Utilizing the Smart City to train Engineering Students on Network Management Topics during the COVID-19 pandemic

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***Abstract*—With the immense opportunities to make a communication network programmable, the virtualization of network functions and software defined networking are gaining momentum in both industry and research circles, being a fundamental skill-set for both electrical engineers and computer scientists. Therefore, in this article, we present and evaluate the educational framework for Service Function Chaining (SFC) practical teaching to undergraduate students aiming to prepare them for future Information and Communication Technologies (ICT) and communication networks market that will demand skillful professionals in the domain. The educational framework was designed for the Network Management course at the University of Antwerp, with the goal to bridge the gap between network programmability concepts applied in industry and those taught at the University. We evaluate the educational framework with two extensive surveys as a feedback from students that provided us with the opportunity to measure and quantify students' experience and satisfaction with the framework.In particular, based on the challenging environment imposed by COVID-19, we identify the gaps in this educational framework and address improvements for both theoretical and practical components according to the students' needs. Our educational framework and the thorough evaluation serve as a useful guideline on how to modernize the engineering courses, and keep up with the pace of technology.**

***Index Terms*—Service Function Chaining, Virtualization, Network Management, Educational Framework, Student Feedback**

I. Introduction and Motivation

This work is an extension of a conference paper published in IEEE Global Engineering Education Conference 2020 (EDUCON2020) [1]. The previous work designed the educational framework detailed in this article. Moreover, it described how a possible maintenance framework should be done to maintain and update the Network Management laboratory classes' quality. Therefore, we extended our previous work with the results and lessons learned of the designed maintenance framework and the classes' implementation.

The synergy of network programmability, softwarization, and virtualization is already recognized as inseparable from the industry. Since network virtualization enables companies to optimize and to dynamically steer the traffic of services among hundreds of servers at the companies disposal [2], the big companies like Google [3] and Amazon [4] have already applied programmability and network virtualization in their datacenters. Moreover, with the emerging popularity of network virtualization, not only big companies will benefit from its implementation, but also the market will boost the demand for professionals with practical knowledge in this area. Academia and industry are united towards the goal to study programmability, softwarization, and virtualization in two major research areas, which are Network Function Virtualization (NFV), and Software-Defined Networking (SDN).

NFV is the virtualization of the legacy physical network functions, while SDN enables the detachment of the network control plane from the data plane [2]. The merge of these two paradigms opened a whole new research area. This area has pros and cons, which are jointly studied under the umbrella of Service Function Chaining (SFC) [2]. For example, the virtualization of network functions brought by NFV enhanced both the scalability and the maintainability of the network infrastructure [2]. Additionally, SDN enables the programmability of the network, which improves the connectivity by allowing dynamic, and fast setup of the data traffic route [2]. However, new challenges such as placement and migration of Virtual Network Functions (VNFs) have arisen as a consequence of such an approach.

To understand the enhancements, and challenges brought by the network virtualization era, it is crucial to discern how the network virtualization is implemented, deployed, and managed. Therefore, a fundamental skillset to have nowadays is the ability to use and manage SFCs, especially for undergraduate students whose aim is to compete for the vacancies of the Information and Communication Technologies (ICT) market in the upcoming years [5]–[7]. Hence, the essential practical knowledge of virtual network management should be provided pedagogically during their study and should be considered in the curricula of every network management course. In this context, for improving the students' skills, it is expected to appraise the best available tools to use in the academic teaching of virtual networks and to find out how the lectures should be structured, and reinforced by hands-on laboratories, to achieve satisfactory learning outcomes in a shorter time.

In particular, in Fig. 1, we illustrate how the teaching

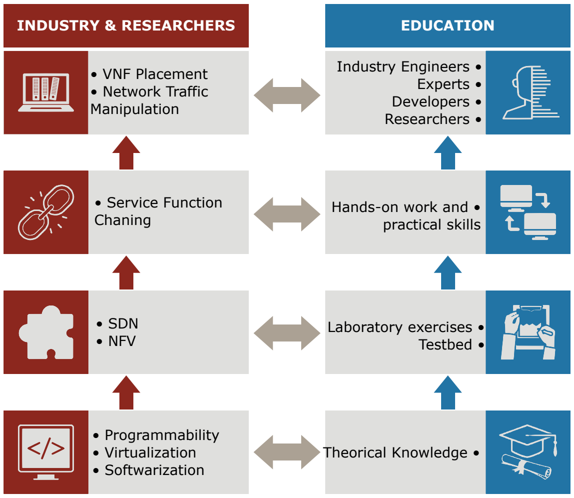

Fig. 1: SFC position in industry and education nowadays

flow should be synchronized with the pace of industry and research, for the specific field of SFC. From bottom-up, the theoretical educational approach would introduce the students to fundaments of Programmability, Virtualization, and Softwarization, which supports the current computer networks tools. The Laboratory exercises reinforce the fundaments that are already learned, and teach the concepts that put the theoretical fundaments in practice, such as SDN and NFV. The hands-on work is where the concepts merge, building up SFC, and the students apply to real-world use cases. In the last stage, the students are expected to move to a specialization in the industry or academia, being prepared to study more complex problems related to SFC.

Slamnik-Kriještorac et al. [8] study the impact of laboratory exercises on students' experience in learning. The authors emphasized the importance of gaining practical skills, and problem-solving abilities for undergraduate students, which can further motivate students to research this specific course-related field, and to exploit both practical knowledge and skills in their day to day work. Furthermore, despite the increase in the availability of diverse technology resources in laboratories, efforts to include them in education remain the same, *i.e.*, following the demonstration-related approach in which teachers demonstrate practical use cases, with students only repeating the examples [9]. Hence, Crocker et al. [9] point at the importance of the more significant involvement of students throughout the learning process. Motivated to support such autonomous learning and provide real-world experimentation in each laboratory exercise, we exploit the large-scale wireless-networking testbed capabilities.

To provide real-world experimentation, we have utilized the Citylab[1] testbed built in collaboration between the University of Antwerp and imec Belgium, which has proved to be the next step in academic research and teaching [10]. Citylab is a smart city large-scale wireless networking testbed which enables experimentation at a city neighborhood level in the unlicensed spectrum. The testbed is located in the city of Antwerp, and its experimentation nodes are attached to buildings and streetlamps. The testbed is equipped with an infrastructure that enables easy remote access. Citylab has proven to be an excellent academic teaching instrument due to its reliable experimentation, heterogeneous network technologies, and close-to-real environments.

In this article we present a pedagogically teaching methodology to introduce undergraduate students to theoretical and practical SFC, providing them with useful knowledge on virtualization of a real-life networking environment, such as smart city testbed. Afterward, we thoroughly present and analyze the students' feedback that allowed us to measure and quantify their experience and satisfaction with the teaching and experimentation setup. Considering a specific circumstance such as campus closure caused by the COVID-19 situation, we also collected the feedback concerning the experience with remote education of both theoretical and practical part. To the best of our knowledge, this is the only work that addresses course modernization towards network programmability applying service function chaining in practical classes.

Our methodology was designed for a sixth-semester Network Management course under the Faculty of Applied Engineering, University of Antwerp[2]. The outcome of our teaching methodology facilitates the incorporation of the lectures into the virtual networks hands-on lab environment, with the ultimate goals: (*i*) to provide undergraduate students solid knowledge on performing basic SFC operations, (*ii*) to increase the interest of students for this or similar topics, and (*iii*) to improve the quality of their learning experience. Finally, the valuable feedback gathered from the students justifies the feasibility and reasonability of creating such a laboratory. Moreover, tackling the challenging environment imposed by COVID-19, this thorough feedback serves as a guideline to efficiently identify the gaps in the proposed teaching methodology and address these gaps and tune the teaching pace by adjusting the content of both theoretical and practical components according to the students' needs.

This article is structured as follows. In Section II, the fundamental concepts of the learning framework for the Network Management course are introduced. In Section III, we show the teaching methodology, including the objectives and sessions. Furthermore, we thoroughly present our educational framework of network management in Section IV, while in Section V we evaluate this framework by analyzing the feedback collected from students. In Section VI, we conclude the article and present our future work.

II. Fundamental Concepts

In this section, we present the fundamental concepts that students need to understand to proceed with the deployment of a virtual network and SFC. To that end, we first describe NFV, and the standardization behind this essential concept. Furthermore, we define SDN and detail on how this concept enhances the legacy network flow. SFC is introduced as the union of both NFV and SDN to provide a dynamic and highly customizable

[1]https://doc.lab.cityofthings.eu/wiki/Main_Page

[2]https://tinyurl.com/y55ulcrc

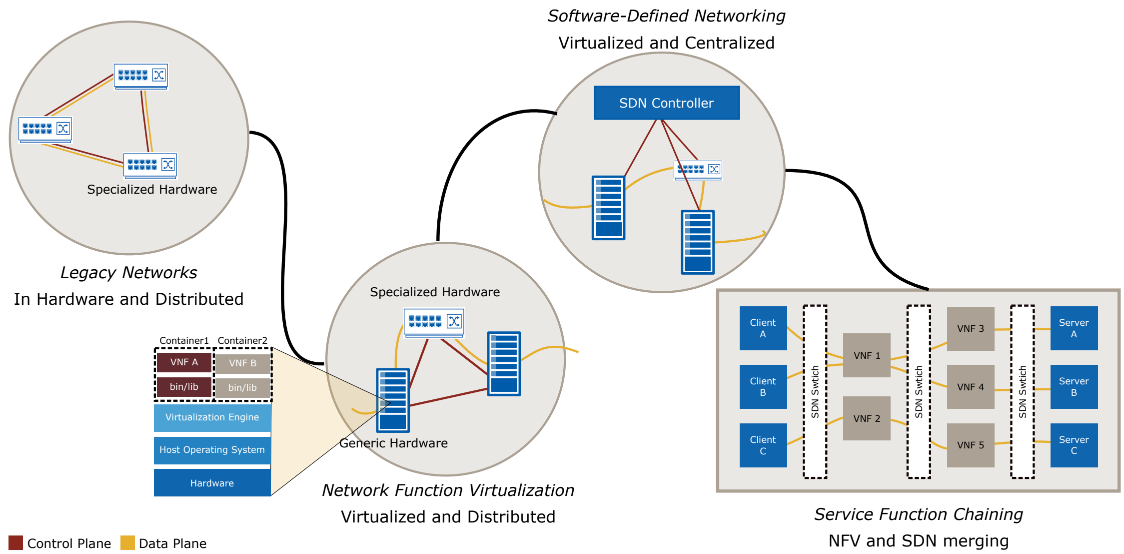

Fig. 2: Fundamental Concepts relationship diagram

network environment. In Fig. 2, we address the view of computer communication networks from hardware-implemented distributed networks to virtualized and centralized networks. In this view, we present the legacy networks, which are composed of mostly specialized hardware and distributed control plane. Moreover, with the advent of virtualization, NFV enabled the execution of Network Function (NF) in generic hardware. SDN comes next, implementing the concept of centralized control plane optimizing the network infrastructure with the feedback of virtual switches in generic hardware or specialized programmable hardware. Finally, SFC is an outcome of the synergy of NFV and SDN, with the sophisticated knowledge of both areas.

A. *Network Function Virtualization (NFV)*

Thanks to the virtualization in computer communication networks, the network functions that could be realized only in hardware now have their software-based variants [2]. Virtualization is a crucial technology that has been widely explored in data centers to enable hardware sharing with data and process isolation. Currently, the most popular technology utilized for virtualization is the Virtual Machines (VMs). However, the container-based virtualization started gaining momentum as an alternative for the VM. Due to the sharing of the host kernel with user-space isolation, containerization enables a lightweight deployment of services and applications, compared to the traditional VMs. As proposed by Bolivar et al. [11], containers are being considered for deploying NFV as a part of the emerging 5G technologies.

The virtualization of NFs has the potential to decrease the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) of computer networks infrastructure. The low costs and the new opportunities attract the interest of the industry, which invests more and more in this area. For instance, South Korea Telecom (SKT) and Viva Kuwait already started the migration of physical to virtual network infrastructure, and this trend will only get more popular [12]. Therefore, the qualification of students to fill the future vacancies are essential to keep up with this increasing industry demand [13].

In the research perspective, Virtual Network Function (VNF) is the main component in NFV, as a result of the virtualization of a network function. This concept enabled network operators and system administrators to deploy VNF instances for different network traffic demands. However, with this possibility of dynamic deployment, challenges such as VNF placement and migration have arisen [14].

B. *Software-Defined Networking (SDN)*

SDN is the decoupling of the network control plane from the data plane [2]. This paradigm came with the necessity to create more efficient network flows by dynamically steering the network traffic and load-balancing among the network nodes. Since the computer networks are connected in a distributed way, it means that each switch or router has its control plane, which is used to discover new devices, and to route the data to the destination. Therefore, there is no single component/entity that controls communication among all devices.

SDN is a widely exploited technology that has robust software implementations such as OpenDaylight [15] and Ryu [16]. While OpenDaylight is recognized a secure solution for the industry, Ryu is more used for academic research due to the lower complexity. This characteristic supports the education, because it implements only the necessary components for a simple SDN deployment.

With SDN, the network operators are able to create and manage routing tables and set up layer two network rules in several devices from a single point. In this context, SDN raised new challenges, such as enabling communication among SDN controllers and allowing the integration of the computer networks from different operators. Moreover, by centralizing the SDN controller, the network control is a single point of failure, which can affect the availability of the whole network.

Since the understanding of SDN is fundamental for a computer network professional, it becomes an indispensable topic in the educational framework and the students' preparation for the market.

C. Service Function Chaining (SFC)

SFC is the deployment of at least two NFs that provide a network service to the user. A simple example of SFC is the Dynamic Host Configuration Protocol (DHCP) server behind a firewall. The network traffic from client requests first passes the firewall that filters the requests before reaching the DHCP server. This managing of the network flows to pass through different functions towards the destination point is called chaining. There are several utilities for this method, such as security in the case of firewalls and Intrusion Detection Systems (IDSs) and statistics in the case of packet counters.

The function chaining can be done by statically setting up the network to steer the traffic through specific functions in the infrastructure. In the legacy network, the concept of chaining different network functions already existed. However, with the fast development of virtualization technologies and the softwarization of NFs, this deployment and management of several network instances became more dynamic.

Therefore, the educators need to introduce the NFV and SDN concepts, which are the basis of future computer networks when teaching SFC. VNFs will provide the deployments of different network services, and the SDN will enable the operators to program the network and steer different network flows on-demand. These characteristics will allow the customization of the network, for instance, per service or per user, which are essential to advancements in the computer networks area.

III. Educational Framework of Network Management

In this section, we present our educational framework. In particular, we present the objectives, and compare the sessions with the learning outcomes for network management specified by ACM/IEEE Computer Engineering Curricula 2017 (ACM/IEEE CE2017) to demonstrate that our framework comprehends the expected results (III-B). Afterward, we describe the sessions and conclude the Section with examples of how network management is applied in practice (III-D).

A. Objectives

The creation and maintenance of the complex virtual network infrastructure will be the daily task for computer network engineers. However, they will encounter many unexpected scenarios that will challenge their knowledge and skills to solve the network-related issues. Therefore, in this educational framework, we focus on hands-on laboratories and activities to:

i) provide undergraduate students with solid knowledge on performing basic SFC operations,
ii) increase the interest of students for this or similar topics,
iii) improve the quality of their learning experience.

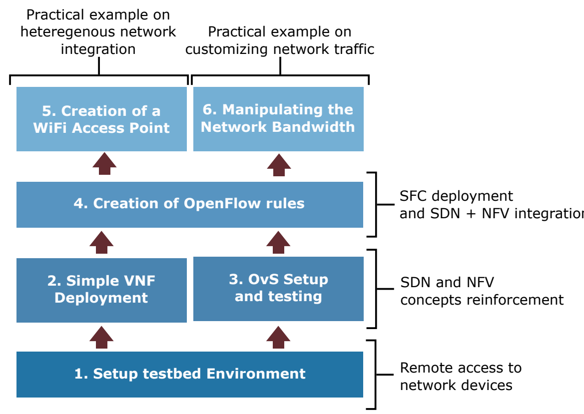

Fig. 3: Educational framework mapping

Label	Learning outcome
A	Main issues
B	Typical architectures
C	Demonstrate the management of a network device.
D	Compare various network management techniques as they apply to wired and wireless networks.
E	Discuss the Address Resolution Protocol (ARP).
F	Exhibit the concepts of domain names and Domain Name Systems (DNS).
G	Describe the Dynamic Host Configuration Protocol (DHCP).
H	Describe several issues related to Internet Service Providers (ISPs).
I	Illustrate several Quality of Service (QoS) issues.
J	Describe ad hoc networks.
K	Teach troubleshooting principles.
L	Describe functional management areas related to networks.

TABLE I: Learning outcomes

We achieve these objectives by building the framework upon six sessions: Remote access to the testbed, VNF deploying with Docker[3], first contact with OpenFlow (OF) switch, using of OFs rules, creation of a WiFi access point, and network bandwidth manipulation. The sessions are mapped in Fig. 3, where the content of one session supports the teaching of the next.

B. Curriculum alignment

The ACM, in collaboration with IEEE, has elaborated the ACM/IEEE Computer Engineering Curricula 2017 (ACM/IEEE CE2017) for information technology to guide institutions with specific strategic suggestions and recommendations. In this recommendation document, ACM/IEEE CE2017 specifies some learning outcomes for the course of network management, which is the focus of this article. Therefore, we present a list of these learning outcomes in Table I.

Our educational framework is supported by four network management theoretical sessions, which have the main objective to present the main concepts of network management and topics that will not be discussed in the specific practical sessions due to time limitation. Moreover, some important

[3]https://www.docker.com/

Week	Session Approach	Duration	Session	CS2017 - Network Management Core Learning Outcomes
1	Theory	2h	Introduction and Fundamental Concepts	A, L
2		2h	Typical architectures with the advance of virtualized and programmable networks	B, D, J
3		2h	Main protocols of Network Management	E, F, G
4		2h	Internet Service Providers and Network Management main issues	H, I
5	Practical	2h	Setting up the testbed environment	C, L
6		2h	Simple VNF deploying with Docker	C, L
7		4h	OvS set up and testing	C, E, I, K
8		4h	Creation of OpenFlow rules to deploy an SFC	C, I, K
9		4h	Creation of a WiFi access point to emulate a client-server application architecture	C, D, E, G, I
			Manipulating the network bandwidth using VNFs	C, H, I, K, L

TABLE II: Educational Framework alignment with ACM/IEEE Curricula 2017

concepts such as service reliability and security are assessed during the theoretical classes in order to introduce students to common topics that network management has with other courses such as Fault Tolerance theory and Computer Security. Table II presents the nine sessions of the network management course, which four are theory only and five that will be hands-on laboratories. The table also presents the content and the learning outcomes achieved at the end of each session.

Since our educational framework, with the support of the theory sessions, is fully aligned with the ACM/IEEE CE2017, it is reinforced to prepare computer network professionals without skipping any essential knowledge in the student development process.

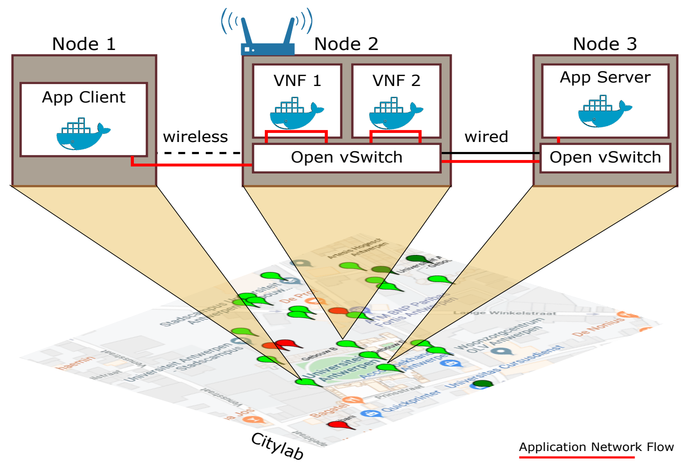

Fig. 4: SFC experiment setup in Citylab

C. Sessions

In this subsection, we detail the laboratory sessions of the educational framework which corresponds to the second part of Table I.

1) Testbed Environment Setup: The Citylab testbed is exploited as a valuable resource for students to experiment with the network management techniques in a real city scenario. This testbed is accessible through jFed [17], which is a tool that groups several testbed facilities and enables remote access through Secure Shell (SSH). Using jFed, the students are able to configure the network topology, and to connect the available nodes in testbed environment.

The testbed setup includes: i) registering to the testbed facilities, ii) creating an experiment, iii) selecting nodes, iv) creating network topology, v) accessing the nodes, and vi) verifying the connectivity between the nodes. The duration of this first experimentation stage is highly susceptible to the levels of students' experience in working with experiment allocation tools, and using a command-line interface. Although it is challenging at first, becoming familiar with the command-line interface is highly appreciated, since this is one of the most common practices in an ICT working environment. The reserved nodes in the CityLab are distributed to the student groups, making sure that the nodes allocated to a group are near to each other in order to establish a wireless connection (Fig. 4).

2) Simple VNF deployment: VNF is a software implementation of an NF that used to be implemented in hardware. However, one of the problems faced by the software is the performance isolation among the programs deployed over the same hardware. Therefore, using the corresponding virtualization solutions is necessary, as they isolate the VNFs and manage them separately. In this course we use Docker, since it has an active community that provides an extensive documentation that can be beneficial to the students.

The objective of this session is to understand the container virtualization, and how the VNFs are deployed in a real-world scenario. To this end, the students are provided with a ready to deploy Firewall VNF in a Docker container.

3) Open vSwitch (OvS) set up and testing: Since the set up of the Open vSwitch (OvS) is the first contact with an SDN switch for most of the students, it is necessary to spend more time exploring the routing features of OvS, thereby trying to avoid breaking the network connectivity with the testbed node.

The students set up the OvS in the Citylab nodes, with an OvS bridge that is created and attached to the experimental network interface. To ensure that the communication between two VNFs passes through the SDN switch, we attach a network interface into the containers and utilize this interface as default for the VNFs. During this session, OvS is tested using traffic generator tools such as ICMP protocol and iPerf3 [18]. The students deploy basic OF rules to block and tag the traffic that matches the pattern described in the rule. Following these steps, students acquire the fundamental knowledge to deploy OF rules, and to exploit the opportunities brought by programmability.

4) Creation of OpenFlow rules: In this session, the students combine the acquired knowledge on NFV and SDN to create an SFC. As an upgrade for the previous sessions, the students create virtual ports in the OvS bridge, thereby connecting to the VNF network stack inside the container. Once VNF is connected to the OvS bridge, the OF rules will be able to redirect the traffic to the port, which the VNF interface is linked to. The students are provided with a basic packet forwarder script that forwards the packets out of the VNF with the data coming through the network interface successfully. Moreover, the students are also provided with a basic script to create new kinds of VNFs, with the goal to teach them how the OF switch and the VNF handle the packets, and how VNF forwards the packets to the next destination (e.g., VNF or application).

5) Creation of a WiFi access point: Manipulating data traffic from traffic generators deployed in the same host is already enough to demonstrate how the SFC works. However, some extra configurations are necessary when receiving traffic from a different network. Therefore, the students deploy a WiFi hotspot in one CityLab node and connect to it from another node. In such a way, the traffic coming from the wireless interface will need to be routed to the OvS bridge to pass through the SFC and reach its final destination.

6) Manipulating the network bandwidth: Exploiting the provided packet forwarder script, the students extend the VNF to manage the network bandwidth from the traffic passing through it. The goal of the last session is to improve students' understanding on how the network operators can provide different Quality of Service (QoS) levels for different network traffic types. Finally, the students assess the trade-off between CPU utilization, network throughput, and latency using VNFs.

D. Network Management on practice

The network simulation tools are usually utilized for undergraduate courses to explain the concepts and demonstrate the network behavior. Since the simulation tools mostly rely on setting the network parameters than cannot be predicted, they might lead to unreliable conclusions. Therefore, for small-scale experiments, experimenting in a real environment becomes valuable, following unpredictable behaviors, and enhancing the significance of the research results. Moreover, in undergraduate courses, hands-on labs stimulate students' interest in using practical tools that can be used later in their careers [8]. By providing students with such an opportunity to gain practical skills in this emerging field at an early stage, we aim to encourage them to break the potential barriers towards hands-on work and to trigger the sparkle for experimenting in general. This practical experience might motivate students to approach research and to expand knowledge later.

The existing undergraduate courses only explain the theoretical concepts of NFV and SDN, excluding any practical implementation. One reason for such phenomena might be the potential lack of proper documentation for the networking tools, and the access to such tools (e.g., high-performance laboratories). Followed by corresponding theoretical guidance, our educational framework with the virtualization tools supports the practical implementation of network virtualization techniques for the undergraduate students and encourage them toward expanding their knowledge and experiencing this innovative and promising career direction. Moreover, the usage of virtualized testbeds such as Citylab for academic teaching is still not as widespread it should be, but efforts in this direction are already being made [19].

Given the importance of introducing hands-on laboratories to students, some researchers have already made some efforts into this. Slamnik-Kriještorac *et al*. created a low-cost network laboratory project for Distributed Systems using Raspberry Pis [8]. The authors present the concepts of distributed systems to the students who further work on the development of these systems in practical labs. The survey that authors designed for students to evaluate their experience with practical experimentation resulted in a valuable feedback, that helped them to recognize the difficulties of each project stage and the practical laboratory efficacy.

Furthermore, Gercek *et al*. dissert about how to implement hands-on laboratories in online courses [20]. The authors say that a practical approach, even in remote courses is essential to specific fields that are not fully theoretical such as computer networks. They explain step-by-step the advancements and how they were able to successfully extend the practical classes to online courses, reinforcing the importance of the students' contact with practical exercises.

Thus, the selection of the fundamental tools for network management and the efforts towards hands-on teaching in laboratories highlight the importance of this movement of network management courses to a practical teaching approach.

IV. Evaluation

One of the fundamental ways to maintain the course's quality is to perform student surveys, because it helps educators to adjust the content of the sessions according to the students' needs. The cyclic process that should be followed to implement a continuous repairing in the educational framework.

After creating an educational framework adapted to the institution's schedule and expected outcomes, the pre-survey can be applied to evaluate the knowledge and skills of the students at an entry-level. At the end of the academic period, the post-survey should be applied to collect the feedback about quality of content, potential effectiveness, and the technical basis. This will provide insights about the skills gained by students when compared with the pre-survey, and help to adjust the educational framework according to the findings.

A. Survey Organization

Surveying the students and teachers helps the validation and the update of the course. The appliance of a questionnaire with the students may support the assessment of the efficacy of the teaching. Therefore, we identified three areas that support the evaluation of the educational framework: (*i*) Quality of Content, (*ii*) Potential Effectiveness, and (*iii*) Technical Basis.

Quality of Content evaluates how the content is delivered to the students, and the difficulty level perceived by them.

The feedback of the students on how prepared they feel for the academia or industry is studied in Potential Effectiveness. Technical Basis assesses the functional knowledge delta of the students, for instance, what is the level of expertise in a specific tool/area and how they perceive their knowledge after the educational framework being applied. The questions for each area can be seen in Table III.

During the educational framework application, we faced the new circumstances implied from the COVID-19 situation. Thus, with an immediate effect, the classes turned from traditional physical to remote only. Since such circumstances are expected to have an impact on the teaching and knowledge acquiring process, we designed the second survey to collect feedback, and understand the real impact of COVID-19 on this educational framework. This survey is shown in Table IV. To collect and understand the information such as the perception of quality and self-improvement, the surveys' questions where implemented on a 5-Likert scale. In the next sections, we present the results of the two surveys mentioned above. The surveys were applied after the end of the course, and we received the feedback from around 45.5% students. We would expect much larger involvement of students in surveying process if we applied survey earlier during semester. However, we argue that the participation in survey was affected by the fact that survey was initiated at the end of the course, and students' prioritization of the final exams contributed to it.

B. Educational Framework Results

Analyzing the survey results about the specifics of the Educational Framework, we first refer to the answers on the Quality of Content. When asked about the usefulness of the laboratory exercises for their education, we see that majority of the students positively evaluated the impact of our course (33.3% of "Strongly Affirmative" and 66.6% of "Affirmative"). However, although they evaluate the workload as being *efficiently* distributed among exercises, we see that more than 50% of the students had difficulties with the organization of the course. Therefore, as a first demonstration of the educational framework, we could highlight the importance of the topic and tools used, but also announce the further enhancements in the organization that need to be done.

The students also evaluated the Technical Basis of the Education Framework. The absence of the processing node and networking components physically were not missed by the majority of the students, having 75% of the students "Strongly Negative" to "Neutral" when asked **Q5** (See Table III), which leads to the conclusion that the majority of the students feels comfortable with the usage of remote testbeds. Moreover, the flexibility provided by the Educational Framework deployment in the testbed had the approval of 100% of the surveyed students. In a more technical view in the educational framework content, 83.33% of the students asked if they could better comprehend the concepts of SDN and NFV after performing laboratory exercises answered positively.

The potential effectiveness section presents a satisfaction of 41% of the surveyed students when asked if the course content is sufficient as a starting point for pursuing a career in this direction. This outcome highlights the need to extend the course content to more complex tools, or even the improvement of the organization, as underlined in the Quality of Content section, could improve the confidence of the students in this area of expertise. Besides not feeling confident for starting in the industry, we can see that 75% of the sample agree that the skills and knowledge gained during the course are beneficial and attractive for the industry needs. This result reinforces the need for the content's extension of the course.

C. COVID-19 impact results

The COVID-19 pandemic, which was first reported by the end of 2019 in China, brought us to face a new reality in our everyday tasks, and education and universities were not different. The adoption of online classes was essential for the continuation of the educational lives of several students. Due to the change from presential courses, the educational framework's evaluation needs to take into account how much this unprecedented pandemic affected its efficacy. In Table IV, it is presented the questions for the COVID-19 impact survey. These questions are classified into four parts: Lectures, Laboratory exercises, Pools, and Combined. In Lectures, we assess how much the adoption of online classes has affected the students' theory learning. We present how much the migration from presential to online affected network management laboratory exercises in the Laboratory exercises part. In this case, we collected students' feedback about a poll system used during the online classes. Additionally, we present a compilation of three areas with two questions, each aiming at how the course could adapt its content to online classes. These areas are Interaction, Recordings, and Study Material.

The first analyzed results were the Lectures, and we can first perceive a significant percentage of neutral/disagree in two topics: (*i*) when asked if the remote classroom was a suitable replacement for a traditional one; (*ii*) if the student could prepare more efficiently to lectures in remote classrooms. These two questions present students' view that the online classes do not lead to efficiency gain on the part of the student, and that 41.67% of the students do not think that online classes are a suitable replacement for the traditional one. However, 75% of the students' sample also answered that they feel comfortable interacting with the teacher. Therefore, other factors that not the teacher-student interaction and content (it is the same for both types of classes) are part of almost half of our students' sample's unsatisfactory experience.

It is an essential part of the survey about the laboratory exercises since the practical classes of a course are usually very interactive, and the flipping from presential to online could have a significant impact. Unlike the lectures, our results show that 50% of the students think that a remote classroom for practical lectures is a suitable replacement for the traditional in-lab. Furthermore, the students coherently disagreed that internet connectivity was not an issue, and the interaction with the teaching assistant was not a challenge in the learning process, having 75% agreed and 58.33% neutral-to-disagree, respectively. Besides, the interaction with teaching assistants and Internet connectivity was not an issue for the students.

Area	Number	Question
Quality of the content	Q1	Do you think that laboratory exercises are well organized?
	Q2	Do you think that the workload is efficiently distributed among exercises?
	Q3	Do you think that instructions for lab. Exercises were clear?
	Q4	Do you think that the instruction material is sufficient for understanding the tasks?
	Q5	Do you think that these laboratory exercises were useful for your further education, as well as general knowledge?
Potential effectiveness	Q1	Do you think that you gained a sufficient level of skills to apply them in your future professional engagement?
	Q2	Do you think that you improved your technical skills while working on the testbed (instead of working on the PCs, or within a simulation evinronment)?
	Q3	Do you think that working on the testbed provided you with a more realistic experimentation environment than simulators that are usually utilized in education?
	Q4	Do you think that your knowledge of network programmability, virtualization, and softwarization, is sufficient as a starting point for pursuing a career in this direction?
	Q5	Do you think that the knowledge and skills that you gained are beneficial, and attractive, for the industry needs nowadays?
Technical basis of the course	Q1	Do you find working on the testbed resources as same as working on the hands-on machines in laboratory?
	Q2	Did your previous experience in working with Linux-based systems help you to grasp the practical work within Network management?
	Q3	Did you find your working on the testbed useful for your overall technical skills?
	Q4	Do you find that is an advantage to have resources available in a more flexible manner than in classroom?
	Q5	Do you feel more comfortable working on the physical machines (e.g., PCs), using physical networking equipment (e.g., WiFi router, network switch)?
	Q6	Do you think that you understand better the concepts of SDN and NFV after performing laboratory exercises?
	Q7	Do you think that you understand better the concepts of network management after performing laboratory exercises?
	Q8	Do these laboratory exercises motivate you to further explore Docker containerization for deploying a large set of applications?
	Q9	Did such technical approach intrigue you to follow similar courses at University, or out of University?

TABLE III: Course related survey questions

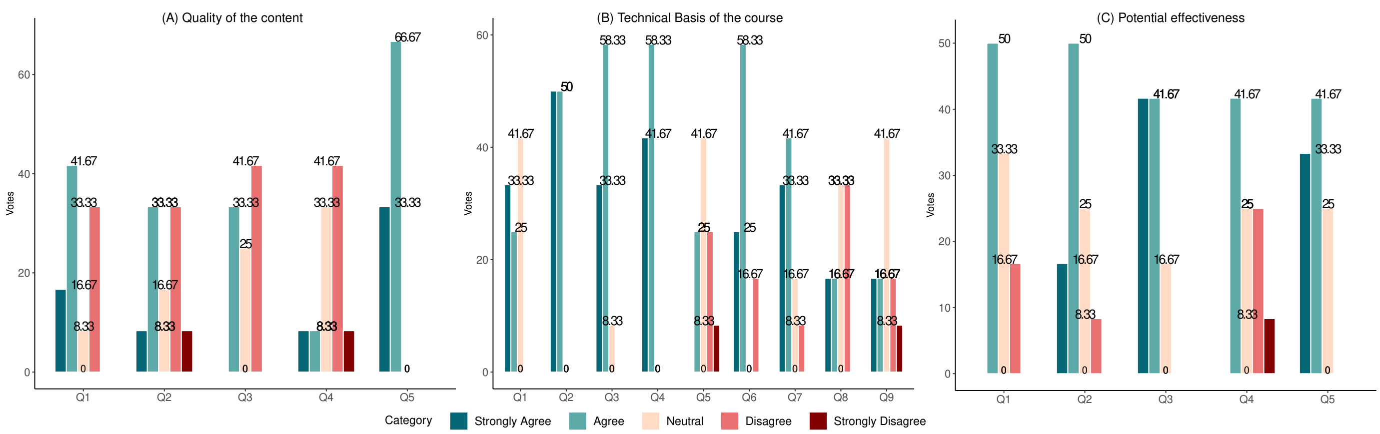

Fig. 5: Educational Framework survey results

Only 8.33% disagreed that the physical absence of teaching assistants affected their understanding of lab material.

In Laboratory exercises part 2, we can see that in Q9, only 16.67% of the students disagree that they would work harder in a physical laboratory. Furthermore, the sample shows that, in Q11, students have divided opinions when asked if they experienced an improvement in their time management efficiency while working in remote environments. While 41.67% of the sample agreed that they improved time management efficiency, 33.33% disagreed. Furthermore, it is important to highlight the 75% agreement that the interaction with teammates was satisfactory. Therefore, for laboratory exercises, the students feel comfortable interacting with teammates and teaching assistants, but still think that would perform better in presential laboratory classes. The poll is one form of interaction with the students. In this survey results, our sample showed positive experience when such a tool was utilized. Overall, the maximum disagreement percentage presented poll-related was 16.67%. As an additional tool, questions such as if the polls were good practice, showed 66.66% agreed. Presuming that, for online environments, polls' utilization to collect feedback from students is an efficient method.

The survey part named combined, presents the results for three different topics: Study Material, Interaction with students, and Recordings, to evaluate the methods of content distribution and interaction. It was asked if the course material's online availability was beneficial and if the students used this resource to enhance its learning, and more than 83% of the students answered that strongly agree or agree for Q1, and 75% agreed with Q2. Tools for students to upload projects

Area	Number		Question
Lectures		Q1	Do you find a remote classroom for delivering lectures as a suitable replacement for a traditional one?
		Q2	Do you feel comfortable interacting with teacher during lectures?
		Q3	Do you think that possible network connectivity issues could block you from grasping the material?
		Q4	Do you easily lose focus during remote lectures?
		Q5	Do you think that you can prepare for the lectures in the flipped classroom more efficiently than for traditional?
Laboratory exercises	Part 1	Q1	Do you find a remote classroom for delivering laboratory exercises and experimentation as a suitable replacement for traditional in-lab?
		Q2	Do you feel comfortable interacting with teaching assistants during lab sessions?
		Q3	Did network connectivity issues influence your interaction with the teaching assistants (i.e., preventing you to share screen)?
		Q4	Do you think that the physical absence of teaching assistants affected your understanding of lab material?
		Q5	Do you find breakout groups as a suitable substitution for working closely with teammates in a physical lab environment?
		Q6	Do you think that teaching assistants efficiently handled the management of breakout groups?
	Part 2	Q7	Are you satisfied with the promptness of the assistant's feedback in your breakout group?
		Q8	Do you think that remote interaction with your teammates is on a satisfactory level?
		Q9	Do you think that you would work harder and more efficiently if in a physical laboratory?
		Q10	Do you think that remote experimentation and remote delivering of lab sessions positively affected your learning outcomes?
		Q11	Do you think that you can use time more efficiently while working on the project in a remote environment?
Pools		Q1	Do you think that short polls in Blackboard collaborate were clear and unambiguous?
		Q2	Did the short polls help you to better understand the matter of theoretical and practical lectures?
		Q3	Did the short polls help you to correct misunderstanding of parts or whole lectures?
		Q4	Did you feel comfortable to participate in polls, as they were not anonymous?
		Q5	Do you think that polls, as auxiliary tool, are a good practice in general?
Combined	Study material	Q1	Do you think that the study material on Blackboard platform is organized in an efficient way (i.e., easy to access and find the needed lecture/laboratory session material)?
		Q2	Do you think that material is uploaded in a timely manner (do you take advantage of reading material before lectures/lab sessions)?
	Interaction with students	Q1	Do you find the system of recording seminars as suitable, and time efficient?
		Q1	Do you think that service for uploading student's electronic material on Blackboard platform is useful, and more practical than distributing material via e-mail?
		Q2	Do you think that important announcements are delivered to students in a timely manner, thanks to the Blackboard platform tool for sending bulk e-mail?
	Recordings	Q1	Do you think that recording lectures is generally useful practice for all courses?
		Q2	Do you take advantage of recorded sessions while studying the material after the actual lectures?

TABLE IV: Remote flipped classroom survey questions

and deliver important announcements were categorized under Interaction with students. This type of instrument was satisfied with the surveyed students, for being an organized and efficient way to deliver notifications (83.33%) and being an excellent method to send reminders and essential reports on time (75%). Besides, the positive outcome for the topics above, the Recording of the classes for late utilization by the students did not present any negative feedback when asking if they are useful and if they use the material after the class being taught. Therefore, the tools utilized for the online classes in this course were helpful for the students' learning process.

V. Conclusion and Future Work

In this article, we present the fundamental concepts of an SFC, and the organization of practical lectures for a network management course. The planning of practical sessions based on the content taught previously in other sessions helps reinforce and to embrace the theory. Therefore, we created a well structured and objective oriented educational framework for SFC teaching to guide the preparation of hands-on teaching laboratories. Furthermore, we designed a survey to analyze the performance of the educational framework based on students' learning experience. Analyzing the results of the applied surveys, we could conclude that the educational framework is a good starting point to bring students closer to what has been done in industry in the network management sector. However, some enhancements on the organization could improve the learning experience. The COVID-19 situation also impacted the learning experience for the Network Management course, since the majority of the students reported that they would perform better in a physical laboratory besides the interaction with the teacher was not compromised. As future work, we aim to enhance the organization of the content for next academic year, and apply again the educational framework maintenance cycle, in order to prepare students even better for the future computer network market.

Acknowledgements

This work has received partial funding from the Fed4FIRE+ project under grant agreement No 732638 from the Horizon 2020 Research and Innovation Programme, which is co-funded by the European Commission and the Swiss State Secretariat for Education, Research and Innovation.

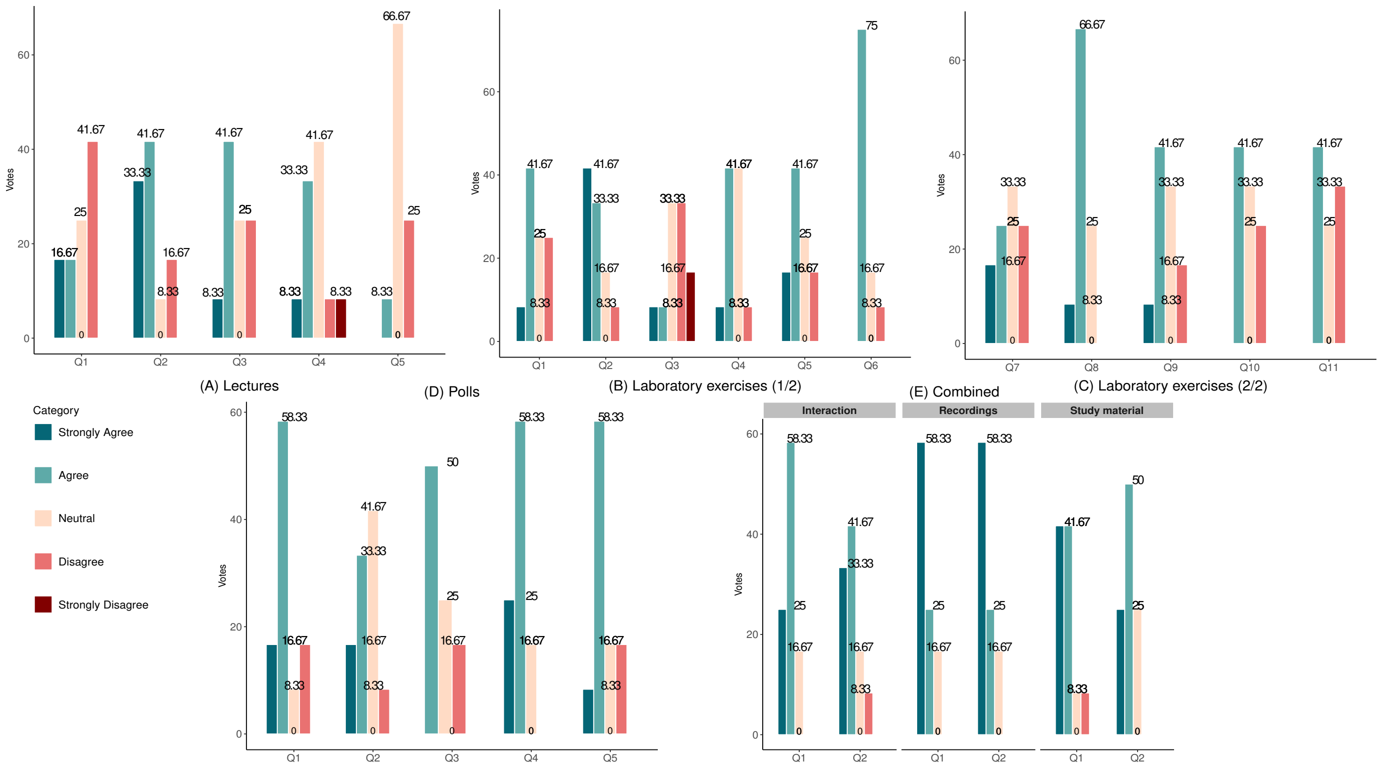

Fig. 6: COVID-19 impact survey results

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