus, descriptors are valuable for planning decisions. To obtain this data, we extend the Data Collector module to be able to collect and store data from VNFDs and NSDs available in the NFV environment. Also, we implement a new module that is responsible for providing visualizations templates for the Visualization Builder module.

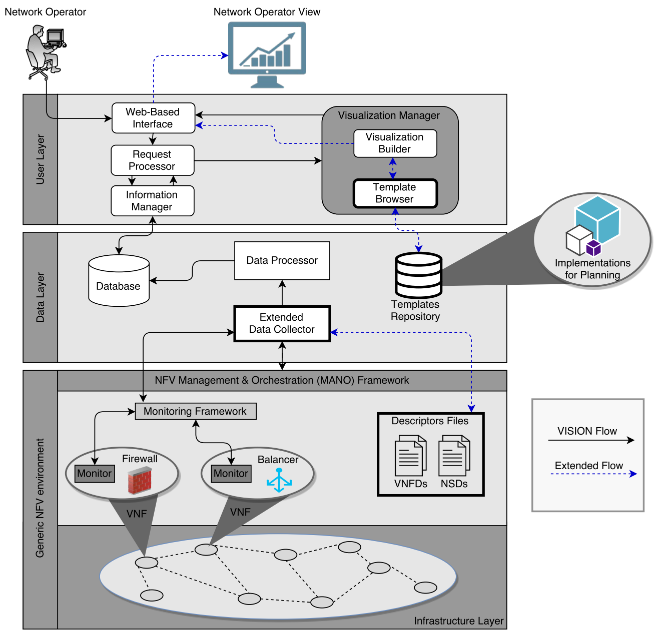


Fig. 1: Extended Conceptual Architecture of VISION

In Figure 1, we introduce the extended VISION conceptual architecture, in which the flow to collect information and create visualizations are depicted with solid lines. Moreover, the dashed lines show the extended flow with new connections that we implemented to build our visualizations. The new modules and components are highlighted with bold borderline. VISION architecture (Fig. 1) is organized in three distinct layers to isolate the modules in relation to their function: *i)* User Layer contains modules that implement the user interface, processes requests, and creates visualizations; *ii)* Data Layer contemplates the modules in charge of collecting, processing, and organizing the data from NFV environment and monitors; and *iii)* Generic NFV environment layer represent the infrastructure and the NFV correspondent elements.

As suggests the architecture flow, we can follow three main steps to build the proposed visualizations. First, the Data Collector communicates with the MANO (Management and Orchestration) framework, VNF monitors, and Descriptors files (extended feature) to populate the database with relevant information. Next, the Data Processor prepares this information to be available for the Information Manager requests. Finally, the Visualization Manager selects the templates and creates the visualizations according to the operator requests.

The Data Collector module obtains data (*e.g.,* VNFs events and textual forwarding graph representation) from MANO framework. For this, the Data Collector can send GETs messages via API REST (Representational State Transfer) to MANO. This module can also access the NFV descriptors files directly to extract information. Besides, this module may collect data from customized monitors placed into the VNFs. The network operator must only configure, in VISION platform, the monitor's parameters (*e.g.,* correspondent VNF, hardware, and IP address from the monitor) to allow the data collection. We define the initial polling time for data collecting as five minutes, but it can be changed in the platform settings, by the operator.

Although the proposed work uses an existing architecture, it is not limited to it. In the rest of this section, we will introduce two visualizations techniques to tackle the challenges of planning and strategy changes in NFV business models. A prototype with main features of our visualizations is available online[1]. This prototype was implemented using the d3js library, which is a javascript library for manipulating documents that allows creating interactive visualizations.

A. *Visualization of Relationships and Business Demands*

In NFV-enabled networks, we have some VNFs from service provider's application and several tenants of the service. The operator needs to have extensive knowledge of the information about relationships and demands related to the business actors (*i.e.,* tenants and VNFs) to efficiently plan the NFV business. In fact, understanding this information is a challenging task itself because of the amount of data involved. In order to simplify the planning tasks, we propose a visualization of relationships and business demands. Our visualization is an adaption of the ClusterVis technique [19], which is an interactive visualization to represent relationships between entities along with multiple attributes. ClusterVis borrows ideas from the Hierarchical Edge Bundling technique [7]. With this visualization (Fig. 2) we present information about the NFV environment in a useful way to ease the planning tasks. The network operator, for instance, can analyze and compare statistics (*e.g.,* how much resources are allocated for each VNF or tenant) to have insights about how to improve or maintain the service health.

The visualization consists of a central circle that contains nodes representing the business actors. The blue and yellow nodes are, respectively, the tenants and VNFs that compound the business. The blue lines inside the main circle show the relationship among the nodes. For instance, a tenant node

[1] http://inf.ufrgs.br/˜mffranco/VisPlanning/

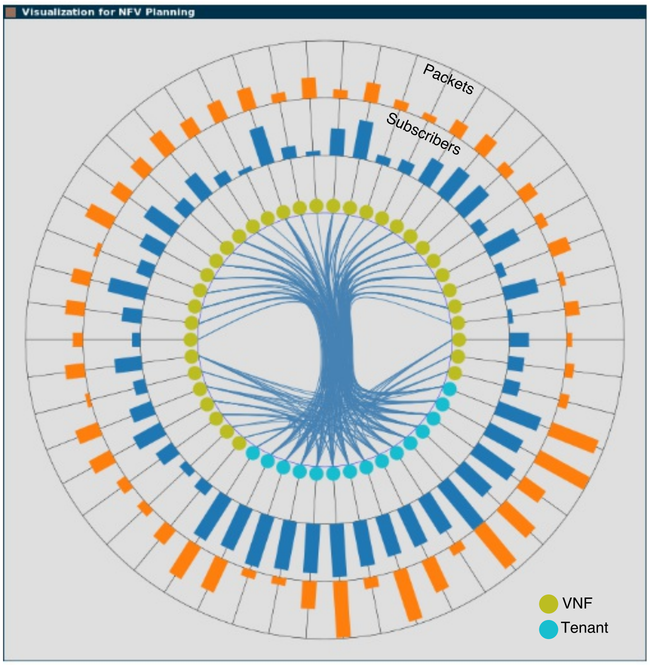


Fig. 2: Visualization of Relationships and Business Demands

is represented with connections (blue lines) to contracted VNFs nodes. Also, the rings around the inner circle contain bar charts, each bar with size proportional to the value the corresponding node attribute the ring represents. The first ring presents the number of subscribers for each node while the outer ring indicates the amount of packets per second associated with each node. A settings menu (see Section IV) allows customizing all the rings for representing any information collected by the Data Collector module, such as calls per second, CPUs cores, and allocated memory. Moreover, the network operator can select a ring to sort the visualization. For example, the operator can sort the nodes by packets per second and the nodes will be presented in increasing order (see Section IV). Thus, the nodes with more packets associated will be displayed first, followed by nodes with fewer packets, hence facilitating the human interpretation.

In summary, our visualization is based on representing three main subsets of data about the NFV environment: *(i)* tenants and VNFs that compound the business; *(ii)* resources allocated to operate the business (*e.g.,* resources assigned for each VNF and flavors contracted by tenants); and *(iii)* relationships among business actors (*i.e.,* tenants and VNFs). In addition, other relevant information (*e.g.,* amount of packets being processed and latency time) can be collected by custom monitors put inside the VNFs [20]. By using our visualization, the network operator can detect planning issues, such as identify when a virtual firewall that is processing a huge amount of packets is with less memory and CPU cores allocated than other VNFs that are idle (see Section IV-A).

Other features that we propose allow network operators to interact and customize the visualization according to their needs. Such features include, for example: *(i)* information about nodes and rings are displayed by hovering the mouse; *(ii)* new rings can be removed or added either to simplify the visualization or obtain details about a node; and *(iii)* color attributes can be defined to nodes according to categories (*e.g.,* red colors to firewalls and green to load balancers). In Section IV, we discuss two examples of these features through case studies.

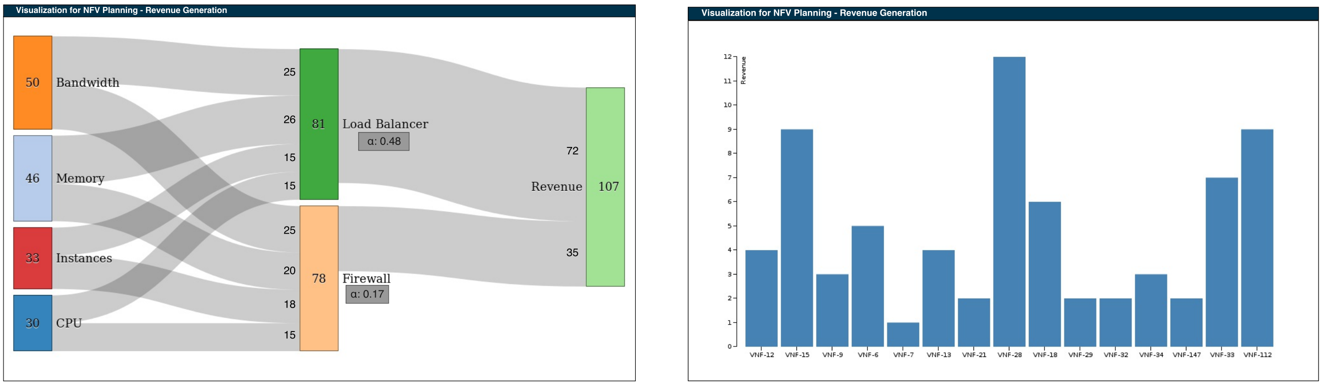
B. Visualization of Allocated Resources and Revenue Generation

Resources Planning (*e.g.,* resources allocation policies and infrastructure investment) is a fundamental task to estimate the amount of resources needed to offer a computing service [21]. This task requires a continuous planning to run in a flexible environment with high dynamic demands. Furthermore, incorrect planning of resources allocation can reduce the potential to obtain profits in NFV-enabled business. For instance, the provisioning of resources to run services that generate little revenue requires attention to avoid implications in the business health. To aid the network operator, we propose a flow-based visualization that shows the amount of resources allocated to run VNFs of a determined group as well the total revenue obtained by all groups of VNFs. Hence, this visualization helps the operator in having insights about the profit potential of each service, which is relevant to make decisions that improve the business strategy.

Our visualization of allocated resources and revenue generation is based on a Sankey Diagram [8]. It presents a flow view to support the interpretation of how many resources are being spent to generate the business revenue. Figure 3a shows this visualization and its main features. The beginning of the flow (left-to-right) represents the resources available inside the rectangles. The connection lines highlight the amount of resources provisioned to a group of VNFs (*i.e.,* services). Next, in the middle of the flow, a representation of the total amount of allocated resources is provided, that means the sum of all allocated resources to run the services. Finally, we present the total revenue obtained by each group. For example, in this case, we observe a group with 15 load balancers, which are consuming 25 units of bandwidth, 26 units of memory, and 15 units of CPU. The total of resources allocated to this group is 81 units of resources, and this generates a revenue of 72 units.

To facilitate the interpretation of our visualization, we define general values as a reference for resources and revenue units: *(i)* one unit of memory is equal to 1GB, *(ii)* each unit of bandwidth corresponds to 10Mbps, *(iii)* one unit of CPU Core is equal to one instance of CPU; and *(iv)* each unit of revenue represents the amount of \$100. Thus, for example, the group of load balancers has allocated 26GB of memory, 250Mbps of bandwidth and 15 CPU cores, thus resulting in a revenue of \$7200 (72 units). Moreover, the network operator can set any value to define one unit of each resource. For instance, 2GB of memory can represent one unit of memory, and \$50 can be the reference value of one unit of revenue.

Figure 3a also shows a revenue coefficient (α). This value is related to each group of VNFs, and it represents a trade-off between the cost of running the VNFs and the revenue that they provide. The objective of showing this coefficient is to help network operators identify groups of VNFs that are lucrative to the business. Thus, the service with higher α is



(a) Visualization based on Sankey Diagram

(b) Complementary visualization with a revenue overview of each load balancer instance

Fig. 3: Visualization of Allocated Resources and Revenue Generation

the most profitable for the business. The revenue coefficient is obtained individually for each category of VNF. For example, in Figure 3a we have two values of potential revenue: one for firewalls and other for load balancers. We compute the average cost C to run a VNF of a given type (*e.g.,* cost of one firewall) according to Equation 1. The rationale behind it is: for each resource i allocated to a VNF j of a group, we add a specific weight (W_i). The weighted sum of resources allocated to each VNF, divided by the number of VNFs in the group (n), results in the average cost to run one VNF in the group. We assume that the network operator is responsible for determining the resource weights (*i.e.,* resources hard to obtain will have a higher W than others in abundance). Next (Equation 2), we calculate the average revenue of one VNF (R), which is the result of a division between the total revenue (Rt) and the number of running VNFs (n). Finally (Equation 3), we obtain the revenue coefficient (α) by dividing the average cost (C) per the average revenue (R).

$$C = \frac{\sum_{j=1}^{n} \left[\sum_{i=1}^{r} A_i * W_i\right]}{n} \quad (1)$$

$$R = \frac{Rt}{n} \quad (2)$$

$$\alpha = \frac{C}{R} \quad (3)$$

In addition, our visualization allows the network operator to set elements that will be visible in the flow, such as which resources and what group of VNFs will be used as the basis for the visualization. Besides, the operator can access a complementary visualization that represents an overview of the revenue of the VNFs being analyzed. Figure 3b shows this complementary visualization and presents the revenue associated to each VNF in the load balancers group. The two visualizations (Figs. 3a and 3b) can be combined to provide powerful resources to help network operators in performing different tasks for NFV planning, hence improving the capacity of operators to understand the business. For instance, the operator can identify abnormal behaviors that lead to a wrong conclusion about the group revenue, such as a unique VNF with high revenue can incorrectly suggest that an entire group is attractive to the business.

IV. Case Studies

We analyze different scenarios to provide evidence of the effectiveness and technical feasibility of our proposed visualizations. In this section, we present three case studies focusing on distinct planning issues in NFV-enabled business. First, we explore the visualization of relationships and tenants demands to provide a way for identifying fails in the resources allocation policies and flavors available in the business. Secondly, we present a visualization to understand where to invest in the business to maintain its health and to increase its competitiveness. Finally, we use the flow diagram visualization to investigate the correlation between allocated resources and revenue generation to determine how much profit a category of VNFs is providing.

A. *Case Study #1*

Let us suppose the following scenario: the network operator perceives a substantial increase in complaints about service performance by tenants. In an initial analysis, monitoring tools inside the NFV environment report an overload of packets being processed in a determined period of the day, which is impacting the latency of some VNFs and, consequently, the service performance. Based on this information, the operator wants to identify the situation and then, conducts a deeper investigation to make decisions to avoid further problems.

Initially, there is no obvious issue that indicates a problem in the NFV-enabled business. In order to investigate the business, the operator accesses our visualization of relationships and business demands. In Figure 4, we present the operator customization: VNFs and tenants as yellow and blue nodes, respectively, and located in the first ring; the amount of packets processed are shown in the second ring; the allocated bandwidth in the third ring; the number of CPU cores in the fourth ring; and the available memory in the fifth ring. Also, in this visualization, the network operator chose the option to sort the visualization by the number of packets processed. Thus, the visualization shows first the nodes that process the larger amount of packets followed by nodes that are processing a smaller amount of packets (*i.e.,* increasing order).

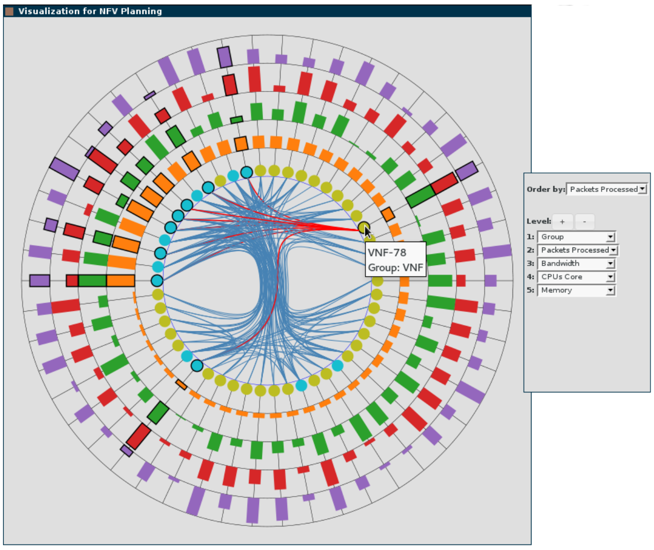


Fig. 4: Investigation about fails in planning of the resources allocation policies and flavors available

By using our visualization, the operator has an insight: there are some VNFs with few allocated resources that are handling many packets per second, while other ones are with idle resources. This problem is highlighted when we analyze the rings of allocated resources and observe that there are several resources allocated to VNFs that are processing few packets. The operator has this insight, for example, by noticing that VNF-78 (see Fig. 4) has a small second level bar graph (*i.e.,* the orange bar that represents the amount of packets being processed) while having a full bar for bandwidth (green bar) and CPU cores (purple bar). Besides, we note that other VNFs share the same behavior. Such problem can occur because the network operator did not consider the business demands when defined the initial business structure, thus resulting in bad policies for resources allocation and incompatible VNFs flavors.

To tackle this problem, the network operator must plan a new strategy for resource allocation, thus changing the allocation policies to consider dynamic demands of the business. As another solution, the operator can decide to perform changes in the way of how the tenants are charged to use one VNF. Thus, tenants that consume more packets will pay more to use flavors that provide high availability of resources. Also, the network operator can structure the business to support flexible flavors in which tenants will pay according to their demands.

B. Case Study #2

In traditional business scenarios, the competition between companies leads to a continuous increase in the quality and variety of products available for customers. It is not different in NFV-enabled business, where the services providers need to implement a better service performance and cost according to tenants longings and markets landscape. Therefore, the SPs need to have a broad knowledge of the tenants' profiles and their demands to realize strategic investments and changes to improve the business competitiveness.

In this case study, we create a scenario where a service provider has a substantial amount of capital to invest in business infrastructure. The network operator needs to understand the business demands to plan how to evolve the business in a right way. For instance, if the tenants are contracting a lot of VNFs that are firewalls with flavors that provide a greater capacity to process packets, then this can suggest that an investment in firewalls with sufficient resources available is a good planning decision. Hence, the operator can use our visualization to plan the next directions of the business expansion.

Figure 5 presents a visualization that provides resources for identifying which category of VNFs (*e.g.,* load balancer and firewall) are the most contracted and what resources are more requested by the tenants. In this visualization, the operator sets an option to display the category of each node in the inner ring. Hence, the colors are defined according to the services that each node represents. For example, the gray and yellow nodes are, respectively, firewalls and DPIs. The purple nodes represent the tenants of the business. The second ring presents how many tenants are contracting each VNF or - when analyzing only tenants nodes - the amount of VNFs contracted by tenants. The last three rings represent information about resources allocated to each node (*e.g.,* memory, bandwidth and CPU cores). Moreover, the operator defines the visualization to be sorted according to the number of subscribers. Thus, the nodes with the largest number of subscribers are presented first, followed by the other nodes.

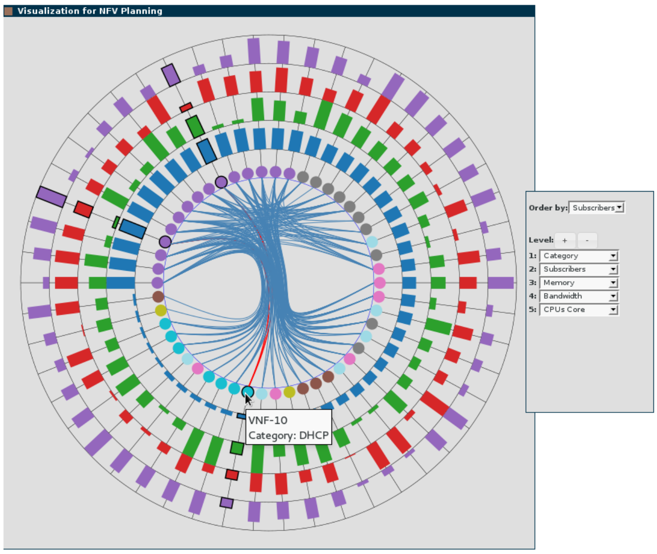


Fig. 5: Visualization for planning of business investment

In a first analysis, the operator observes that VNFs with more subscribers are firewalls (gray nodes). Besides, one can notice that the tenants have a preference for firewalls with more memory allocated, and by observing, one can conclude that the VNFs with more subscribers (largest blue bar) are firewalls that have more memory allocated (largest green bar) than others. Moreover, the operator can have another insight: there are many DHCP (blue nodes) with few or none subscribers (*e.g.,* VNF-10). This suggests an incorrect investment in a service that does not comply with the tenants' interest.

The network operator needs to make decisions to mitigate these behaviors, thus adapting the business to the market tendency and tenants demands. To achieve this, the operator could invest capital to run firewalls with flavors that provide a large amount of memory. Furthermore, some DHCPs could be removed from the business, hence releasing resources for other services. The tenants that need an individual DHCP, for example, must pay to contract a special flavor. Thus, based on these decisions, the operator obtains a profitable business model, which provides both high-performance VNFs according to tenants demands (*e.g.,* firewalls and other interesting services) and VNFs that supply the necessities of individual requirements (*e.g.,* DHCPs with low demand but attractive to some tenants).

C. Case Study #3

This case study is based on a situation where the network operator identified, in a previous investigation, three categories of VNFs which may be interesting for improving the business. The operator has the following relevant information: *(i)* firewalls and load balancers are the VNFs with more subscribers in the business; and *(ii)* some video caches have few subscribers but high demand (*i.e.,* many packets being processed and calls-per-second). Even though load balancers have more subscribers than video caches, this is not an obvious indicative about which of them are more profitable. Based on this information, the network operator needs to understand how profitable to the business is each service.

The operator accesses our visualization of allocated resources and revenue generation to have insights that help in planning new business strategies and investment. Figure 6 presents the amount of resources allocated and subscribers for each group of VNFs being analyzed. The visualization contains, in the flow start (left), the amount of allocated resources (*e.g.,* CPU cores, memory and bandwidth) to run a group of VNFs and the number of tenants contracting it). The middle of the flow represents the sum of all allocated resources. Finally, we present the revenue of each group of VNFs. Besides, the revenue coefficient (α) highlights the services that are being the most profitable to the business.

For this case study, we define the following values as reference to allocated resources and revenue: *(i)* one unit of memory is equal to 1GB, *(ii)* each unit of bandwidth represent 10Mbps, *(iii)* one CPU unit is equal to one CPU core; and (iv) each unit of revenue is equal to $500 (five hundred American dollars). Thus, the operator needs to use these references when converting the visualization values to real outgoing and incomes.

By analyzing the flow visualization (Fig. 6a), the operator identifies that even though there are only a few subscribers to the video caches, this service is very profitable for the business. Such insight occurs by comparing the amount of revenue ($75000) and the α of video caches with others. Thus, this service needs to be maintained in future planning. Moreover, the firewalls demonstrate that are also attractive to the business. Many tenants are subscribing firewalls (79 subscribers), and there is a significant revenue ($67500) and α value. On the other hand, the load balancers, which have a good number of subscribers and allocated resources, provide a revenue below of the expected. Therefore, the network operator must plan an strategy to make available VNFs that correspond to the business goals, such as new load balancer pricing and flavors to supply tenants demands and, also, ensure a profitable service.

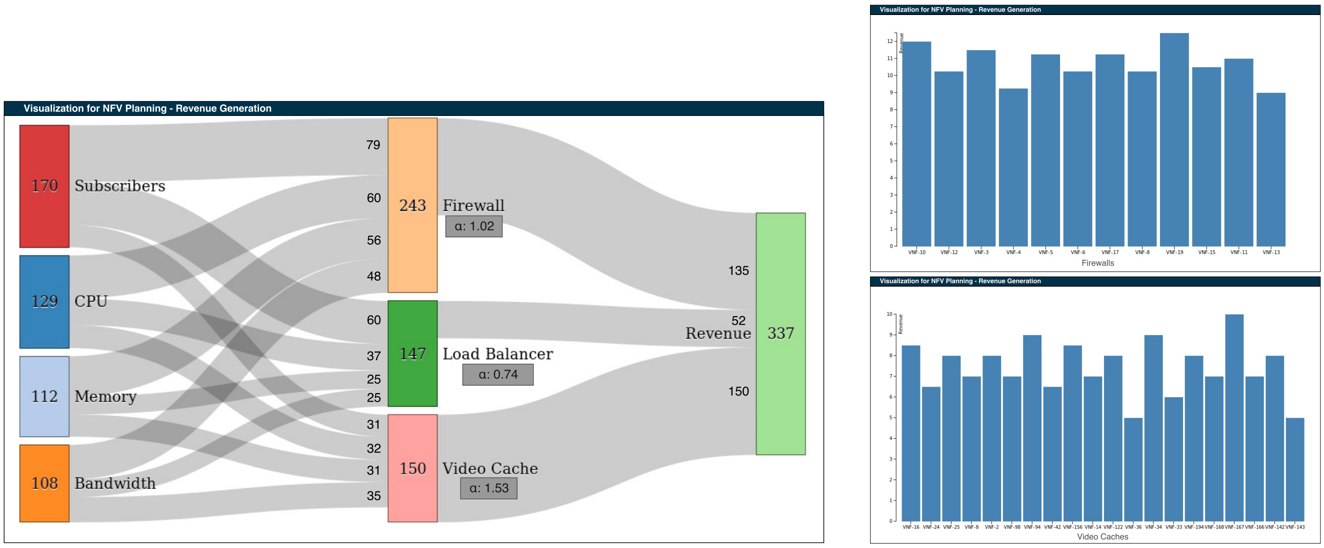
Moreover, the complementary visualization (Fig. 6b) provides information to conclude that there are more video caches (20 VNFs) than firewalls (12 VNFs); it also suggests that, in the mean, one firewall generates more revenue than one video cache. However, the video caches obtain a better result for α because one instance of video cache is less expensive for implement than others services. Based on this analysis, we can note that another attractive approach to the business can be based on defining a new strategy that reduces the cost to run a firewall, thus increasing the profit potential of this service.

V. Conclusions and Future work

In this paper, we have introduced two interactive visualizations that help network operators make planning and strategic decisions in NFV-enabled business. Such visualizations provide insights for a better planning of infrastructure investment, resource allocation policies, and services pricing. By using our visualizations, operators can identify mistakes in the business strategy and highlight priorities that require attention, thus improving the operator ability to maintain the business health and competitiveness. Furthermore, we proposed an extension of the VISION platform to integrate new visualizations, hence enabling the platform to collect and process relevant data for supporting our visualizations.

Case studies provided evidence of the effectiveness and feasibility of proposed visualizations. In the case study #1, we detailed a scenario where the network operator needs to identify fails in resource allocation policies and flavors available in the business. The operator uses the visualization of relationships and business demands to detect that there are VNFs with few resources allocated, which are handling many packets per second, while some VNFs have idle resources. In case study #2, the service provider has a substantial amount of capital to invest in infrastructure and needs to know the better way to improve the business. Thus, the operator accesses our visualization to identify which VNFs and services are most interesting for tenants. Finally, in case study #3, we provided a deep investigation of business profits. The operator uses our visualization of resources allocated and revenue generation to determine which is the most profitable group of VNFs, hence understanding which service is more lucrative for the business.

As future work, we will extend our visualizations to provide addition features for NFV planning, such as profit estimation, simulation of planning changes, and an integrated editor for contactable flavors. Also, we intend to investigate artificial intelligence techniques to provide a prognostic about market tendency and business problems. Besides, we plan to provide a collaborative solution for network operators to share information that helps others operators in NFV-enabled business planning tasks.



(a) Flow visualization to understand amount of resources spent for each service to generate the business revenue and profits

(b) Complementary visualization with a revenue overview of each video cache and firewall available

Fig. 6: Determining most profitable group of VNFs and business priorities

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