Software-Defined Networking: Current State, Adoption Factors and Future Impact on Network Engineers

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Declaration

I declare that the work described in this dissertation is, except where otherwise stated, entirely my own work, and has not been submitted as an exercise for a degree at this or any other university. I further declare that this research has been carried out in full compliance with the ethical research requirements of the School of Computer Science and Statistics.

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Alberto Martinez Aranda

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Abstract

Conventional networks are complex and challenging to operate. On top of that, they have limited flexibility to react to device failures and flow changes. On the other hand, server virtualization and cloud computing have made the server side of the Data Center become more flexible to the ever growing applications' requirements placing traditional networks in the spotlight. A new networking paradigm, Software-Defined Networking (SDN), purports to redress manageability, flexibility and scalability limitations of traditional networking by making use of network management centralisation and foster automation using network programmability.

The primary objective of this dissertation is to determine the current state of SDN implementations and identify what its top adoption factors are. In addition to this, this research evaluates what is the impact that the adoption of SDN will have on the network professionals. A lack of comprehensive academic research on what the top adoption factors of SDN are and its impact on network engineers seems evident.

This exploratory research adopted a positivist methodology. It applied a quantitative approach to data gathering via an online survey. The findings, relevant to organisations planning or currently involved in SDN initiatives, network engineers and academic researchers, conclude that the majority of organisations will be involved in SDN initiatives within the next two years. The simplification of network provisioning and configuration, the better utilisation of network resources and the ability to perform traffic engineering proved to be the top adoption drivers. On the other hand, organisations identified the challenges of integrating SDN with legacy networks, the immaturity of vendor solutions and the immaturity of OpenFlow as the top inhibitors of SDN adoption. Furthermore, network engineers predicted changes in the structure of their teams and found imperative to master programming skills for them to stay relevant in the market. This research culminates with a proposed framework for SDN-SWOT analysis and a roadmap to help organisations overcome the challenges identified in integrating SDN whilst maximising the benefits.

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List of Abbreviations

API – Application Program Interface

CAPEX - Capital Expenditures

CEO – Chief Executive Officer

CTO – Chief Technology Officer

IPv4 – Internet Protocol version 4

IPv6 – Internet Protocol version 6

IT – Information Technology

MAC – Media Access Control

NaaS – Network as a Service

NFV – Network Function Virtualization

ODL – OpenDayLight

OPEX – Operation Expenditures

ONF – Open Networking Forum

SDN – Software-Defined Networking

TE – Traffic Engineering

1 Introduction

Conventional networks connecting most of today's internet have proved to evolve slowly; are limited in functionality; have a relatively high level of Operation Expenditures (OPEX) due to manual maintenance and deployment, and are, in nature, relatively static to device failures and flow changes. On the other hand, server virtualization and cloud computing have made the server side of the Data Center more flexible and adaptable to the ever growing and changing applications' server requirements. Applications are now able to be served by high numbers of virtual machines that can quickly scale in CPU and memory resources. This landscape has placed traditional networks in the spotlight, positioning them as a bottleneck for application deployment and scalability. Therefore, at present telecommunications service providers and IT organisations, in general, are under increasing pressure to be more efficient and agile than ever before.

A new networking paradigm, Software-Defined Networking (SDN), promises to help to overcome the flexibility and scalability limitations of traditional networking by making use of network management centralisation and by fostering automation using network programmability. Even though the idea of a programmable network is not new, SDN has recently become a hot topic in the networking community. Software-Defined Networking is already changing the way some organisations deploy and manage their networks. Microsoft, Amazon, Google and Facebook among others, who run most of the internet traffic today, are early adopters of SDN and drivers of several SDN initiatives. They are part of the Open Networking Foundation, ONF, established in 2011 with the aim of standardising SDN architecture and protocols. Moreover, A study by SDNCentral, indicates the market will grow from $1.5 billion in 2013 to $35 billion in 2018. (SDNCentral, Plexxi & Lightspeed Ventures, 2014).

However, more traditional IT and non-IT organisations, with large legacy networks supporting their businesses, struggle to enable SDN initiatives. It becomes especially challenging for them to migrate from a legacy distributed control plane to a centralised control plane under an SDN controller. Some big players in the networking industry like Radware's Sinha warned that SDNs could remain a corner technology if organisations

don’t make highly programmable networks a priority. Adding to this, the results from QuinStreet Enterprise survey which surveyed 321 IT professionals show that, despite the amount of attention SDN has gauged over the past couple of years, SDN is still a new and evolving technology and has relatively small diffusion in the enterprise. Less than 30 percent of the respondents had deployed or planned to deploy SDN in the following 12 months, while another 40 percent had no plans to implement SDN at all. (QuinStreet Enterprise, 2014)

This research draws a clear picture of today's grade of SDN adoption by IT (Information Technology) and Non-IT organisations. It also provides a comprehensive analysis of what are the most relevant adoption factors of SDN by reviewing all the benefits and challenges listed in the literature review and rank them based on the input of surveyed network engineers. In addition, this research studies what impact the adoption of SDN may have on the future of the network engineer role.

1.1 Relevance of the Study

This research tries to understand what is the present state of the Software-Defined Networking (SDN) technology; its adoption factors, and its impact on network engineers. Software-defined networking is an emerging model that, by favouring centralisation of network control, and enabling network programmability, promises to ease network deployments and configuration and enhance network resources performance. However, there is substantial uncertainty amongst network engineers and IT organisations about SDN implementation challenges. There are several causes of that uncertainty, including, the immaturity of vendor solutions and SDN enabling standards, technical difficulties around network scalability and security, and challenging migration processes from legacy networks to SDN.

This research gives a rich understanding of SDN as an emerging technology in network deployment and management. It will provide insights into what is the current status of the different technical aspects of SDN through a thorough literature review of the subject. Ultimately, it will focus on the most important adoption factors of this new technology, and its impact on network engineers.

1.2 Research Question

The fundamental research question is:

Software-Defined Networking: Current State, Adoption Factors and Future Impact on Network Engineers

In attempting to respond the research question the following questions were raised:

- SQ1: What is the present state of the SDN deployments?
- SQ2: What are the key adoptions factors for SDN?
- SQ3: What is the network engineer's perception on the impact SDN may have on their jobs?

1.3 Scope of this Research

This research primarily focuses on evaluating the current state of SDN deployments in the IT landscape. It focuses on unveiling and ranking the top benefits derived from SDN and what benefits are the ones driving the implementation of SDN initiatives in a broad group of organisations. Complementary to this, it also focuses on the major challenges faced by organisations when getting involved in SDN initiatives, thus creating a portfolio of the adoption factors driving and stopping SDN adoption with the goal of providing a focus group of benefits and challenges for researchers and practitioners to address with future research. At last, the research also investigates the consequences impacting network engineers and organisations structures involved in SDN initiatives.

1.4 Beneficiaries of this Research

Aside from the certain interest to network engineers, this research could also benefit companies who strive to embark on deploying SDN networks by pinpointing the current status of the SDN enabling technologies and the challenges and benefits of implementing

it. This study is based on an extensive literature review on the SDN technology and the conclusions derived from the quantitative results directly gathered from network engineers through an online survey, which can be of benefit to organisations and academic researchers for further extensive research in this area.

1.5 Literature Research Sources

It is worth remarking the limited volume of business and academic related literature regarding the research question. Albeit, various companies and the Open Networking Forum (ONF) made white paper reports publicly accessible; there was very limited research data available on the current status of SDN deployments, its adoption factors and its possible impact on network engineers. Given the limited academic literature on the research topic, it is expected that this research will help to complement the currently available literature for further studies related to SDN.

1.6 Dissertation Roadmap

Chapter one presents background information concerning the research question and sub-questions. The chapter closes with the importance of the research and its beneficiaries.

Chapter two offers a critical review of the literature on SDN including a definition of SDN, its architecture, and a bottom-up analysis of its different layers. are explained. Moreover, the chapter provides the state of current SDN enabling technology, and it also highlights the benefits and challenges related to SDN.

Chapter three outlines the methodological foundations of this research employed to solve the research question. The chapter presents the different strategies and approaches available and explains which were the ones chosen by the researcher by debating pros and cons of the options available. The section closes with the ethical process and considerations practised in this research.

Chapter four introduces the findings and analysis of data procured from the online survey, which aims to solve the research question.

Chapter five concludes the research by highlighting the principal findings, the constraints of the investigation and recommends future research directions around the research topic

2. Literature Review

2.1 Introduction

The primary objective of this section is to evaluate available literature relating to Software-Defined Networking: it's adoption factors and its future impact on network engineers. It primarily aims to present a profound understanding of what the SDN paradigm is for network management and provide a deep explanation of its different architectural layers. This literature review is presented in several sections beginning with the description of the traditional networking landscape and the irruption of SDN as a new disruptive networking paradigm in following section 2.2.

Section 2.3 offers a high-level description of the Software-Defined Networking standard for network management describing its four principal dimensions

Section 2.4, examines the Software-Defined Network standard with a detailed Bottom-Up description of the diverse layers of the SDN architecture.

Section 2.5 offers an overview of some SDN Benefits as possible drivers for the adoption of SDN initiatives.

Section 2.6 discusses the literature surrounding SDN Challenges and Existing Solutions

Section 2.7 summarises and concludes the chapter.

2.2 Traditional Networking and the SDN Paradigm

This section paints a clear illustration of the traditional networking landscape and the limitations associated with it that have driven the networking community to develop a new standard in network configuration known by the name of Software-Defined Networking.

2.2.1 Traditional Networking

In traditional networking, the network transport protocols and the distributed control within the switches and routers constitute the key technologies that enable information to travel across de globe through digital packets. Despite their extensive adoption, traditional IP networks are not only difficult to manage but are also complex (Benson, et al., 2009). For expression of the required high-level network design and policies into a real-time packet forwarding network, network operators should re-configure each network device with particular vendor low-level commands.

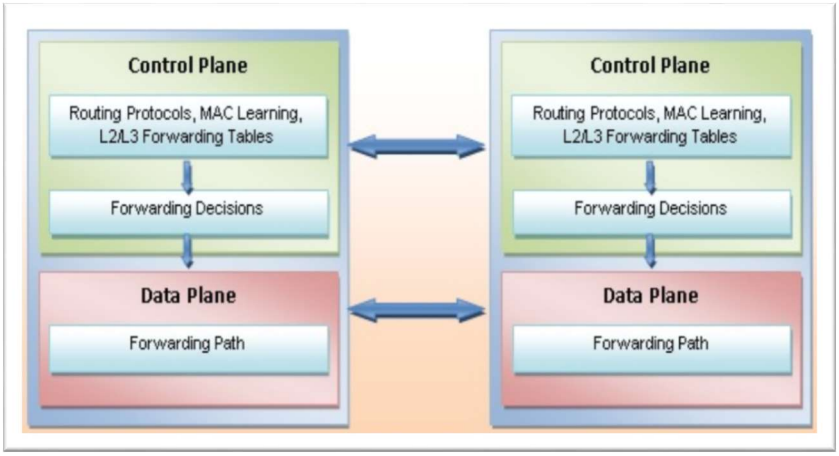

Figure 2.1 - Legacy networking (Jammal, et al., 2014)

To complicate the issue further, as seen in *Figure 2.1*, existing networks are integrated vertically. The control plane, which decides the way of handling network traffic, and the data plane, which pushes traffic based on the decisions that the control plane makes, are bundled in the networking devices, hindering evolution and innovation and reducing the flexibility of the networking architecture. Since the control and data planes are vertically integrated into each node of the network, automatic response and reconfiguration mechanisms are, in traditional IP networks, limited to each individual node intelligence.

As an example for the legacy networking limitations, Raghavan et al, argue that the shift from IPv4 toward IPv6 began more than 20 years ago and is yet to be completed; this demonstrates the challenge, while indeed IPv6 merely represented an update of the protocol (Raghavan, et al., 2012). Ultimately, Ghodsi explains how the arduous

configuration tasks and the vendor dependency have escalated the operational cost OPEX and capital cost CAPEX for running an IP network today. (Ghodsi, et al., 2011).

2.2.2 The SDN Paradigm

Software-Defined Networking (SDN) (Mckeown, 2011) (Schenker, 2011) is a new networking paradigm, which offers hope of transforming the drawbacks associated with existing network architectures.

- First, it simplifies the vertical integration through separation of a network's control plane (control logic) from underlying switches and routers, which forward the data plane (traffic).
- Second, using the delineation of the data and control planes, network switches are simplified into forwarding devices, thus facilitating the implementation of the control logic in a centralised logic controller, simplifying network evolution, configuration, and policy enforcement (Kim & Feamster, 2013).

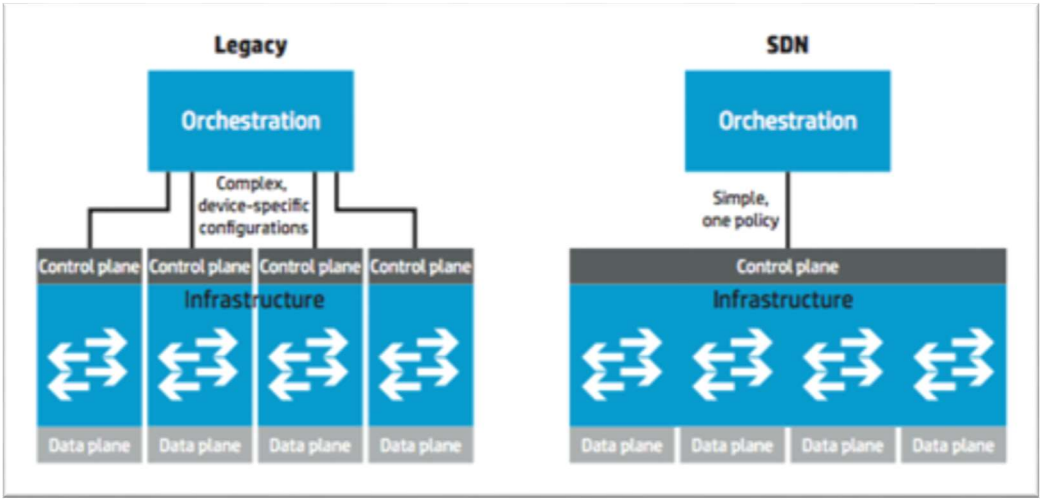

Figure 2.2 - Legacy Networking vs SDN

The delineation of the data plane and control plane may be achieved using well-defined programming interfaces between the SDN controller and the switches. The controller

assumes direct control of the management of the data plane elements through the use of Application Program Interfaces (APIs) such as OpenFlow (McKeown, et al., 2008). In an SDN deployment switches become just hardware flow processors. Based on the controller application-installed rules, an OpenFlow switch may, through the instruction of controller, serve as a firewall, switch, and router, or undertake other functions, for instance, traffic shaper or load balancer.

Although OpenFlow and SDN began as academic tests (McKeown, 2008), they gained considerable traction in the industry in the recent years. Many commercial switch vendors now incorporate OpenFlow API support within their equipment. The SDN momentum compelled Deutsche Telekom, Verizon, Microsoft, Yahoo, Facebook, and Google to finance the Open Networking Foundation (ONF) (2014) to promote and adopt SDN via open thresholds development. As the early issues with the scalability of SDN were tackled (Yeganeh, et al., 2013). Since then, SDN concepts have evolved and matured from academic exercises toward commercial success. For instance, Google has installed a software-defined network for interconnecting its Data Centers in the entire world. Google production SDN network has been operational for a period of 3 years, thus enabling the firm to reduce costs and enhance operational efficiency. (Jain, et al., 2013). Another example can be found in VMware SDN solution NSX. NSX provides a high level functioning programmable network without directly relying in individual underlying networking devices but in a pool of available hardware, based entirely on the network abstraction principle of SDN (VMware Inc, 2016).Finally, the largest IT firms in the world such as Cisco, Facebook, Google or Juniper have joined the SDN standardisation consortia OpenDaylight, ODL (OpenDaylight, 2013), another demonstration of the SDN significance from the industrial point of view.

2.3 SDN Architecture

A clear way of defining SDN architecture would be by describing the four main domains contained in any SDN design. According to Manar et al, these four domains are:

- Control plane;
- Northbound Application Programming Interfaces;
- East-West Protocols;

- Data Plane and Southbound Protocols.

(Manar, et al., 2014)

Figure 1.3 shows the different interfaces of a typical SDN deployment.

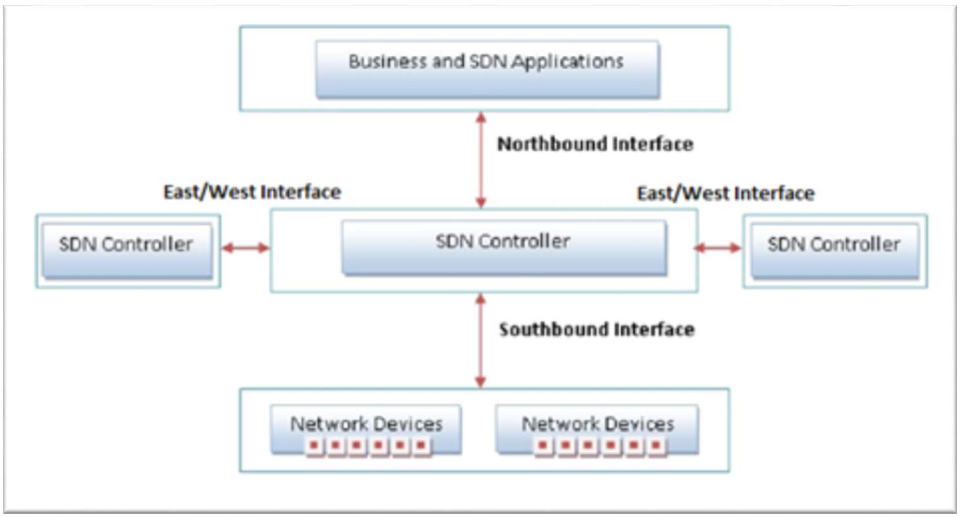

Figure 2.3 – SDN Architecture (Manar, et al., 2014)

Control plane

In an SDN design, the control plane is centralised in a network controller. The network controller is able to provide an abstracted view of the entire networking infrastructure allowing the network administrator to use custom protocols/policies across the network hardware. The network controller is the network operating system responsible for discovering the real-time state of all the network devices connected to its southbound interface and make sure that they are performing according to the network policies learned from the application layer via the northbound interface. As explained by Gude et al, a key feature of the network operating system is its ability to enable management applications to be written as centralised programs over high-level names contrarily to the highly time-consuming distributed algorithms over low-level addresses used to configure legacy networks. (Gude, et al., n.d.)

There are several initiatives in the network operating systems area. As observed in *Table 2.1* provided by Rao's analysis of the most used controllers, ODL OpenDaylight Controller proves to be the best performing controller today. (Rao, 2015)

Use-Cases \ Controllers	Trema	Nox/Pox	RYU	Floodlight	ODL	ONOS***
Network Virtualizaiton by Virtual Overlays	YES	YES	YES	PARTIAL	YES	NO
Hop-by-hop Network Virtualization	NO	NO	NO	YES	YES	YES
OpenStack Neutron Support	NO	NO	YES	YES	YES	NO
Legacy Network Interoperability	NO	NO	NO	NO	YES	PARTIAL
Service Insertion and Chaining	NO	NO	PARTIAL	NO	YES	PARTIAL
Network Monitoring	PARTIAL	PARTIAL	YES	YES	YES	YES
Policy Enforcement	NO	NO	NO	PARTIAL	YES	PARTIAL
Load Balancing	NO	NO	NO	NO	YES	NO
Traffic Engineering	PARTIAL	PARTIAL	PARTIAL	PARTIAL	YES	PARTIAL
Dynamic Network Taps	NO	NO	YES	YES	YES	NO
Multi-Layer Network Optimization	NO	NO	NO	NO	PARTIAL	PARTIAL
Transport Networks - NV, Traffic-Rerouting, Interconnecting DCs, etc.	NO	NO	PARTIAL	NO	PARTIAL	PARTIAL
Campus Networks	PARTIAL	PARTIAL	PARTIAL	PARTIAL	PARTIAL	NO
Routing	YES	NO	YES	YES	YES	YES

Table 2.1 SDN Controllers comparison

Looking at the evidence provided by *Table 2.1* seems evident why OpenDaylight, ODL, an open source SDN controller outperforming the rest of the controllers, has become the de facto operating system for servicing companies making the transition to SDN. (Logan & Buerger, 2016). It is imperative to remember that ODL is the standardisation effort of an SDN controller driven by the ONF. (OpenDaylight, 2013)

Northbound Application Programming Interfaces

The northbound interfaces of the controller connect it to the application layer. The application layer contains the applications in charge of building network policies and a representation of the high-level design of the network. Applications can communicate with the controller using API. The “northbound" interface denote the software interfaces between the SDN applications running on top of the network platform and the controller platform’s software modules. According to shin et al, these APIs expose global network parameters that can be used by network applications to manipulate the network. (Shin, et al., 2012)

East-West Protocols

From an infrastructural perspective, one critical aspect pertains to whether they are distributed or centralised. East-West protocols are only used within the scenario for a

multi-controller-based architecture, the East-West interface protocol controls interactions between different controllers.

A centralised controller refers to one entity, which controls all forwarding devices of the network. Naturally, it denotes one failure point and might have scaling drawbacks. On the other hand, a distributed network operating system may be scaled upward to fulfil the needs of any possible environment, from small to large-scale networks. A distributed controller may constitute a centralised node cluster or manually distributed elements. Moreover, Jain et al argue that, while the centralised option might provide high throughput for dense Data Centers, the latter may exhibit greater resilience toward different forms of physical and logical failures (Jain et al., 2013).

Data Plane and Southbound Protocols

The data plane represents the forwarding hardware within the SDN network architecture. The network controller uses its southbound interfaces to manage such data forwarding devices. OpenFlow is today the standard protocol for southbound interfaces. OpenFlow specification is controlled and defined by the Open Network Foundation (ONF).

ONF is a non-profit organisation led by a board of directors from companies that own and operate some of the largest networks in the world such as Facebook, Google, Deutsche Telekom, Microsoft, Verizon, Yahoo, and NTT. Najam Ahmad is its current director. (ONF, 2016). At present, the networking hardware from the biggest vendors such as HP, IBM, and CISCO use OpenFlow protocol in their SDN solutions.

2.4 SDN Benefits

An analysis of the available literature review shows that SDN is laden with numerous advantages for addressing the challenges facing traditional network architectures. This section explains all the benefits observed and serves as a base for a further analysis of the real appreciation of these benefits by the network engineers and their impact as drivers for the adoption of SDN initiatives. The following benefits were the most mentioned in the available literature.

2.4.1 Simplify Network Provisioning and Management

SDN is capable, by segregating of the control and data planes, of tackling the complexity and inflexibility of the conventional network. SDN enables organisations to manage their networks in a programmatic manner and to scale the networks without undermining user experience, reliability, and performance (Brocade Communications Systems, n.d.). Through the SDN approach, network administrators are not required to implement custom protocols and policies on each device separately within the network. Generally, SDN architecture control-plane functions are delineated from physical devices and are operated by an external controller (for instance, a standard server running SDN software).

On top of that, the SDN approach has the potential of facilitating the incorporation and provision of new devices into the current architecture. The SDN controller, by taking advantage of its holistic view of the network, enhances the traffic engineering capacities of the network operators through video traffic. It allows the network operators to manage their congestion areas and decreases the complex nature of traffic engineering.

2.4.2 Network Flexibility

SDN offers a potential opportunity for controlling hyper-scale Data Centers (DC). Data Centers raise considerable scalability issues, particularly with the current virtual machines' (VM) continuous growth where new servers can be deployed by pressing a button. Shifting a virtual machine and upgrading the Media Access Control (MAC) address table through traditional network architecture can interrupt user applications and experience. (Shin, et al., 2012) Following the same concept as server virtualisation, SDN uses Network virtualization to build virtual networks that have the flexibility to adapt to hyper-scaling DCs requirements. SDN, for instance, can enable multi-tenant hosting providers to connect their virtual and physical servers and remote and local facilities into one logical network. By doing this, network providers can provide to each of their clients a differentiated virtual network. Put simply, SDN is a potential method for providing networks as a service (NaaS), which will allow virtual network operators and flexible service operators with the ability to control Data Centers along with their traffic.

2.4.3 Better Use of the Available Network Resources

SDN offers the capacity of encouraging innovation within the networking field by providing a programmable avenue for experiments on novel policies and protocols through production traffic. Delineating test flows from data flows to enhance the use of emerging ideas and protocols into the networking domain (HP, 2012). From a wider perspective, SDN provides a management of the network where the decisions of packet routing are delinked from the switching hardware (HP, 2012). Because of its central point of view of the network topology from the network controller, the consolidation of Ethernet fabrics and SDN achieves real networking intelligence (Brocade Communications Systems, n.d.). This feature enables SDN deployments to better use the available hardware resources available than legacy networks would traditionally do.

2.4.4 Lower Capital Expenditure (CAPEX)

In order to guarantee service, in traditional networking network resources such as circuits or network hardware need to be often Over-dimensioned to respond under flow peaks. Contreras et al argue that over-dimensioning network links to accommodate traffic where the peak load varies widely and changes frequently creates a significant Capital Expenditure (CAPEX) inefficiency. (Contreras, et al., 2015)

Software-Defined Networking supports logically centralised intelligence and network virtualization. This feature, by enabling a central controller to take intelligent decisions based on a holistic view of the network translates into minimising the stranded capacity and maximising network resource utilisation. Put simply; higher resource usage turns into less equipment. On top of that, SDN deployments lessen dependencies on proprietary hardware and dedicated appliances what often translates into capital savings. For instance, Google networking team with the implementation of SDN in their network under the project named B4 was able to B4 deploy substantial cost-effective WAN bandwidth, running many links at near 100% utilization for extended periods of time, reporting big savings to the organisation in circuits leases. (Jain, et al., 2013)

2.4.5 Lower Operational Expenditure (OPEX)

In a legacy networking ecosystem there is no common integrated way of operating the diversity of network technologies and vendor solutions present in the network. This implies different implementations of the same concepts and standards, for each vendor hardware installed. (Contreras, et al., 2015) Furthermore, these implementations are not always totally compatible because of specification gaps and proprietary differentiators causing exhausting troubleshooting involved several vendors.

Software-Defined Networking remodels operations by automating network configuration, provisioning, and management making use of central network administration and network programmability. It provides a uniform control and management capability across multiple technologies and network layers. Through infrastructure automation, provisioning and configuration times improve, complexity decreases and manual mistakes are significantly reduced. For instance, according to Krish Prabu, CTO and president of the big networking player AT&T Labs, the organisation has the goal of virtualizing 75% of its network by 2020 applying SDN and NFV technology. Once this objective is achieved, he foresees savings in operational costs of up to 40 or 50 percent. (Prabu, 2016)

2.4.6 Performing Traffic Engineering

SDN deployments, by having a centralised view of the whole network deployed stored in the Network Controller, can provide much more efficient and intelligent Traffic Engineering (TE) mechanisms compared to the conventional approaches such as ATM, IP, and MPLS. (Akyildiz, et al., 2014). Moreover, according to Agarwal et al, SDN provides centralised visibility including global network information (e.g., network resource limitations or dynamically changing the network status) and global application information (e.g., QoS requirements); (Agarwal, et al., 2013) therefore allowing for a more flexible network that can react on real time to changing factors such as bandwidth and delay.

2.5 SDN Challenges and Existing Solutions

Although software-defined networking offers a potential solution for network providers and IT organisations, it experiences some challenges, which might undermine its implementation and performance. A set of SDN challenges were found during the

literature review available around the SDN topic. An analysis of the challenges found are explained in the following subsections and are the base for the research performed to rank what are the top challenges that network engineers face during SDN implementations.

2.5.1 SDN Network Reliability

In traditional networks, when a single or multiple network devices fail, new traffic gets routed via adjacent or other nodes or devices for the sustenance of flow continuity. However, in a centralised controlled infrastructure (SDN) where there is no stand by controller, only a single core controller oversees the entire network. Therefore, if the controller fails, the entire network might collapse. To overcome the reliability challenge, companies should focus on the exploitation of the main redundancy functions of the controller capable of increasing network reliability (Ashton, Metzler, and Associates, 2013). (Jammal, et al., 2014)

Research shows two main initiatives to resolve SDN reliability issues;

- To add redundancy to the network controller in a central controller architecture. This is achieved using protocols such as Vitual Router Redundancy Protocol, VRRP. With this method there is only one active SDN network controller with one or more backup controllers in stand-by mode
- To deploy a distributed network controller architecture where several network controllers are active at the same time and are responsible to maintain different zones of the network. The failure of one controller would be mitigated by another controller taking control of the network nodes that lost connection to the active controller in their area.

2.5.2 SDN Network Scalability

Decoupling between control and data planes differentiates SDN from a conventional network. In SDN centralised network deployments the network controller view of the control increases management possibilities within the control plane. The exponential growth of control plane data in the SDN controller puts at risk its ability to perform and

scale. Voellmy and Wang (Voellmy & Wang, 2012) observed that if the network scales upward in the quantity of end hosts and quantity of switches, the SDN controller may present a huge drawback. As the quantity and bandwidth of flows and switches escalate, additional requests would be dispatched to the controller that might not have the handling capacity for all of them. For instance, studies from Tavakoli et al estimate that a mega data centre comprising 2 million virtual machines might produce 20 million flows in each second. (Tavakoli, et al., October 2009)

The performance of the SDN network is dependent on the software (controller) and switch resources (memory, CPU) performance. If a network controller faces performance issues, it will add a delay on the update period for the switch's forwarding information base introducing a delay in creation of any new flows representing a challenge for network scalability. Organisations with big legacy productions networks may therefore be facing issues when trying to implement SDN in their infrastructure.

2.5.3 SDN Security Threats

According to Akhunzada et al, the emergence of SDNs requires additional security requirements because of newly deployed infrastructural entities as security was not considered part of the initial SDN architecture design (Akhunzada, et al., 2016). SDN, leads to an enthralling evolution of networking designs; nonetheless, its network centralised management and programmability also increases security risks. With the its fast adoption, SDN has already become a prominent target for attackers. Li et al argue that there are three major components in a SDN deployment that may represent security threats: switch, controller and channel.

- At the switch plane, an attacker can try to snoop on southbound conversations between the network component and the network controller. The sniffed information by the attacker could then be valuable for a replay attack or for surveillance purposes;
- At the controller level, if attackers could force the vulnerable northbound API, then the attacker would have full control over the network. In this position, attackers can

create their private SDN policies and consequently obtain control of the SDN environment;

- At the OpenFlow channel level, the principal hurdle is the absence of trust mechanism among the controllers and the switches. (Li, et al., 2016)

The literature review on this subject shows that securing SDN is still in its initial state. At the same time, results from a survey from Juniper Networks in the same article claims that 34% of the respondents had Security as their bigger concern (SDxCentral, 2014).

2.5.4 Immaturity of Enabling Technology (OpenFlow)

The first investment in SDN is risky and high. The several non-interoperable southbound APIs available today constitute a major impediment for acceptance and introduction of any new emerging network technology. From this perspective, the rise of a standard SDN southbound API proposal, such as OpenFlow, is considered critical by many within the industry. Such standards enhance interoperability, allowing vendor-agnostic network devices to be deployed. This interoperability has been already exhibited in tests that interconnect equipment from numerous vendors using OpenFlow as a common southbound protocol. While ONF is working in standardising OpenFlow, this is an ongoing effort, and it has not reached yet a mature state.

2.5.5 Immaturity of Vendor Solutions

SDN technology has been newly adopted by the biggest networking vendors such as VMWare and Cisco while other startups have flourished from the SDN paradigm including Brocade, BigSwitch, Pica8. On the other hand IT landscape giants such as Google or Facebook have developed their own SDN solution based on open source standards. At present, the selection of an SDN vendor can be a complicated process caused by the lack of strong standards and clear strategies from the SDN vendors. Supporting this idea, Cliff Grossner, director at Infonetics, argued that “There’s still some work to do on the part of SDN vendors. Expectations for SDN are clear, but there are still serious concerns about the maturity of the technology and the business case”. (SDxCentral, 2014)

2.6 SDN Influence in Network Engineers

During the literature review, several sources mentioned possible impacts that the SDN adoption may produce in the network engineer role were identified. As part of this research, these possible impacts were presented to the surveyed network engineers in order to gauge their opinion and study the accumulated data generated from their responses.

2.6.1 SDN Influence in the Network Engineers' Skills

With the adoption of SDN initiatives, Network engineers will need to adapt their skills to be able to manage highly programmable networks. The first step for network engineers to keep relevant in the market may be to learn programming skills.

Numerous CEOs and other Network engineering experts support that network engineers will need to learn programming skills. For instance, Pascale Vicat-Blanc, founder and CEO of networking start-up Lyatiss, argues that engineers, who used to use CLI, will now have to learn scripting and higher-level languages to program or optimise the network. The same way, Vijay Gill, General Manager for Global Network Services at from Microsoft advised that network engineers may need to learn languages such as Python, C# and PowerShell. Moreover, on the same article Najam Ahmad, Facebook's director of technical operations for infrastructure, explained that at Facebook's network engineering team, everybody was already writing code. (Banks, 2016)

Based on the evidence gathered from the different subject matter experts and SDN stakeholders, it is safe to assume that Network engineers will need programming skills added to their usual purely network protocols knowledge and network configuration skills.

2.6.2 SDN Influence in the Network Engineers' Role

With the adoption of SDN, network teams will need to evolve to be able to perform accordingly to the new reality of configuring networks. A way of adapting network teams to the potential of SDN will imply that network teams will not only divide into the traditional

network designers and network operators' roles but, on top of that, will include a new role defined as network programmers.

According to Lawson, Network designers will ascertain network requirements and how to meet them, then based on these requirements set the specifications for network applications. Writing those applications be the responsibility of a new type of network staffer, the software automation developer. These developers will have background knowledge concerning networking along with skills in standard programming languages such as Java, Python, and C. Once the software is written, network engineers and support engineers will install the new network application and troubleshoot it. (Lawson, 2013)

2.6.3 SDN Influence in Network Planning and Configuration Cycles

Based on the review of the little literature available, experts expect network configuration and operation to be reduced significantly with the adoption of SDN. Luis M. Contreras et al disclose that the network programmability notion of SDN provisions common ways of operation detached from the technology or vendor hence simplifying network operations. At the same time, controlling and operating a network adopting logically centralised administration as conceived in SDN, empowers automation of network operations. Moreover, Self-learning and self-healing capabilities can be programmed or developed hence decreasing manual intervention. (Contreras, et al., 2015)

On the other hand, Network engineers instead of spending time in mundane operational tasks may now spend more time on more proactive network management tasks such as capacity planning, design or reporting.

2.6.4 SDN Impact on Workforce Training

From the company perspective, any organisation evaluating to engage in any SDN initiative needs to examine the impact that adopting an SDN initiative in-house will have on its networking staff and operations.

From the network engineer perspective, Several SDN training options for network engineers have become available in recent years both from networking vendors and open source organisations. On one hand Cisco System, arguably the largest vendor for network equipment, has added four new certifications to their career path including; Cisco Business Application Engineer Specialist, Cisco Network Programmability Developer Specialist, Cisco Network Programmability Design Specialist, and Cisco Network Programmability Engineer Specialist. (Cisco, 2016)

On the other hand, the open source SDN foundation ONF, has launched the ONF-Certified SDN Professional Program (OCSP) providing vendor-neutral education and skills validation for engineering professionals wishing to improve their knowledge of Software-Defined Networking. ONF offers currently two Certifications; OCSA (Associate) and OCSE (Engineer) (ONF, 2016)

2.6.5 SDN Impact on Network Teams' Organisational Structure

A typical network operator's technical organization is structured in different departments such as network architecture, capacity and planning, network security, ornetwork operations and support. With the adoption of SDN and NFV and its capability to add an extra level of abstraction in the network, this structure will be subjectable to changes since both the departmental and technical boundaries and responsibilities become more blurred. According to Contreras et al, this traditional structure needs to be re-adapted to the new cross-technical and cross-functional reality brought about by both innovations. (Contreras, et al., 2015)

2.7. Conclusion

Conventional networks are not only complex but are difficult to manage as well. One reason revolves around the fact that data and control planes are vendor-specific and vertically integrated. On top of that, typical networking devices are also closely linked to different vendors making the integration and management of the different network nodes an arduous task.

SDN represents a significant paradigm shift in network creation and evolution, unveiling a new innovation speed within networking architecture. In spite of the latest and interesting efforts to examine this new chapter in network history, one extensive and thorough summary of SDN's current adoption fase and the top benefits and challenges driving its adoption is still missing. Attempting to tackle this gap, the current literature review adopted a layered method in dissecting the architecture concerning software-defined networking components, ideas, and concepts, traversing an extensive range of existing solutions, and future directions.

The literature review explored the comparison of the new paradigm against conventional networks, providing a discussion on how industry and academy assisted in shaping software-defined networking continuing with an overview of the SDN architecture. Following to that, this chapter covered the adoption factors for SDN, by explaining what are the benefits or adoption drivers for SDN. Benefits such as simplification of network provisioning and management, increase the flexibility of the network, the better use of available network resources and a decrease of OPEX and CAPEX were discussed.
On the other hand, the other side of the adoption factors, the adoption inhibitors or the challenges faced when implementing SDN were also discussed. These included technical SDN challenges such as reliability, scalability and security challenges and adoption challenges such as the immaturity of enabling technology and SDN vendor solutions. The last part of this section analysed what impact the adoption of SDN may have in the network engineering workforce.

3 Methodology and Fieldwork

3.1 Introduction

This chapter explains the methodology adopted for researching and obtaining answers to this dissertation paradigm.

Saunders et al. (2009) define research as a systematic, methodological and ethical process of enquiry and investigation undertaken to find out things in order to increase knowledge. Sanders' Research Onion, depicted in *Figure 3.1* below, demonstrates the layered nature of the research process.

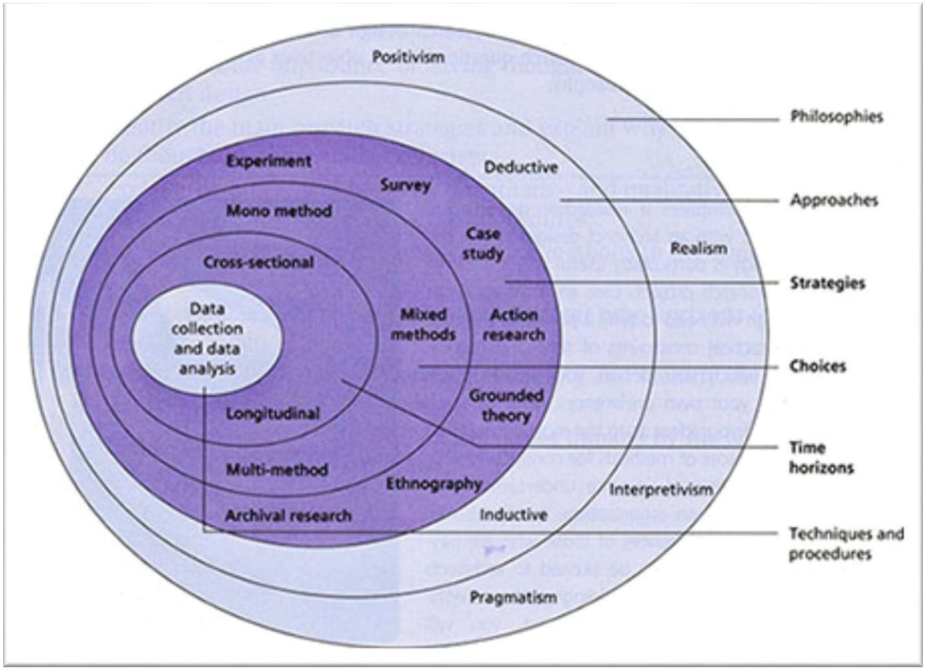

Figure 3.1 Saunders Onion (Saunders, et al., 2009)

This chapter presents the different methodological approaches that were considered and the rationale for selecting the best fitting method for this dissertation while describing the implementation of the research strategy.

3.2 Research Philosophy

In order to conduct proper research a researcher must be aware that research, by definition, is carried out based on underlying philosophical assumptions made by the researcher. Sanders et al describe the concepts of ontology and epistemology both of which describe the underlying assumptions the researcher is making about the world. (Saunders, et al., 2009).

Ontology relates to the nature of reality and has two primary differentiated perspectives; Objectivism and subjectivism. These aspects also impact epistemology which centers in the best way to perform research.

- **Objectivism** advocates that social entities or realities exist independently of the nature of the observer
- **Subjectivism**, in contrast, is based on the interpretations of the observer, rather than the realities of what is being observed.

Objectivism has typically been correlated with the positivist perspective while subjectivism has been associated to interpretivism. This section examines what have been arguably the most predominant and influential of the various research philosophies: Positivism and Interpretivism.

3.2.1 Positivism

A positivist perspective, claims that only observable phenomena can lead to conceivable data. The data is typically developed from hypothesis creation, procured from existing theory, and empirical testing and measurement. The positivist researcher, using neutral observation, seeks for objectivity by being disengaged from the participants of the research.

According to Flowers, this position is mainly focused on data acquired from experience or direct observation, which are empirically measured using quantitative methods, such as surveys and experiments (Flowers, 2009).

Positivism is the adopted philosophy for this research as it endeavours to test hypotheses formed from theory assumed from the literature review by using purely quantitative methods.

3.2.2 Interpretivism

Interpretivism in opposition views knowledge differently from Positivism. Interpretivism argues that no objective reality can be discovered by researchers and replicated by other. It reveals that our knowledge of reality, including the domain of human action, is a social construction by human players and that this applies equally to researchers.

Put simply; Interpretivism highlights the necessity to understand people in their role as social actors rather than solely as objects. Thus, interpretivists favour to do research on people rather than objects and practice a qualitative rather than quantitative approach when conveying their research.

3.3 Research Approach

There are two main approaches when it comes to research. The deductive approach and the inductive approach.

Deductive thinking involves the development of a hypothesis that is subjected to a rigorous test. It is the most popular research method in the natural sciences, where the data collection and analysis techniques need to be structured in a way that enables facts to be measured quantitatively (Saunders, et al., 2009). Deductive reasoning, as shown in *Figure 3.2,* utilises facts, rules, definitions or properties to arrive at a conclusion.

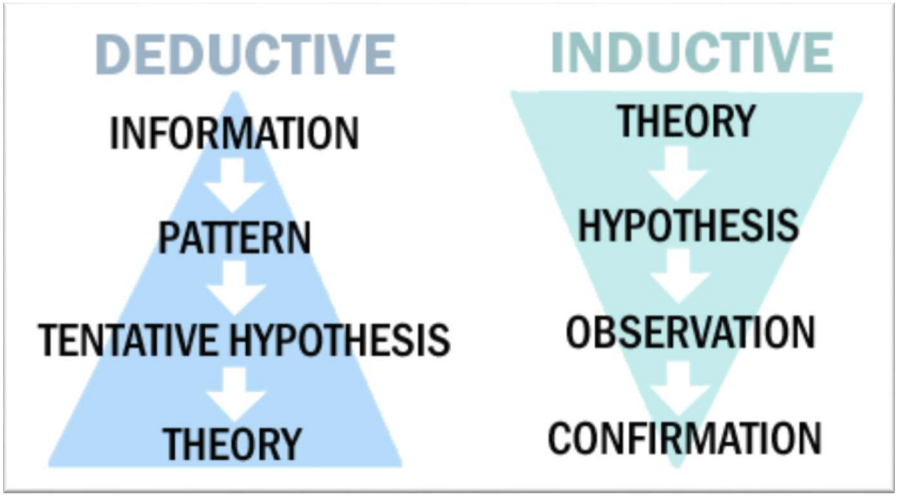

Figure 3-0.2 Inductive VS deductive (Saunders, et al., 2009).

Based on the comprehensive literature review conducted, this study will adopt the deductive research approach. Objective quantitative data will be collected using an, informally referred to, “top-down” approach.

3.4 Research Methods

Research methods and research data can be arranged into two basic categories: quantitative or qualitative.

Quantitative Research: The principal goal of the use of quantitative methods is the formation of generalisations that subscribe to theory by facilitating the researcher’s understanding or definition of a phenomenon. Quantitative Research is practised to quantify attitudes, opinions, behaviours, and other defined variables – and theorise results from a larger sample population. In other words, this approach entails the acquisition and analysis of data in the numerical format through experiments and surveys.

Qualitative Research is principally exploratory research. It is applied to achieve an understanding of underlying reasons, opinions, and motivations. It provides insights into the dilemma or helps to generate ideas or hypotheses for potential quantitative research. This method comprises recognising and revealing theories or models to explain a phenomenon by use of non-numeric data that can be collected by different means, such as case studies, in-depth interviews and focus groups. The representation size is habitually modest, and respondents are selected to satisfy a given quota.

According to McLeod, Analysis of qualitative data is complex and requires an accurate description of participant responses, for example, sorting responses to open questions and interviews into broad themes (McLeod, 2008). This dissertation will use quantitative data obtained from an online survey.

3.5 Research Methodology used for this Research

3.5.1 Philosophy

The data required to be able to conduct this research will be gathered only from IT professionals who hold the basic technical knowledge about Software-Defined Networking. These include network engineers and network team managers. A positivist approach was selected where quantitatively data will be collected.

This dissertation aims to ascertain the current status of SDN implementations and identify trends. It focuses on the challenges faced and the benefits obtained by the IT professionals who venture in its implementation. Therefore, the positivist philosophy is guaranteed as the details regarding the challenges and benefits are measured objectively using quantitative means.

3.5.2 Approach

Due to the relationship between the theory formed during the literature review and quantitative accumulated data in this study, this research used a deductive approach. During the literature review a relevant number of challenges and benefits of SDN were identified. This research aims to establish a ranking of priority on the many benefits and challenges gathered that could benefit researchers and practitioners to focus in what are the top priorities to be addressed in order to foster SDN adoption and evolution.

3.5.3 Strategy

Several strategies to conduct this research were contemplated and dismissed due to various reasons; Semi-structured interviews with stakeholders were considered. However, interviews cannot be applied to make statistical generalisations about the entire population as this is based on a small and unrepresentative number of cases. A case study was also envisioned. Nonetheless, it has shortcomings about this research. A case study is time-consuming, subjective and narrow focused. Thus, rendering generalisation impossible. At last, a survey research strategy was adopted for this study as this research endeavours

to collect the opinion of IT professionals, in particular, network engineers and other SDN stakeholders, to test hypotheses.

Primary data collection employing a survey is an efficient method of accumulating extensive volumes of data from a geographically dispersed population, thus enabling the findings to be generalised. The data collected can also be standardised, making comparison easy; it can be quantitatively or qualitatively analysed using descriptive and inferential statistics (Saunders, et al., 2009). The survey was created in such a way that the questions were clear and concise, and kept to the minimum to avoid survey being abandoned, or filled in randomly.

3.5.4 Research Method

As SDN is a new and disruptive technology, secondary data is scarce and difficult to gather. The research strategy adopted involved the collection of only primary data from Network engineers and SDN stakeholders using an online survey.

Horrigan et al, state that researchers may find the Internet an extraordinarily rich domain for conducting survey research. Virtual communities have flourished online, and hundreds of thousands of people regularly participate in discussions about almost every conceivable issue and interest (Horrigan, 2001)

An online survey was chosen for this research for its versatility, efficiency and ability to form generalisations. The researcher found that the most suitable option to gather sufficient quantitative results from a widespread sample population who have access to the internet in their day to day life.

3.5.5 Survey Population

The target population for this survey consisted of ICT professionals especially those who may have expertise and familiarity with Software-Defined Networking and are involved in both legacy and new SDN network related ventures. These professionals know the complex aspects between both, legacy and SDN, technologies and are in an excellent

place to present the current status of SDN implementations in Ireland and what are the key adoptions factors of this new disruptive technology.

Nevertheless, the survey was also introduced to other SDN stakeholders, before-mentioned as IT Managers and other business parties, who have interplays with the team administering and managing SDN network environments. Their view was also taken into account as they are expected to be included in the decision-making process to adopt SDN technologies and management of the manpower involved in administering SDN networks.

3.5.6 Survey Design and Content

Saunders et al, recognise that it is considerably difficult to design a good survey and that the survey should be designed in such a way that it would collect accurate data around the research question and objectives (Saunders, et al., 2009).

“Qualtrics”, a web-based application was used to design an online survey. The survey was carefully designed with the understanding that the questions were to be read by a busy target population; consequently, the questions were short and very precise and were always designed keeping in mind the research question and the target research population.

Closed-ended questions were applied through the whole questionarie as they were considered the most appropriate to gather the most accurate information in the smallest amount of time. The survey took approximately 8-10 mins to complete and consisted of 15 closed questions. The questionnaire included multiple choice and ranking type questions organised in three different sections:

- Section1 provided participants information regarding the survey. A consent form and a definition of SDN technology.
- Section 2; covered participants’ demographics and company background details and evaluated the respondents’ knowledge of SDN and its significance to the business or the organisation where it is implemented.
- Section 3 focused on SDN technology based questions, such as what SDN technologies they had experience with and what barriers they thought would

impede its successful implementation. The next set of questions sought to gather information in the form of the perception from SDN stakeholders on how SDN would shape their company organisation structure and their day to day work.

3.6 Research Ethics

Ethics approval was sought and obtained in June 2016 from the School of Computer Science and Statistics Research Ethics Committee before distributing the survey. In line with the Research Ethics Committee guidelines, the goal and aim of the research were disclosed to the respondents before they provided their consent to engage. Participation was confidential, anonymous and voluntary. The participants were also advised they could abandon the questionnaire at any point in time.

The following documents were submitted to the Ethics Committee:
Informed consent form for organisations.

- Survey invitation.
- Completed ethics forms.
- Research proposal.

3.7 Conclusion

This section illustrated a detailed description of the methodology utilised in this research. The research adopted a positivist approach, and an online survey was used as the research strategy. This section concludes with the ethical considerations recognised and methodology constraints in this research. Following section four presents the analysis and interpretation of the data collected from the survey.

4 Findings and Analysis

4.1 Introduction

This section outlines the findings and presents a comprehensive analysis of the empirical data collected for this research. As explained in Chapter 3, to answer the research question, empirical data was accumulated using an online survey. The online survey was only exposed to IT practitioners and people with relevant business background on the SDN topic. More specifically, Network engineers or managers who are informed and aware of SDN initiatives from an IT aspect.

The section first evaluates the response rate and data analysis from the data obtained from the survey. Next, this section presents a comprehensive explanation of the survey findings. Findings are shown divided into subsections appointing on each of them which analysis method was used and their corresponding findings

4.2 Response Rate and Data Analysis

According to Yehuda Baruch's study, Response Rate in Academic Studiesthe average response rate to surveys is 55.6% with a usual deviation of 19.7; however, there is a lower level response to be found in studies involving management or organisational representatives averaging 36.1, with a standard deviation of 13.3, (Baruch, 2016).

Since the study was to be conducted within the Irish IT professionals landscape and SDN is a relatively new technology, a target sample population size of 100 respondents was envisioned. The link to the online survey was circulated to close contacts such as co-workers, partners and LinkedIn contacts. Furthermore, it was also posted to online meetup and LinkedIn groups formed by Network Engineers, Network Operation managers and IT professionals, who may be familiar or have a significant interest or knowledge in SDN technologies.

Even though there was an extensive usage of personal contacts and the broadness of the groups' populations reached online, there were only 60 responses to the survey; therefore, the response rate to the survey was 60%.
The survey, once Ethics approval was conceded, was made available online for 3 weeks, from the 1st of July 2016 to the 21st of July 2016 and earned a total of 58 responses. Out of the 60 total answers, some of them had some questions unanswered. To give the participants the option to skip questions was a requirement asked by the ethics approval committee in order to concede ethics approval. The data obtained was analysed using Qualtrics reporting tool.

The review and analysis of the data collected will ultimately provide answers to the following research questions and sub-questions

Research Question: What is the current status of the SDN movement in Ireland; Adoption factors and impact on Network engineers

Sub-questions:

- SQ1: What is the present state of the SDN deployments?
- SQ2: What are the key adoptions factors for SDN?
- SQ3: What is the network engineer's perception on the impact SDN may have on their jobs?

4.3 Survey Findings

The online questionnaire was distributed into the subsequent four sections for analytical purposes:

1. Participants Profile.
    A. Years of experience in IT
    A. Familiarity with SDN technology
    B. Size of the managed network
    C. Influence on SDN related initiatives
    D. Type of industry of their organisation

2. Present state of SDN implementations
    A. involvement by the participant on SDN initiatives
    B. Where in their network SDN will be deployed in the nearest future

3. SDN adoption factors
    A. Rank of benefits of adopting SDN
    B. Rank of challenges when implementing SDN

4. SDN implementations impact on Network engineers
    A. How much impact SDN will have on the nature of the role of network engineers
    B. What changes participants anticipate on the nature of their role
    C. How much impact SDN will have on the participants' organisational structure
    D. What structural changes participants anticipate.

4.3.1 Participants Profile.

In order to establish profiles for the different participants who answered the online survey the following sub categories were established;

1. Years of experience in IT
2. Familiarity with SDN technology
3. Size of the managed network
4. Influence on SDN related initiatives
5. Type of industry of their organisation

Participants' years of Experience in IT

Question asked to the participants on survey;

How long have you been working in IT?

Survey participants were asked to indicate for how long they had been involved in IT activities. An 80% had more than seven years of experience in IT related activities and from those, a 36% had more than ten years. Therefore, the results extracted from the online survey come in their vast majority from highly experienced IT professionals. Details of the data gathered can be observed in *Table 4.1.*

Answer	%	Count
Less than a year	0.00%	0
1 to 3 years	6.90%	4
4 to 6 years	20.69%	12
7 to 10 years	36.21%	21
Over 10 years	36.21%	21
Total	100%	58

Table 4.1 Participants experience in IT

Participants' Familiarity with SDN technology

Question asked to the participants on survey;

How familiar are you with Software-Defined Networking?

As seen in *Table 4.2*, 100% of the respondents answered that they had some familiarity with SDN. 59% of the participants considered they were "*moderately familiar*" or "*very familiar*" with SDN, and the other 41% replied that they were at least slightly familiar.

Answer	%	Count
Very familiar	13.79%	8
Moderately familiar	44.83%	26
Slightly familiar	41.38%	24
Not familiar at all	0.00%	0
Total	100%	58

Table 4.2 - Participants' Familiarity with SDN technology

Two possible conclusions could be derived from the data gathered. First conclusion revolves around the idea that the survey was targeted to the relevant population. On the other hand, the second hypotheses would argue that most of today's network engineers are at least slightly familiar with the SDN topic which would prove some grade of adoption of SDN technology knowledge by the network engineers.

It is worth mentioning that a categorization of the data gathered around the participants SDN knowledge by the participants experience in IT did not show a direct relation between a higher knowledge of SDN with more years of experience.

Size of the managed network

Question asked to the participants on survey;

How big is the network you operate/provision/manage?

To be able to categorise further results by network size, possible different adoptions factors of SDN technologies based on the size of the network where SDN would be implemented, participants were asked to specify the size of the networks that they operate. As shown in *Figure 4.1*, from the 57 responses obtained, a significant 43% of the respondents manage large networks with over 1000 nodes.

From the remaining 57% respondents, 21% managed networks sized between 500 and 999 nodes and another 24% managed networks sized between 100 and 499 nodes, which represent the respondent managing medium sized networks. Finally, only a 12% of the respondents managed small networks with less than 100 nodes managed.

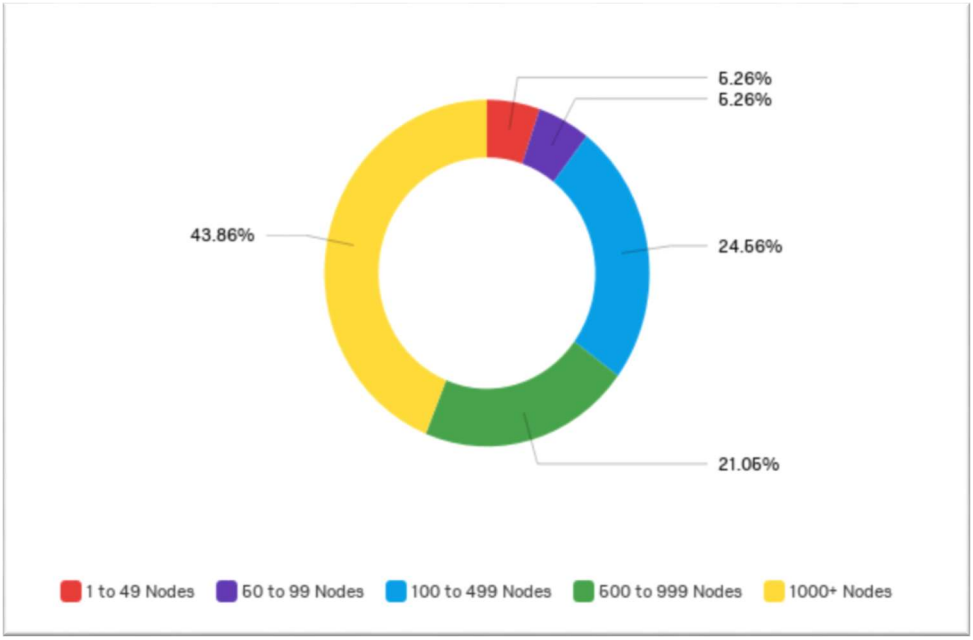

Figure 4.1 Size of the network managed by participants

The high number of replies from participants managing large and medium sized networks could be related to the replies on the section before as highly experienced network engineer tend to manage larger networks.

Influence of the participants on SDN related initiatives.

Question asked to the participants on survey;

> How much influence your opinion on adopting SDN would have in your organisation?

Survey participants were asked about their influence as decision makers when it came to implement SDN initiatives in their organisations. As shown in *Table 4.3*, 90% of the participants had some influence as technical experts on the implementation of SDN in their organisations. A 60% of the respondents were directly responsible for the decisions around SDN implementations on their organisations. From those, 12% being the maximum responsible in their organisations around network design and implementations including SDN. Contrarily, only a 10% of the participants responded that they had no influence at all when it came to deciding whether or not any SDN initiative would be adopted by their organisations.

Answer	%	Count
I am the maximum responsible and decision maker for network design and implementations including SDN	12.07%	7
I am part of a decision making group for network implementations including SDN	48.28%	28
I am NOT part of a decision making group but my opinion would be considered by the decision making group in my organisation	29.31%	17
I have no influence at all	10.34%	6
Total	**100%**	**58**

Table 4.3 Influence of the participants on SDN related initiatives

The evidence that the 90% of the survey respondents had some influence when it comes to deciding about SDN initiatives in their organisation manifests that the questionnaire targeted a highly relevant population to the SDN Topic.

Type of industry of the participants' organisations

Question asked to the participants on survey;

In which industry are you currently employed? (What is your company primary business)

The last question submitted to the participants in the participants' profile section asked them to specify what the nature of the business of the organisations was. As shown in *Table 4.4*, around 52% of the respondents worked for I.T. organisations. This 52% was composed by 43% belonging to IT/Internet/software organisations and a 9% belonging to Telecommunications providers.

The remaining 48% of the responses belonged to engineers working for organisations where the primary business was not related to Information Technology. Half of this non-IT organisations were Finance or Insurance companies with a 25% while the other 23% was scattered in several other industries.

Answer	%	Count
Information Technology / Internet / Software	42.86%	24
Telecommunications provider	8.93%	5
Finance or insurance	25.00%	14
Construction	1.79%	1
Forestry, fishing, hunting or agriculture support	0.00%	0
Public administration	3.57%	2
Transportation or warehousing	3.57%	2
Real estate or rental and leasing / Accomodation	0.00%	0
Management of companies or enterprises / Consulting services	3.57%	2
Educational services	1.79%	1
Health care or social assistance	5.36%	3
Other	3.57%	2
Total	100%	56

Table 4.4 Type of industry of the participants' organisations

Additional analysis of the data accumulated relating to the nature of the business of the organisations combined with the data gathered about the respondents' familiarity of SDN managed produced the following results.

A categorisation of the data collected concerning the nature of participants' organisations business by the participants' familiarity with SDN returned the results observed in *Table 4.5.* These results showed how I.T. and Finance or Insurance companies employed a workforce of network engineers more familiar with SDN. This knowledge was especially high by the respondents employed by IT/Internet/Software organisations with a 25% of respondents being very familiar with SDN and a 50% being moderately familiar.

	Very familiar	**Moderately familiar**	**Slightly familiar**	**Not familiar**
Information Technology / Internet / Software	25%	50%	25%	0%
Finance or insurance	14%	36%	50%	0%
Other	0%	0%	100%	0%
Construction	0%	100%	0%	0%
Forestry, fishing, hunting or agriculture support	0%	0%	0%	0%
Public administration	0%	0%	100%	0%
Telecommunications provider	0%	60%	40%	0%
Real estate or rental and leasing / Accomodation	0%	0%	0%	0%
Management of companies or enterprises / Consulting services	0%	50%	50%	0%
Educational services	0%	100%	0%	0%
Health care or social assistance	0%	0%	100%	0%
Transportation or warehousing	0%	50%	50%	0%

Table 4.5 Nature of organisations' business vs familiarity with SDN

The results above prove that Software Organisations, which have a workforce with a high knowledge in programming, have network engineers more proficient on SDN technology. The results in this section are in line with the data derived from section 2.3 in the literature review that showed how I.T. companies like Google, Facebook, Amazon, Cisco have been early adopters of SDN and are collaborating in its development and standardisation with their participation in the ONF. (ONF, 2016)

4.3.2 Present State of SDN Implementations

In order to establish the present state and a forecast for the nearest future of the SDN implementations the online survey the following sub categories were established;

A. Present involvement by the participant on SDN initiatives
B. Where in their network participants think SDN will be deployed in the nearest future

Present involvement by the participant on SDN initiatives

Question asked to the participants on survey;

Are you part of any Software-Defined Networking initiative? (Check all that apply)

- *We have not conducted any study of SDN yet*
- *We will likely study SDN possibilities next year*
- *We are studying the VALUE that SDN can bring to our organisation*
- *We expect to have SDN running in a Lab environment within a year*
- *We are currently studying different SDN vendors' solutions*
- *We already have SDN running in a Lab*
- *We already have SDN running in our production network*

From the valid responses received from the online survey, *"We are studying the VALUE that SDN can bring to our organisation"* with 27.6% and *"We already have SDN running in*

a LAB" with 25.8% were the most voted responses. The remaining choices that made reference to an active attitude towards implementing SDN were slightly less voted. *"We are currently studying different SDN vendors solutions"* was chosen by a 17.2% of the participants while *"We expect to have SDN running in a Lab environment within a year"* and *"We will likely study SDN possibilities next year"* where equally replied by 13.8% of them. Ultimately, *"We have not conducted any study of SDN yet"* was replied a 15.5% of the time by the respondents to the survey.

Table 4.6 shows the results explained above;

	%	Count
We have not conducted any study of SDN yet	15.52%	9
We will likely study SDN possibilities next year	13.79%	8
We are studying the VALUE that SDN can bring to our organisation	27.59%	16
We expect to have SDN running in a Lab environment within a year	13.79%	8
We are currently studying different SDN vendors' solutions	17.24%	10
We already have SDN running in a LAB	25.86%	15
We already have SDN running in our production network	12.07%	7

Table 4.6 SDN Initiatives

As seen in following *Figure 4.2* a deeper analysis of the 15% that replied *"We have not conducted any study of SDN yet"* shows that 5 of those respondents also expressed that they would *"likely study SDN possibilities next year"*. That results imply that only 4 out of the 58 respondents did not envisage that they will be involved in any SDN initiative during the next two years.

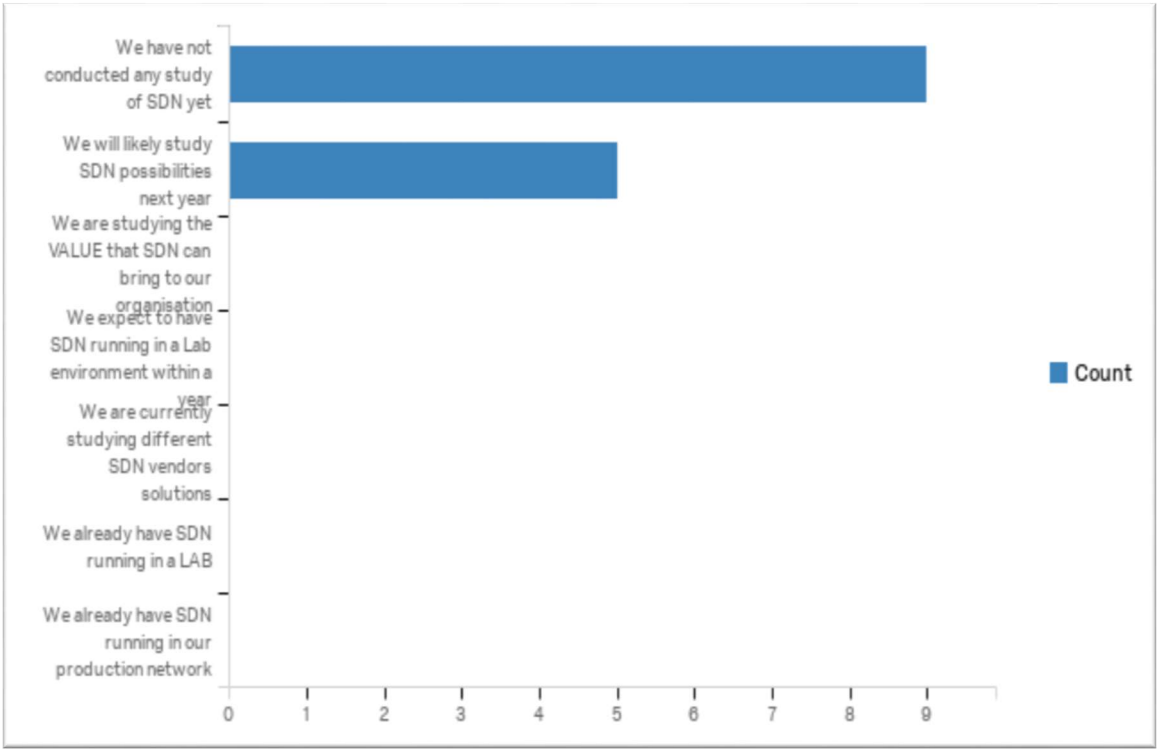

Figure 4.2 Passive SDN initiatives

Moreover, as shown in *Figure 4.3*, a categorisation by the nature of business of the organisations that employed the 9 participants that replied *"We have not conducted any study of SDN yet"* indicated that only 2 participants were employed by IT organisations while the other 7 participants worked for non-IT organisations.

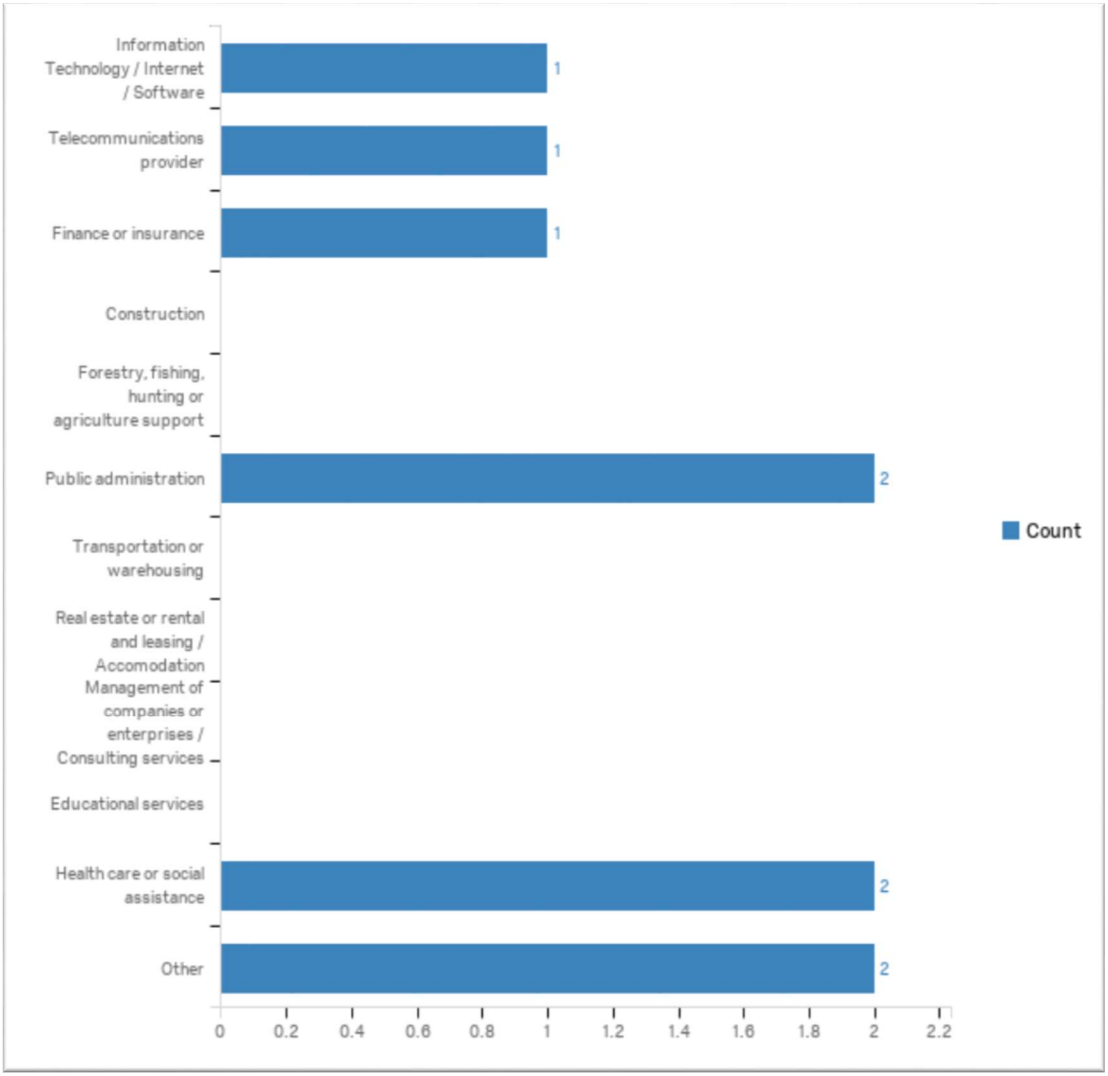

Figure 4.3 Passive SDN initiative vs Organisation primary business

On the other hand, a breakdown by organisation nature of business of the data gathered from the 7 participants that replied *"We already have SDN running in our production network"* revealed that 5 out of 7 organisations were IT organisations. As seen in *Figure 4.4*, the remaining 2 responses were allocated to Finance or Insurance organisations.

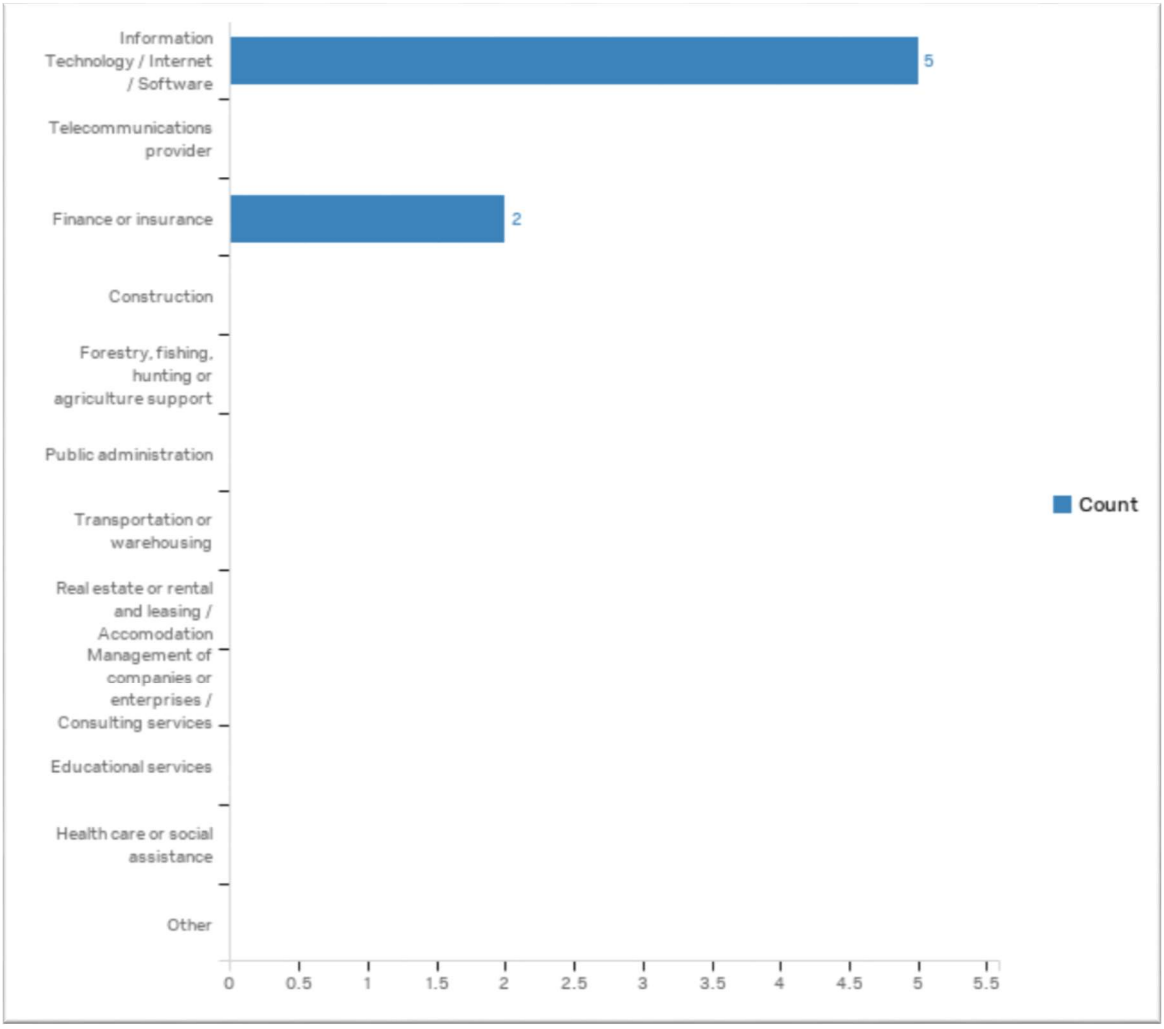

Figure 4.4 Production SDN initiative vs Organisation primary business

Based on the evidence gathered, it is safe to say that IT organisations rank higher in organisations having SDN running in their production network and lower in organisations not being part of SDN initiatives than non-IT organisations do. Therefore, IT organisations can be considered earlier adopters of the SDN technology than non-IT organisations.

Where in their network participants think SDN will be deployed in the nearest future

Question asked to the participants on survey;

Check all the scenarios where you think you will deploy SDN in the next 2 years. (check all that apply)

Participants were asked where in their managed network they thought SDN was more likely to be implemented. A multiple choice answer was chosen as network engineers usually manage multiple networks separated by different environments. The responses are represented by *Table 4.7.*

Answer	%	Count
DevCloud/Test network	62.07%	36
Corporate/Campus network	27.59%	16
WAN network	50.00%	29
Production Data Center Green field deployment (new network)	32.76%	19
Production Data Center Brown field deployment (existing network)	18.97%	11
I don't think I will deploy SDN in the next two years	10.34%	6

Table 4.7 SDN initiatives by network environment

62% of the participants indicated deployments on *"DevCloud/Test network"*. The second most voted network environment by the participants was *"WAN Network"* voted by a 50% of the participants. The third most answered environment was *"Production data centre Greenfield deployment (new network)"* with 32% of the responses. Following down the ranking of environments most replied by the participants, deployments of SDN in *"Corporate/Campus network"* was, with a 27% the fourth most voted environment for present and future SDN deployments. On the other hand, the response *"I don't think I will deploy SDN in the next two years"* was the least replied by the survey participants only answered 10% of the time.

As observed in *Figure 4.5*, A further analysis of these responses and breakdown of the 6 answers by the nature of the business of the participants' organisations showed that only 1 organisation was IT related (Telecommunications provider) while the other 5 responses came from network engineers employed by non-IT organisations. Therefore, it can be observed as a trend that IT organisations are being earlier adopters of SDN than non-IT organisations.

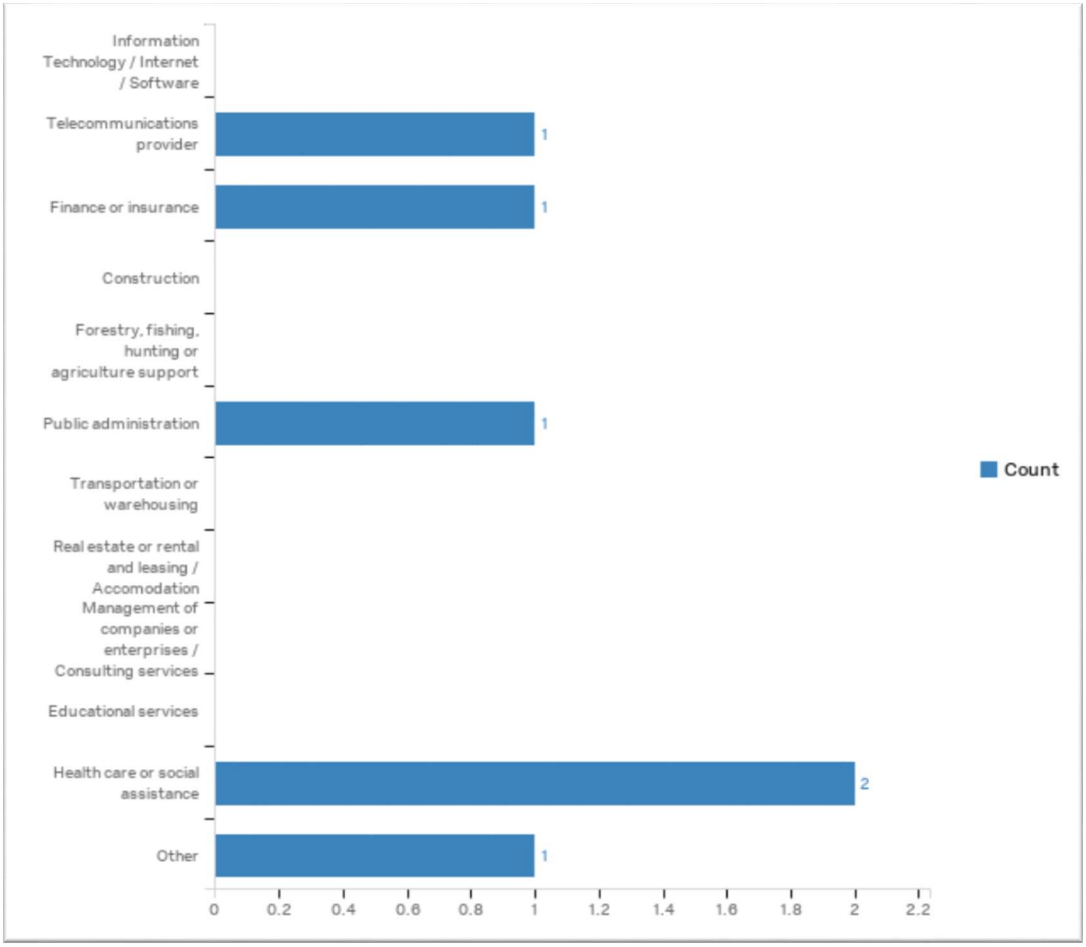

Figure 4.5 SDN not being adopted by organisations primary business

4.3.3 SDN Adoption Factors

In order to be able to research what would be the most relevant adoption factors of SDN, the possible adoption factors extracted from the literature review findings were grouped into two different questions that grouped SDN benefits and challenges;

a. Ranking of benefits of adopting SDN
b. Ranking of challenges when implementing SDN

<u>Ranking of benefits of adopting SDN</u>

Question asked to the participants on survey;

Rank the benefits that would drive you to implement an SDN solution? Drag most important (TOP) to less important (BOTTOM)

- *Simplification of network provisioning and configuration*
- *Perform traffic engineering*
- *Better utilisation of network resources*
- *Reduce OPEX*
- *Reduce CAPEX*
- *Support network virtualisation*

As shown in *Table 4.8*, an initial overview of the results obtained determines a clear association between the 3 most valued and the 3 least valued benefits by the participants. Simplification of network provisioning and configuration, Better utilisation of network resources and Perform traffic engineering where constantly voted among the 3 first positions of the ranking while Reduce OPEX, Reduce Capex and Support network virtualization were ranked in positions sixth, seventh and eighth.

	1st	2nd	3rd	4th	5th	6th
Simplification of network provisioning & configuration	63%	17%	7%	9%	4%	0%
Perform traffic engineering	11%	20%	30%	11%	13%	15%
Better utilisation of network resources	11%	39%	20%	13%	13%	4%
Reduce OPEX	7%	2%	24%	30%	20%	17%
Reduce CAPEX	6%	4%	15%	20%	35%	20%
Support network virtualization	2%	19%	4%	17%	15%	44%

Table 4.8 SDN benefits ranking

The top three benefits voted by the participants were further researched by performing different categorisations such as the size of network managed, or the network environment where the participants were planning to implement SDN.

Simplification of network provisioning and configuration

Traditional network provisioning and configurations are highly resource consuming and often consist in a manual configuration of each network component. "*Simplification of network provisioning and configuration*" was consistently ranked as the most valued benefit of SDN. This benefit was ranked 1st 63%, 2nd 17% and 3rd 7%. The data gathered from the participants who ranked "*Simplification of network provisioning and configuration*" 1st was broken down by the size of the network they were managing when they completed the survey.

As seen in *Figure 4.6*, the majority of the network engineers who operated networks with 1000+ managed nodes ranked "*Simplification of network provisioning and configuration*" as their top benefit of implementing SDN.

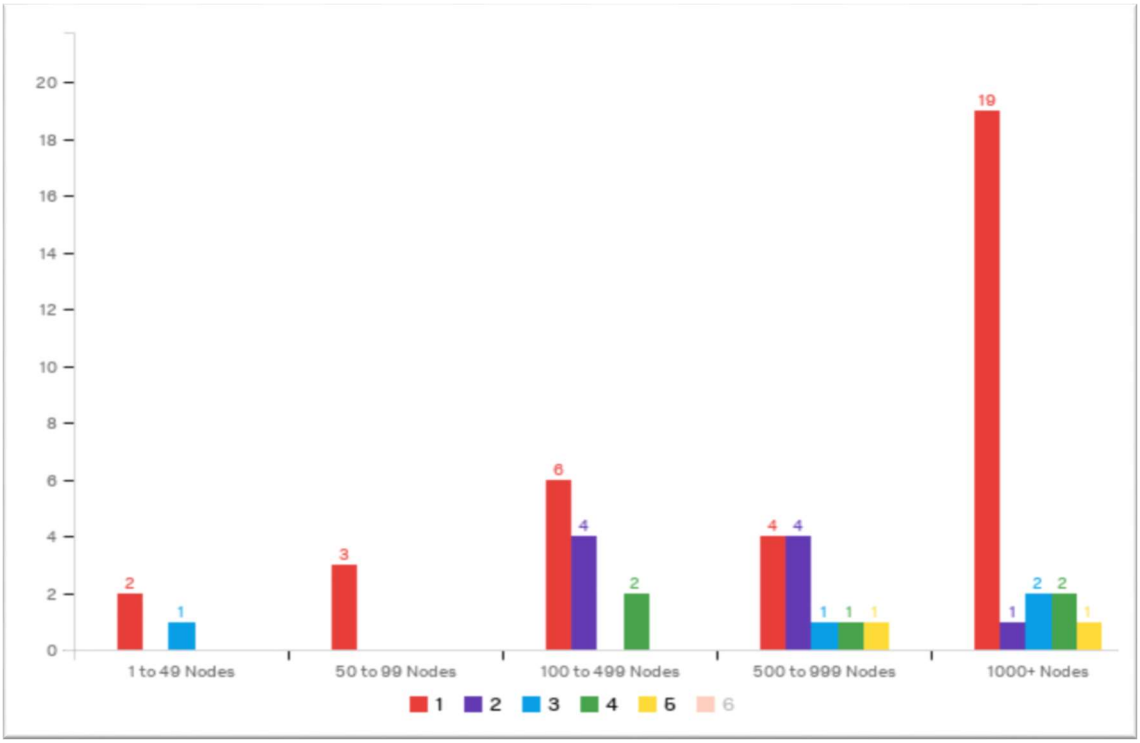

Figure 4.6 Simplification of network configuration by network size

A categorization of the answers that ranked 1st "*Simplification of network provisioning and configuration*" by network environment reveals that this benefit remains the most preferred benefit across all network environments. This categorisation is represented by *Figure 4.7*.

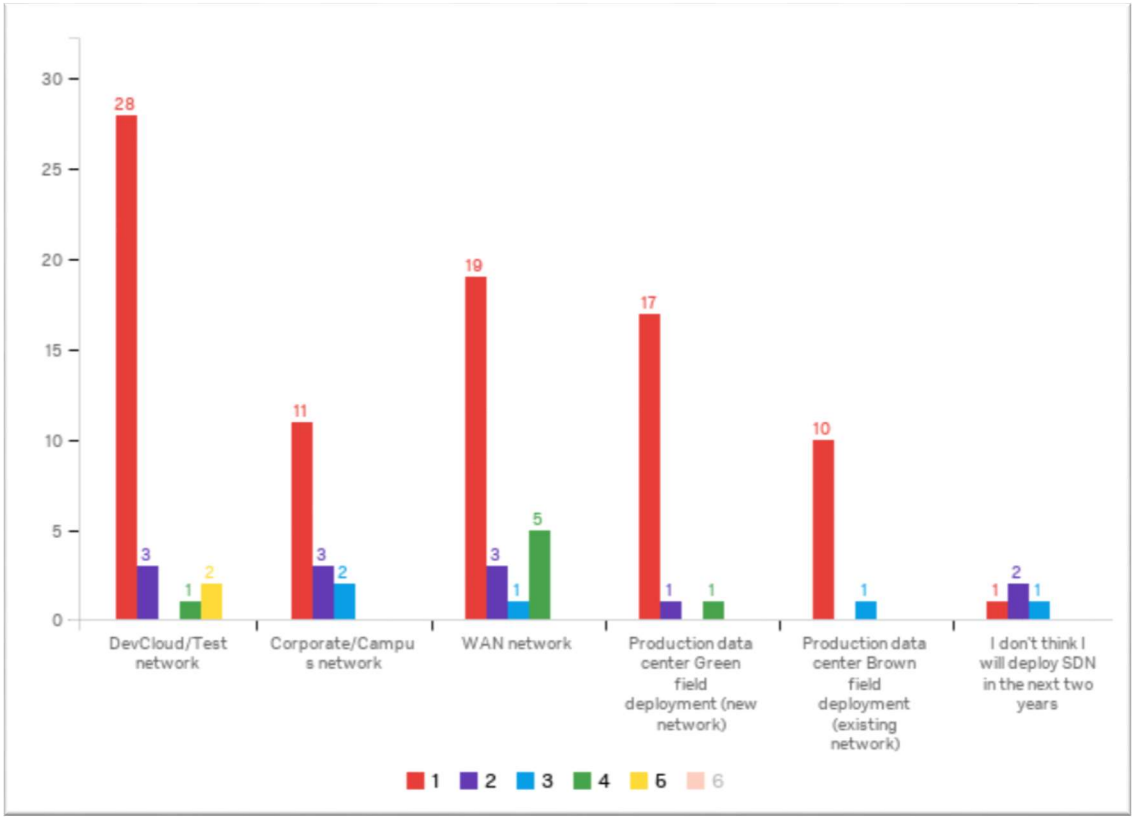

Figure 4.7 Simplification of network configuration by network environment

It seems safe to assume that the simplification of network provisioning and configuration through central management and network automation through network programmability is the biggest driver for SDN adoption, especially for network engineers who manage vast network infrastructures.

Better utilisation of network resources

"Better utilisation of network resources" was, with a 39% of the responses, consistently ranked as the second most valued benefit. It was also voted into the third position by a 20% of the participants and equally ranked as 4th and 5th option by a 13% of them.

A categorization of the replies received around this benefit, implementing SDN by the size of the network managed, shows that this benefit was equally valued as the second option across the different network sizes. As shown in *Figure 4.8*, the response "*Better utilisation of network resources*" was also ranked as 3rd most important benefit of SDN when it came

down to managing big networks. Summarising, a categorisation of the data gathered around the answer "*Better utilisation of network resources*" by network size, places this benefit of SDN as the second biggest driver for SDN implementations after "*Simplification of network provisioning and configuration*", especially in mid-size to large-size managed networks.

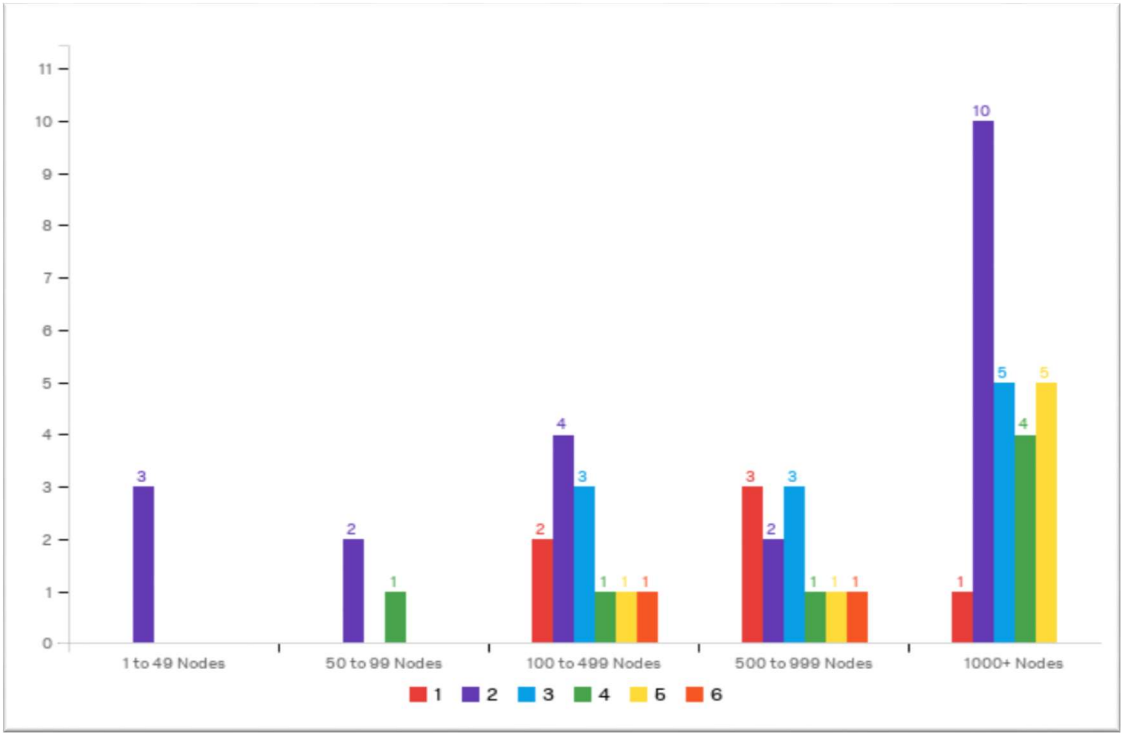

Figure 4.8 Better utilisation of network devices by size of managed network

Following the classification of the responses for "*Better utilisation of network resources*" by network size, the responses of this benefit were also classified by the network infrastructure where participants will likely implement SDN. The idea behind this classification was to try to identify on what network environments the participants valued mostly the "*Better utilisation of network resources*" benefit.

As shown in *Figure 4.9*, the benefit was highly valued by engineers who have plans of implementing SDN in DeveCloud/Test networks and WAN networks. Understanding Dev/Test network as a prior state of a Production network, the research combined both environments into Data Center networks. Therefore, it can be observed how a Better

utilisation of network resources ranks highly in both Data Center and WAN networks and then ranks average in Corporate/Campus network.

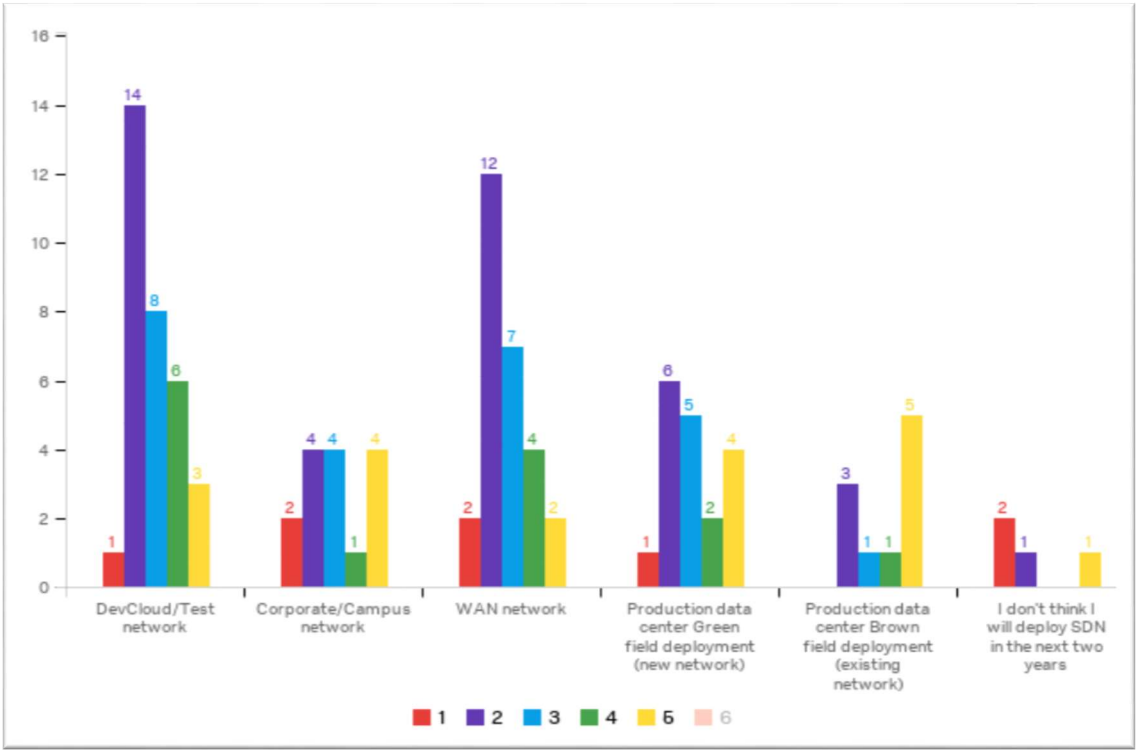

Figure 4.9 Better utilisation of network devices by network environment

On the other hand, Corporate SDN solutions have been gauging interest by startups and organisations that are trying to bring the benefits of SDN for Data Center and WAN to the campus network. This landscape could resolve, if new products are developed and launched, into a higher rank of this benefit in future studies.

Performing Traffic engineering

"*Perform traffic engineering*" was the third ranked benefit by the respondents to the online survey. It was ranked 1st by 11%, 2nd by 20% and 3rd by 30% of the participants having a total of 60% of the votes positioning this benefit in the top 3 positions of the ranking.

A classification by the size of the network managed related to the benefit in question does not exhibit a preference for "*Perform traffic engineering*" by any particular group of participants. As seen in *Figure 4.10*, the participants of all the different groups rank this benefit around the third position of the ranking having the other votes equally dispersed in high and low positions of the ranking.

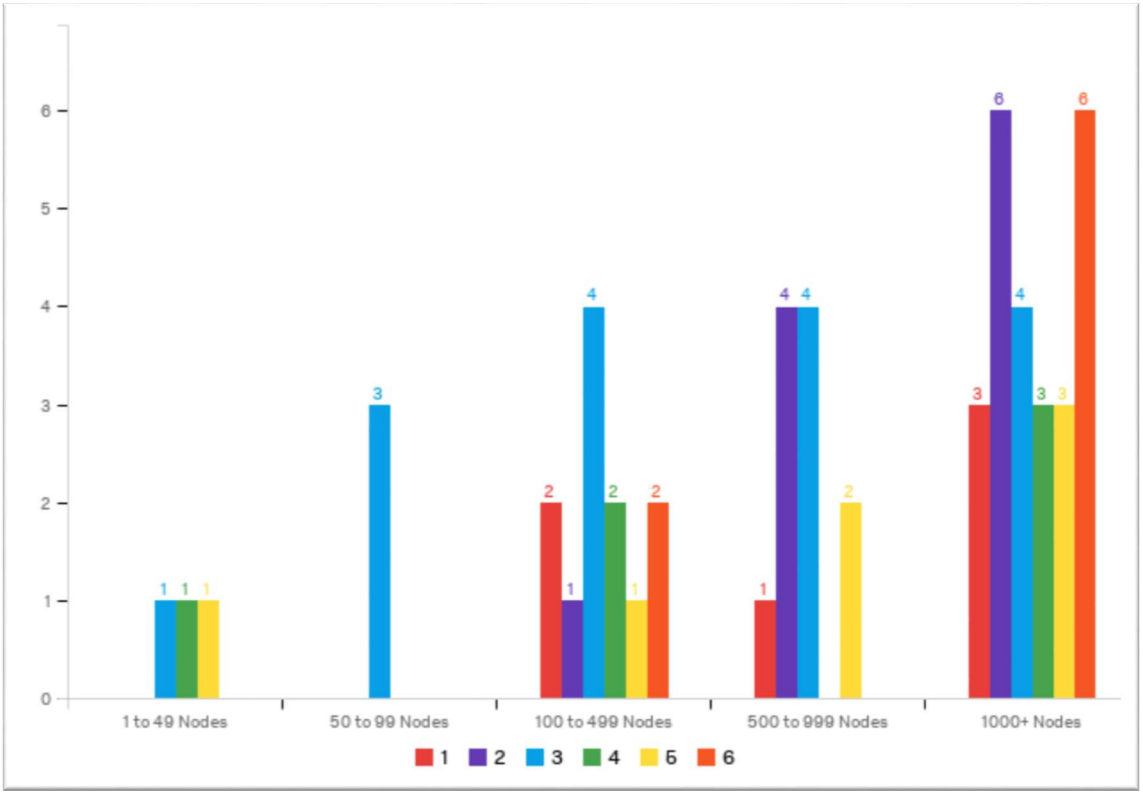

Figure 4.10 Perform traffic engineering by size of managed network

On the other hand, a breakdown of the responses received for *"Perform traffic engineering"* by network environment shows that both Data Center environments (the sum of Dev/Test + Production) and WAN network value this benefit over Corporate and test network. However, it is particularly on the WAN network where the *"Perform traffic engineering"* benefit becomes highly voted in the first three positions of the ranking as seen in *Figure 4.11.*

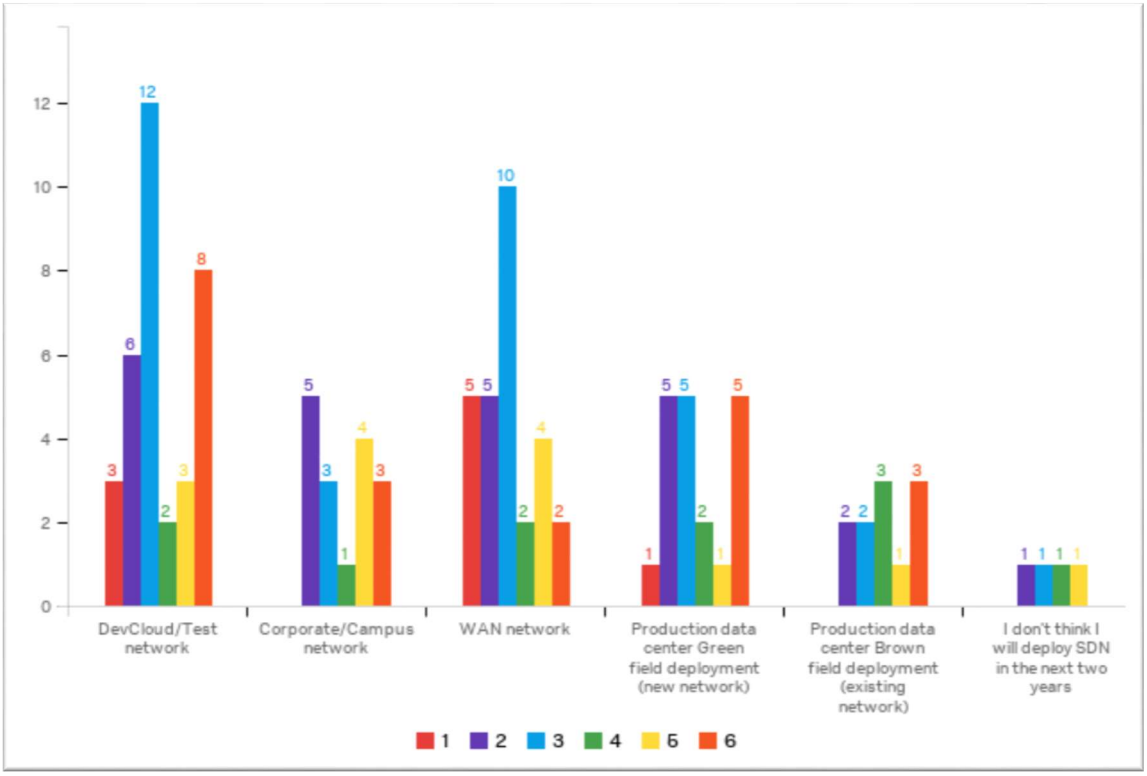

Figure 4.11 Perform traffic engineering by network environment

Traffic engineering permits SDN network deployments to make traffic decisions in real time based on present variables such as delay, bandwidth available, congestion or packet loss. This capability allows the SDN deployments to make a better use of available circuits which becomes a highly valuable skill when it comes to WAN circuits. The ability by SDN to react to the changing present state of the WAN circuits prevent incidents when circuits are underperforming due to congestion or packet loss and increase performance by redirecting traffic through them when extra bandwidth becomes available.

Ranking of challenges when implementing SDN

Question asked to the participants on survey;

> *Rank the following challenges that would stop or delay you deploying SDN Drag most important (TOP) to less important (BOTTOM)*

- *Concerns about Integrating SDN with existing network*
- *Immaturity of current products*
- *Immaturity of the enabling technologies (OpenFlow)*
- *Concerns about the ability of SDN to scale for organisations requirements*
- *The need to significantly train our staff*
- *No real business case for it*
- *Lack of definition in strategies from vendors*
- *Possible security threats*

Participants were presented with eight inhibitors of SDN and were asked to rank them from top to bottom. Data was extracted from the survey, and a coloured table based on the accumulated responses was created using Excel. *Table 4.9* shows the results from the data gathered.

Question	1st	2nd	3rd	4th	5th	6th	7th	8th
Concerns about Integrating SDN with existing network	34%	19%	21%	9%	11%	4%	2%	0%
Immaturity of current products	21%	15%	13%	19%	15%	13%	4%	0%
Immaturity of the enabling technologies (OpenFlow)	17%	15%	40%	15%	8%	6%	0%	0%
Concerns about the ability of SDN to scale for organisations requirements	8%	6%	0%	4%	15%	34%	26%	8%
The need to significantly train our staff	8%	11%	2%	9%	13%	9%	42%	6%
No real business case for it	6%	0%	4%	2%	0%	0%	6%	83%
Lack of definition in strategies from vendors	4%	9%	11%	32%	21%	19%	4%	0%
Possible security threats	4%	25%	9%	9%	17%	15%	17%	4%

Table 4.9 SDN Challenges Ranking

As discerned in *Table 4.9*, a first analysis of the data gathered revealed 3 challenges that regularly ranked within the first three positions of the ranking. These challenges were *"Concerns about Integrating SDN with existing network", "Immaturity of current products"*

and *"Immaturity of the enabling technologies (OpenFlow)"*. Besides that, *"Possible security threats"* showed most of the votes obtained outside the top positions of the ranking even though it showed 25% of responses ranking in a second position. A further study of these 4 challenges was undertaken.

Concerns about Integrating SDN with existing network

Concerns about Integrating SDN with existing network was ranked as the foremost important challenge that would cause SDN deployments to be stopped or delayed. It ranked 1st 34%, 2dn, 19% and 3rd 21% of the times. As observed in *Figure 4.12,* a categorisation of the responses received for the choice *"Concerns about Integrating SDN with existing network"* by the size of the organisation managed, positioned this challenge recurrently in the 1st or 2nd position.

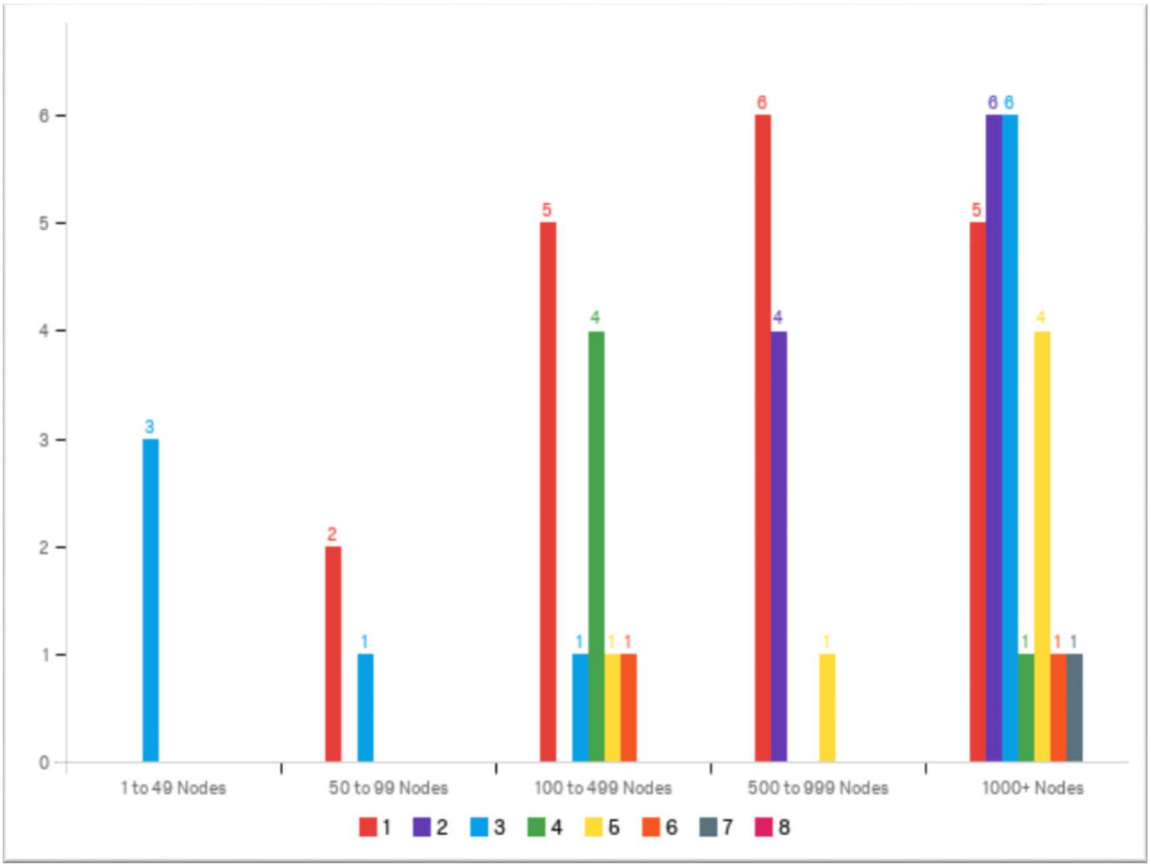

Figure 4.12 Concerns about Integrating SDN by network size

In the same line, a categorisation by network environment of the responses "*Concerns about Integrating SDN with existing network*", presented a uniform distribution across the different environments as seen in *Figure 4.13.*

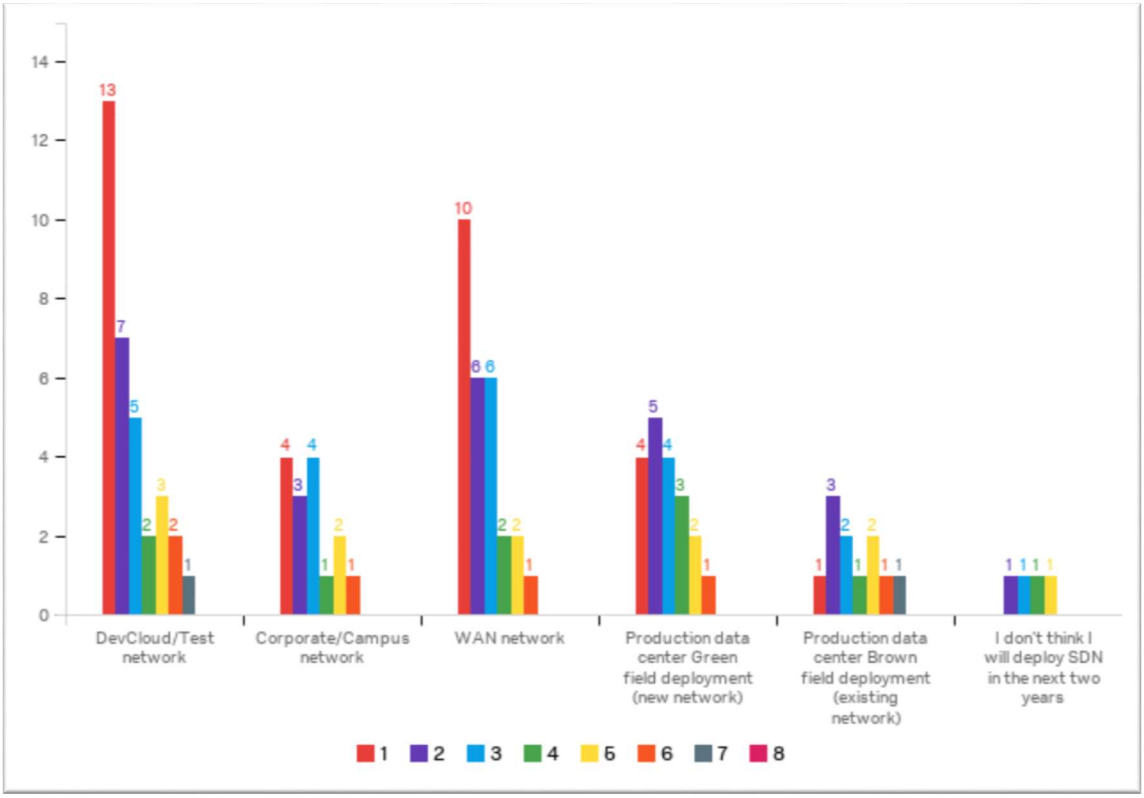

Figure 4.13 Concerns about Integrating SDN by network environment

Therefore, based on the results exposed from the data gathered, it seems safe to affirm that "*Concerns about Integrating SDN with existing network*" represents the most significant challenge to overcome by researchers and practitioners in order to facilitate the adoption SDN. An extensive research on a breakdown of the different challenges faced when integrating SDN into legacy networks and its possible solutions would be highly beneficial for researchers and practitioners.

Immaturity of current products

Participants ranked "*Immaturity of current products*" as the second major challenge to overcome when deploying SDN initiatives. Participants placed it 1st 21%, 2nd 15%, and 3rd 13% of the times.

As observed in *Figure 4.14,* a categorisation of the replies collected for "*Immaturity of current products*" by the size of the organisation managed placed this challenge recurrently in the first three positions. On the other hand, companies with 1000+ nodes networks also placed it 4th and 6th in large amounts. This phenomenon could be caused by the nature of the organisations involved in the survey. It is known that Engineers from companies like Google, Facebook or Amazon formed part of the surveyed population, unfortunately as the company was kept confidentially there is no way to identify the responses individually for each distinct company. These organisations have home brewed Open source SDN solutions and depend less on vendor SDN products.

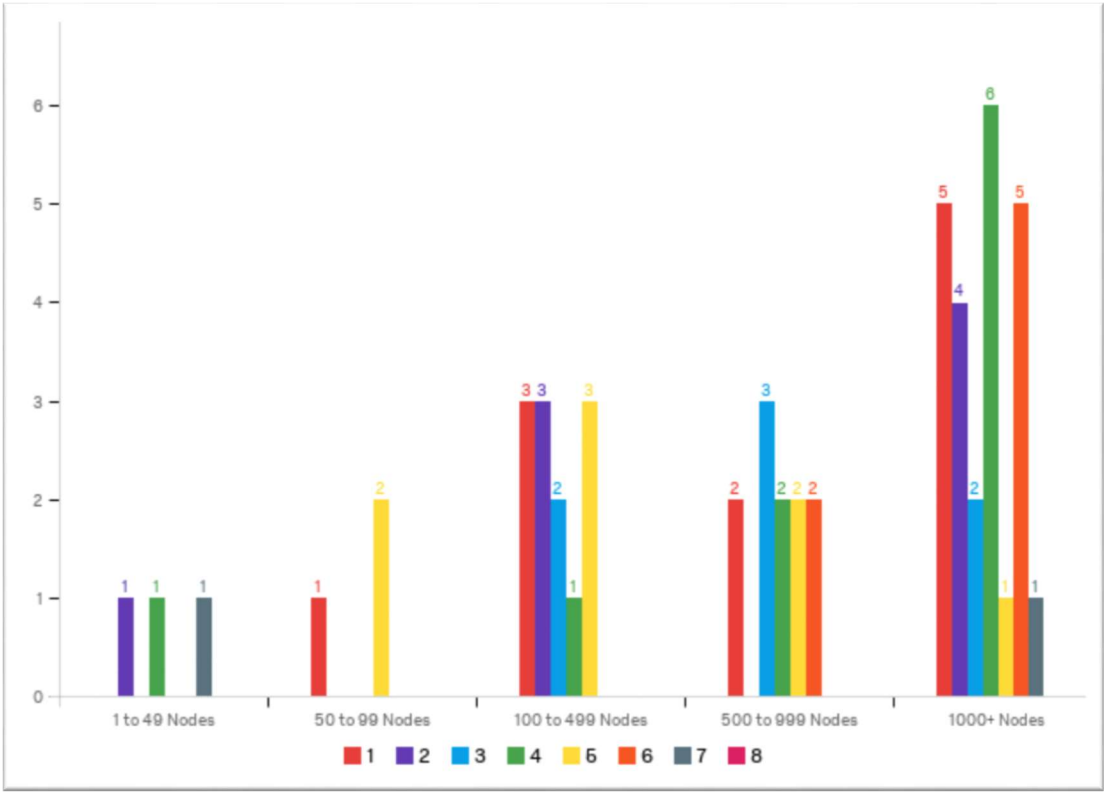

Figure 4.14 Immaturity of current products by network size

When the distribution by network environment of the responses "Immaturity of current products" was studied, as shown on *Figure 4.15,* it was found that responses were equally allocated among Corporate, WAN and Data Center environments.

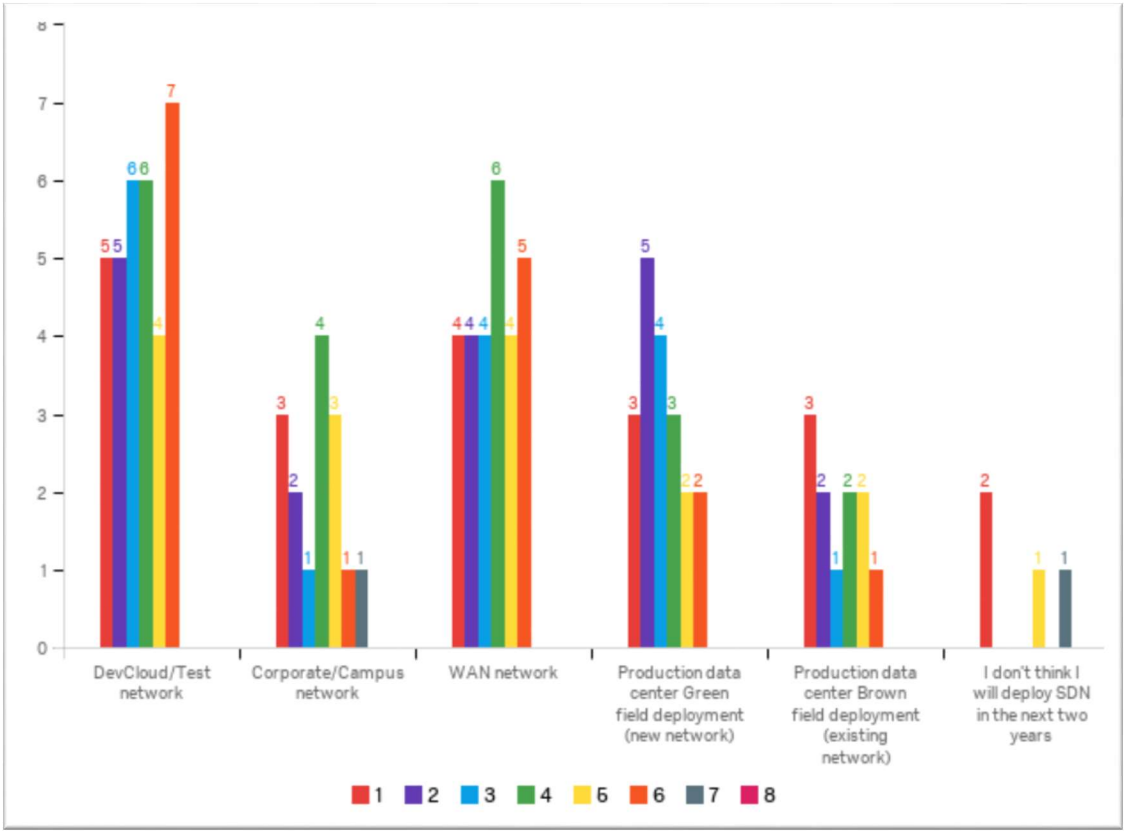

Figure 4.15 Immaturity of current products by network environment

"I*mmaturity of current products*" demonstrated to be a significant challenge to be taken into account when deciding to move towards an SDN initiative implementation. As derived from the data gathered from the online survey, it consistently ranked between the top 3 major challenges to overcome. There is room for possible further research around this challenge by investigating the possible different aspects between Open Source and Vendor deployments and its implications around this it.

Immaturity of the enabling technologies (OpenFlow)

Participants ranked "*Immaturity of the enabling technologies (OpenFlow)*" as the third major challenge to overcome when deploying SDN initiatives. Participants placed it 1st 17%, 2nd 15%, and 3rd a total 40% of the times.

As observed in *Figure 4.16*, a categorisation of the replies collected for "*Immaturity of the enabling technologies (OpenFlow)*" by the size of the organisation managed placed this

challenge recurrently in the third position. The 3rd place in the ranking was more accentuated for participants who were in charge of big sized networks. As explained in the literature, this scenario could be related to the scalability and reliability issues that OpenFlow presents when scaling to big size networks.

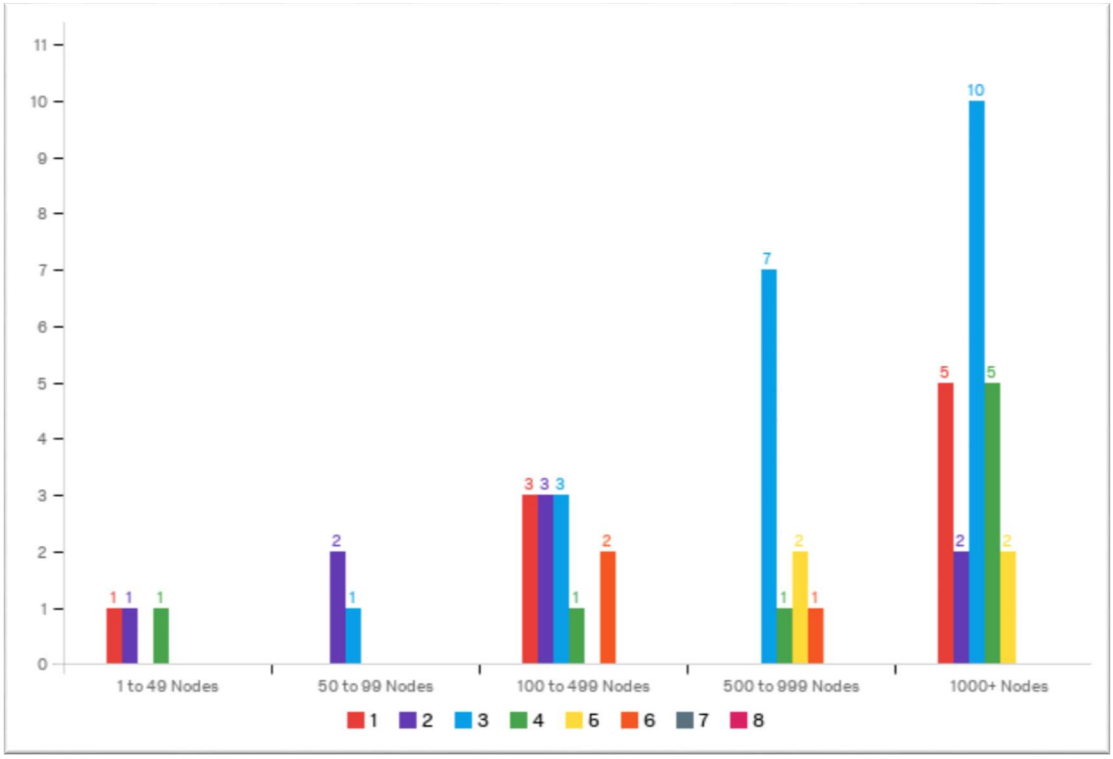

Figure 4.16 Immaturity of enabling technology by network size

When a distribution by network environment of the responses "Immaturity of the enabling technologies (OpenFlow)" was studied, as shown on *Figure 4.17,* it was found that responses equally placed this challenge as the most important third challenge across Corporate, WAN and Data Center environments.

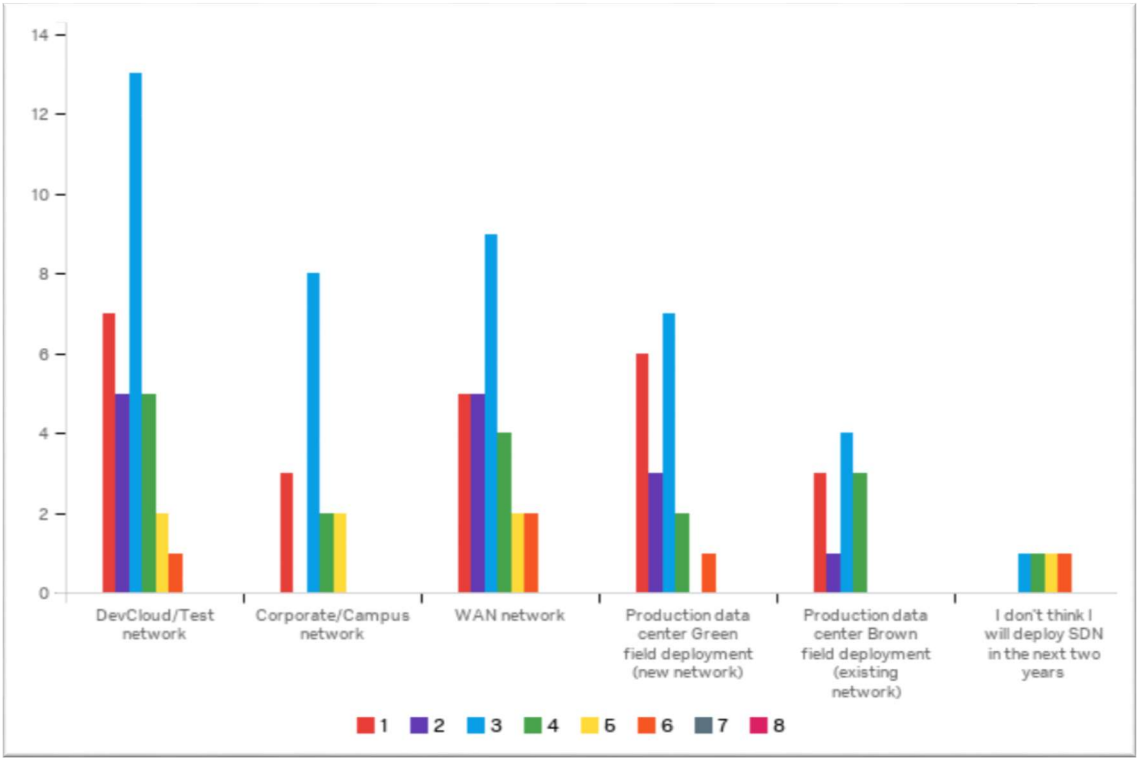

Figure 4.17 Immaturity of current products by network environment

"*Immaturity of current products (OpenFlow)*" was constantly voted in position 3; however, a closer analysis of the results in *Figure 4.17* shows that Corporate network received less responses in position 1 and 2 than WAN or Data Center environments. The cause of these results could revolve around the idea that Corporate SDN initiatives are less advanced than WAN or Data Center deployments which have been much more developed by vendors. It is possible that OpenFlow limitations continue to undercover once Corporate SDN initiatives continue to develop.

4.3.4 SDN Implementations Impact on Network Engineers

With the goal of researching the perception and awareness of the network engineers of the possible impact of the adoption of SDN in the nature of their roles, the following questions were asked to the survey participants

a. How much impact SDN will have on the nature of the role of network engineers

b. What changes participants anticipate in the nature of their role

c. How much impact SDN will have on the participants organisational structure

d. What structural changes participants anticipate

Following a study of the results obtained for each question are presented.

How much impact SDN will have on the nature of the role of network engineers

Question asked to the participants on survey;

> *How much impact do you think an SDN implementation would have on the nature of your work within the next two years?*

Figure 4.18 represents the data obtained around this question. 75% of the participants anticipated an important impact on the nature of their jobs. 46.6% of them responded "*Moderate Impact*" and 28% responded "*Significant impact*". The remaining 25% of the responses, were divided into 19.3% for answers expecting "*Little Impact*", 6.2% "No Impact" and a 1.7% that did not know.

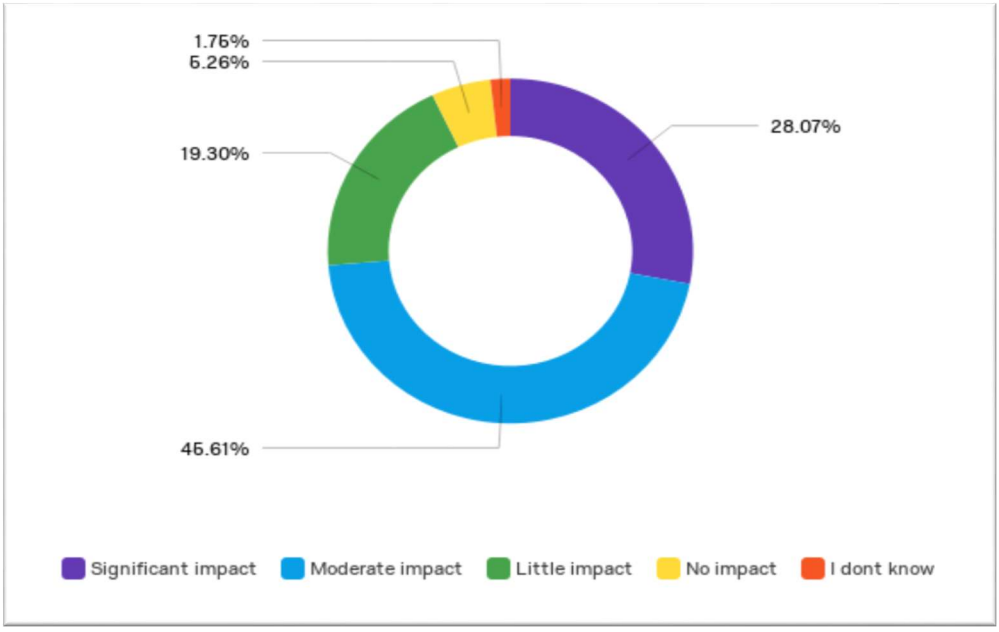

Figure 4.18 Perception of SDN impact on network engineer role

The data gathered in the online survey for this question suggests that Network engineers are aware of the possible impact that adopting SDN would have on the nature of their job.

What changes participants anticipate in the nature of their role

Question asked to the participants on survey;

> *What changes do you think the SDN movement will bring to the nature of your job? (Check all that apply)*
>
> - *Skills needed will shift from networking to programming and scripting*
> - *My role will blend with application teams causing confusion*
> - *Configuration time will decrease and planning time will increase*
> - *I will need to be trained to be able to support the SDN initiatives*
> - *I don't think SDN movement will bring any change in the nature of my job*

As seen in *Figure 4.19,* 72% of the participants replied *"Skills needed will shift from networking to programming and scripting"*, 56% *"Configuration time will decrease and planning time will increase"*, 47% *"I will need to be trained to be able to support the SDN initiatives"*, 11% *"My role will blend with application teams causing confusion"* and only 7% *"I don't think SDN movement will bring any change in the nature of my job"*.

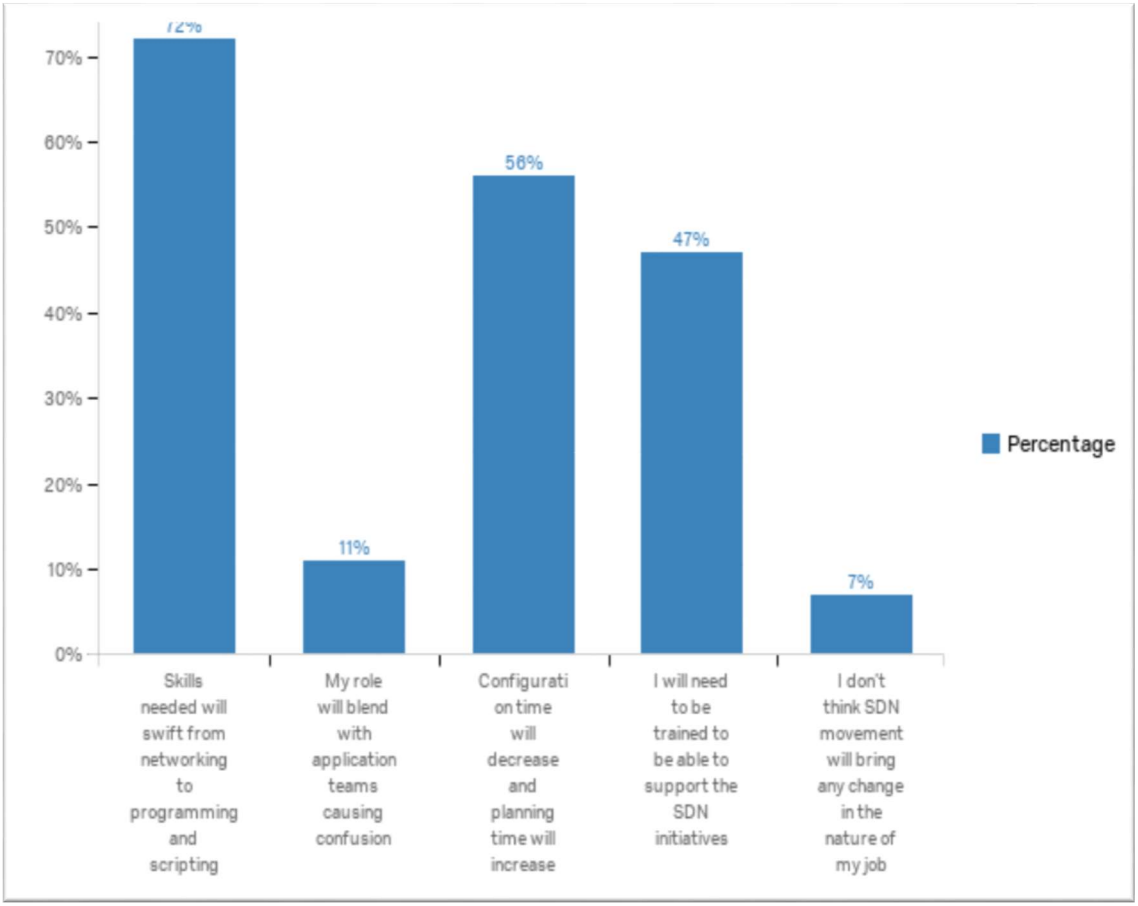

Figure 4.19 SDN impact on network engineer role

The total results gathered represented both reality and expectations about the impact of SDN from a broad range of network engineers. It included highly SDN educated individuals who would have had more expert insight based on real experience, and slightly familiar individuals who would have based their responses on their understanding from studying SDN-related initiatives rather than hands on experience or direct impact from the exposure to SDN. Therefore, a categorisation by the different grades of knowledge from the totals in above *Figure 4.18* was done in *Figure 4.19* with the aim to visualise any different trend on the responses from the participants according to their subject expertise.

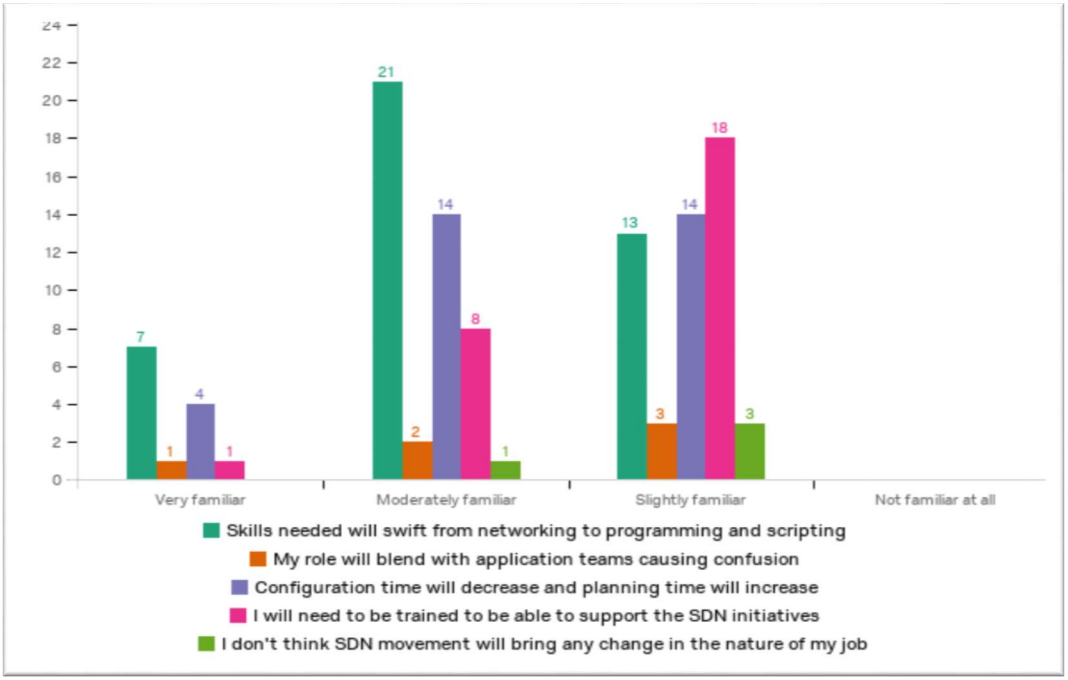

Figure 4.20 SDN impact on network engineer role by SDN familiarity

As seen in *Figure 4.19* and *Figure 4.20*, the several categories of SDN knowledge mimicked the same distribution as the totals responses for the topics *"Skills needed will shift from networking to programming and scripting"* and *"Configuration time will decrease and planning time will increase"* were both more SDN experienced and less experienced participants. However, by doing this categorisation a trend was uncovered as the results for the *"I will need to be trained to be able to support the SDN initiatives"* response became higher as the knowledge of the participants on SDN decreased. This result implied the fact that both network engineers are aware of their lack of knowledge in SDN and the importance of learning this new technology to stay relevant in the marketplace.

How much impact SDN will have on the participants organisational structure

Question asked to the participants on survey;

> *How much impact do you think an SDN implementation would have on your department organisational structure in the next two years?*

To identify the awareness of network engineers around the impact that SDN may have on their organisation organisational structure, participants were asked to specify what grade of impact they were foreseeing. As seen in *Figure 4.21*, 16% of the participants expected significant impact, 53% moderate impact, 17% little impact, 12% no impact and 2% didn't know.

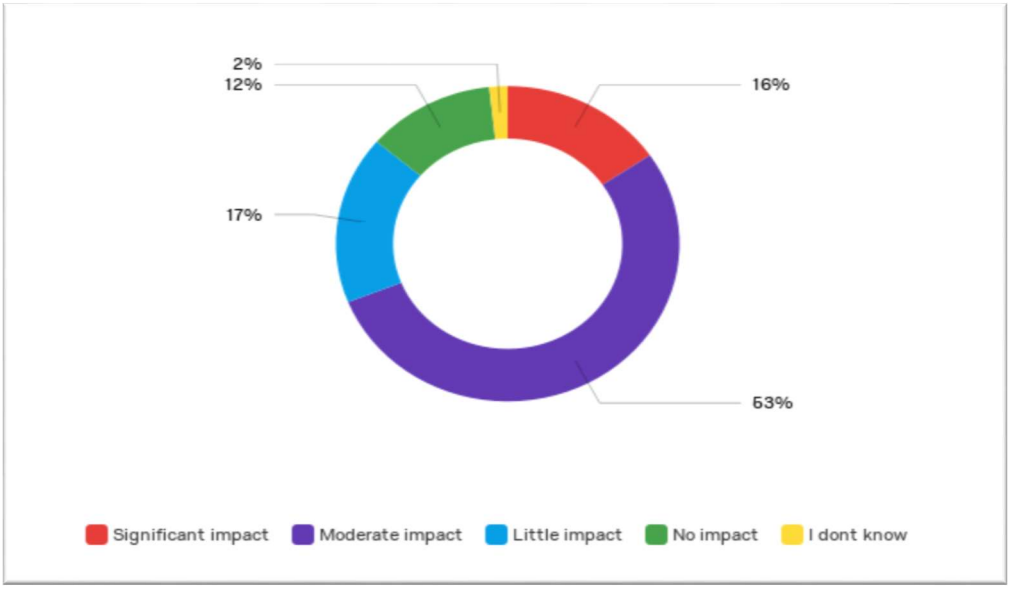

Figure 4.21 Perception of SDN impact on organisational structure

The results above seem to suggest that a majority of SDN stakeholders foresee some sort of impact on the organisational structure of their organisation.

What structural changes participants anticipate

Question asked to the participants on survey;

> *In your opinion. what structural organisational changes do you think an SDN implementation would bring to IT organisations? (Check all that apply)*
>
> - *A likely reorganisation of network operations team*
> - *An increase of cross-functional teams and projects*
> - *A move to DevOps model within the network team*
> - *I don't think SDN will bring any organisational structure change*

Participants to the online survey were asked to check all the answers from above that they thought would apply to any organisational change that their organisations would face within the next two years because of SDN. As seen in *Figure 4.22*, 51% of the responses included *"An increase of cross-functional teams and projects"*, 49% *"A likely reorganisation of network operations team"*, 39% “I don't think SDN will bring any organisational structure change".

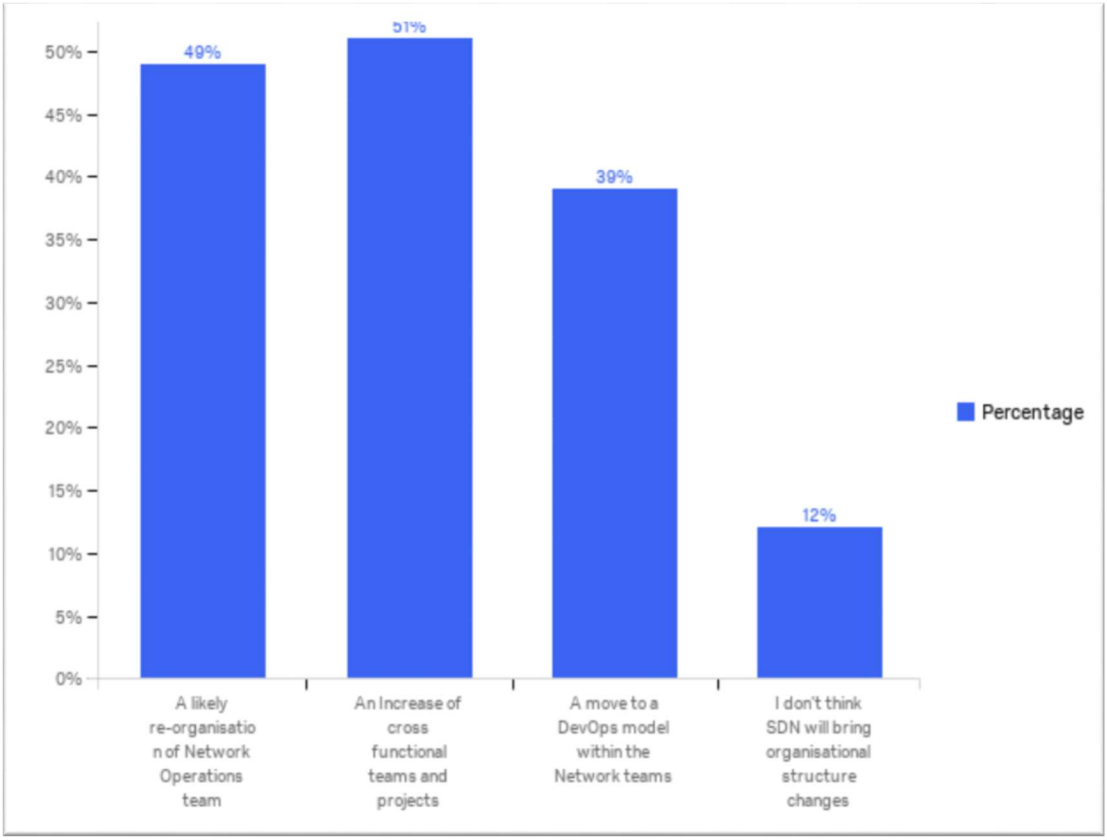

Figure 4.22 SDN impact on organisational structure

From the evidence gathered around this question, it seems fair to assume that all of the possible organisational changes presented around this question was broadly voted by the participants. Half of the participants predicted a likely reorganisation of the network operations team and an increase of cross functional teams and projects while a little bit more than a third of them predicted a move to a Devops model.

4.4. Summary of findings

This section exhibited a comprehensive analysis of the results of the data accumulated by the research. The survey findings were driven by the necessity to respond the research question and were divided in 4 sections.

The first section included a complete breakdown of the profile of survey participants. The results obtained for this section showed a diverse mix of subject matter experienced and knowledgeable participants. The majority of these participants accumulated more than 7 years of experience in IT and proved to be moderately familiar with SDN. These participants represented organisations with different sized networks and with different nature of businesses. IT organisation's participants proved to be more proficient in SDN technology than participants working for non-IT organisations.

The second section included findings around the present state of SDN initiatives. Results on this section proved that, at present, most of the organisations have SDN initiatives running at different stages including; study of the value of SDN, vendor selection, SDN labs and SDN deployments running production networks. In addition to this, participants also indicated Data Center SDN and WAN SDN as the top network environments where SDN initiatives will be taking place in the nearest future.

Section three included findings around what the top adoption factors were. The top three benefits or adoption drivers and top three challenges or adoption inhibitors were identified and exhaustively analysed. The top three SDN benefits included Simplification of network provisioning and configuration, Better utilisation of network resources, and Performing Traffic engineering. Contrarily, the top challenges included; Concerns about Integrating SDN with existing network, Immaturity of current products, and Immaturity of the enabling technologies (OpenFlow). Moreover, an in-depth study of each of this six adoption factors was done utilising categorisation methods. Results were categorised by the size of the network managed or the network environment to identify where these adoption factors would apply differently.

At last, the fourth section included the findings around the possible impact of SDN on the nature of network engineer's role and the organisational structure of their organisations. Participants proved a strong awareness on this subject and their belief of a significant impact of both the organisational and role aspects. Furthermore, regarding the impact of SDN deployment on their role, a majority of participants identified that the change on their role will include learning programming skills which will result in increasing the time spent in planning and decreasing the time spent in the configuration of the network. Half of the participants indicated that they would need to be trained in SDN. On the other hand, regarding the impact of SDN on the organisational structure of their organisation, half of the participants foresaw a likely re-organisation of the network team, and an increase of cross-functional teams and projects. A third of them foresaw a move to a DevOps model within the network teams.

The findings of the research corroborate findings from the extensive literature review. Chapter five highlights the key conclusions of the research, discusses its limitations and recommends areas for future research.

5 Conclusions and Future Work

5.1 Introduction

This chapter reviews how the findings of the research answered the research question and sub-questions. The first two subsections in this chapter highlight the principal findings and the answers to the research questions, and discuss the contribution of this investigation to the present body of knowledge. The last two sections explain the limitations of the research and outlines recommendations for future research in this area.

5.2 Key findings, Answering the research question

The reviewed literature and the data accumulated from surveying SDN decision makers and stakeholders during this research provide confirmatory evidence that SDN initiatives are gaining traction among SDN stakeholders. This section tries to answer the research question and sub-questions in light of the findings;

SQ1:What is the present state of the SDN deployments?

SQ2: What are the key adoptions factors for SDN?

SQ3:What is the network engineer's perception on the impact SDN may have on their jobs?

5.2.1 Present State of SDN Deployments

From a business adoption point of view and based on the evidence gathered during this research, *Section 4.3.2*, it seems fair to suggest that Software-Defined Networking initiatives are being adopted and maturing at different adoption levels and network environments, both by IT and Non-IT organisations.

Survey respondents confirmed that, at present, over a 90% of the organisations are at various active phases of adopting SDN ranging from studying the possible value that SDN

can bring to their organisation to having SDN already running on their production network. More precisely, the majority of the network engineers were either studying the value that SDN could bring to their organisations or already had SDN running in a lab. Evidence gathered during this research, *Section 4.3.2*, also confirmed Software organisations as early adopters of the SDN technology and are already running SDN on production networks. Contrarily Non-IT organisations were still in an early adoption state of SDN.

From a network environment point of view, evidence gathered during this study reveals that network engineers and SDN stakeholders predict implementations of SDN across the different network environments in their organisations.

SDN Data Center. The results gathered in *Section 4.3.2* of this study reveals that the Data Center will be the main environment where SDN initiatives will take place during the next years. 62% of SDN stakeholders that participated in this study anticipated 62%) indicated deployments on their DevCloud/Test network. DevCloud and Test networks support, by definition, low business impact services and are usually the environments where engineering teams test newly adopted initiatives. A 62% of responses in DevCloud/Test would indicate that network engineers and organisations are already testing SDN solutions that, once successfully tested, could be deployed in production.

In addition to this, 50% of the participants also foresaw opportunities to deploy SDN networks in their production environments. Production networks sustain the business infrastructure of the organisations and they are considered to be a high-impacting platform. Therefore, production networks are typically highly redundant and usually hosted in multiple Data Centers. Production network changes are usually conducted under a change control process, and complex changes are often tested in a sustained test environment before being deployed in production. Even though Greenfield deployments in production networks have always a risk implied, they are considered to have less impact and have an easier roll back process than Brownfield deployments.

Brownfield deployments often involve downtime, migration of services and difficult rollback procedures. The fact that 18% of the participants considered deploying SDN in production networks implies a strong involvement with SDN technology and a remarkable confidence on the reliability and stability of an SDN managed network. This data also shows that, despite the technical challenges, SDN deployments are starting to be integrated successfully with legacy networking by some organisations.

SDN WAN. The results from *Section 4.3.2* in this study revealed WAN environments to be the second environment where more SDN initiatives will take place during the nearest future. WAN network stands for Wide Area Network. According to Cisco's definition, a WAN is "a network that covers a broad geographic area and often uses transmission facilities provided by common carriers". (Cisco, 2012)

ONF states that, WAN traffic continues to double every 18 to 24 months (ONF, 2014). Simultaneously, mobility networks and cloud-based services are originating traffic patterns to become ever more unpredictable. Therefore, transport networks need to become more flexible and dynamic to support end-user demands.

SDN approaches traditional WAN challenges such as complexity and high cost by automating the continuous configuration of WAN edge routers providing the following benefits:

1. Lower cost
   With a software-defined WAN, an enterprise should be able to rely more on broadband and less on private links, reducing cost.

2. Reduced complexity
   Software-Defined WAN deployments are centrally managed and reroute traffic dynamically based on the current environment of the network, thus reducing troubleshooting.

3. Increased flexibility

Software-Defined WAN technology allows the hybrid WAN to respond to fluctuating network conditions automatically.

The high number of replies, 29 (50%), from the participants, foreseeing Software-Defined WAN deployments manifests a strong interest from the network engineers community to adopt SDN solutions in the WAN space positioning this environment as the first production environment where SDN will be implemented.

Corporate/Campus network. Corporate networks vary in importance depending on the kind of organisation and the nature of their business. Results from this study exposed on *Section 4.3.2* demonstrate that Corporate deployments will be the third most important environment in terms of adopting SDN. Corporate networks enable company offices to communicate and enable applications such as email, accounting and internal applications data. Corporate networks are usually treated as production networks by non-IT organisations, which do not have a production network environment supporting applications that produce their primary source of income.

The corporate network deployments observed in most of today's organisations support capabilities such as Mobile clients, "Bring your own device" (BYOD) solutions, video, and a constant grow of number of connected devices and applications. All these sub-environments are quickly transforming the network landscape. These moving changes burden the capacity of legacy networks to deliver agility, performance, and seamless user experience. Software-Defined Networking can ease these challenges, offering adaptability and the capacity to develop new capabilities promptly and cost-effectively.

In summary, the principal environments where SDN will continue to be implemented at present and during a near future will be the Data Center and DevCloud environments. At the same time, SDN initiatives in WAN deployments are gaining traction as half of the survey respondents predicted SDN WAN deployments within the next two years. Lastly, even though SDN technology for the campus/corporate network environment is still in early development by vendors an SDN stakeholders, it is also starting to be considered

by the network engineers. Precisely, as seen in *Section 4.3.2*, one of each four network engineers predicting SDN adoptions in that environment within the next two years.

5.2.2 SDN Adoption Factors

Based on the analysis of the data obtained, the top three benefits produced by SDN driving its adoption initiatives by the organisations at present are;

1st - Simplification of network provisioning and configuration

Treasured for the majority of the network engineers that participated in this study and especially by organisations with big sized managed networks. This benefit provided by the programmability of SDN infrastructures fosters automation in deployment and self-healing operations, thus resulting in savings in OPEX. Since the Data Centers are now running virtual servers able to scale fast and multiply in the Data Center, network teams are under extraordinary pressure to deploy a network with the same flexibility that can expand and be reconfigured quickly to meet the ever growing and changing application needs.

2nd - Better utilisation of network resources

Better utilisation of network resources was the second most valued benefit of SDN by the network professionals surveyed during this research. SDN provides the capability for network virtualisation inside the data centre, maximising the performance of the available network devices and reducing CAPEX. Put simply, network components via SDN and network virtualization can now run several networks for several clients or applications on top of the same network fabric increasing the active time of the network nodes.

Through the use of SDN and Network virtualisation service providers are able to host a large number of virtual networks sharing the same physical substrate while preserving the confidentiality of each network, leading to an increased level of resource utilisation (Leonardo Richter Bays, et al., 2016). Amazon for instance, by using SDN can offer

network as a service to its Amazon Web Services customers providing secure network segregation. This SDN feature is enabling Amazon not only to scale quickly but also a highly competitive price to offer its customers.

3rd - Performing Traffic Engineering

SDN empowered networks have the ability to react to the changing present state of the WAN circuits, prevent incidents when circuits are underperforming due to congestenion or packet loss, and increase performance by redirecting traffic through them when extra bandwidth becomes available. Google and Amazon have been early adopters of SDN traffic engineering. According to Chloe Ma, despite the initial SDN products primarily concentrated on automation and orchestration inside a Data Center, the more mature SDN solutions, such as those from Google and Amazon, are designed to take software-defined WAN with centralised traffic engineering into consideration. Looking to the service-provider world, traditional BGP, MPLS, and L3VPN/EVPN technologies are still the dominant and proven technologies that can scale, isolate, and guarantee SLA over WAN(Chloe Ma, 2016).

On the other hand, the analysis of the possible challenges when adopting SDN initiatives highlighted the following as the top three inhibitors stopping or delaying SDN initiatives;

1st - Concerns about Integrating SDN with existing network

SDN stakeholders and especially network engineers are finding technical challenges when trying to adopt SDN initiatives that involve the integration of SDN with legacy production networks. Since SDN concentrates the intelligence of the network in a central controller, it is often difficult to remove the intelligence of the different individual legacy network nodes. This operation includes high risk and it might be difficult to achieve without involving downtime on the network.

According to ONF, SDN integrations fall in three main categories: legacy-to-greenfield, legacy-to-mixed, and legacy-to-hybrid. (ONF, 2016)

- **Greenfield scenarios.** There is no need to support integration or interoperation with an existing non-OpenFlow based network infrastructure. Despite the concerns about integrating SDN with legacy networks, 32% of the network engineers queried during this research replied that they expected to implement SDN in production greenfield scenarios during the next two years.
- **Legacy-to-mixed.** New OpenFlow devices co-exist with legacy switches/routers. OpenFlow controllers and traditional devices need to exchange routing information via the legacy control plane.
- **Legacy-to-hybrid**. Hybrid devices interface with both OpenFlow controllers and legacy control plane. Google and Stanford University are two promises examples of successful hybrid migrations. (Jain, et al., 2013) (ONF, 2016)

The ONF has a Migration Working Group that releases white papers with recommendations for SDN migration methods, tools, and systems, including additional SDN migration use cases as they are defined and deployed. (ONF Migration Working Group, 2015)

2nd - Immaturity of current products.

Compared to legacy networking solutions, SDN solutions are relatively new and have not had the time yet to mature enough to earn the confidence of some networking professionals that are still reluctant to the stability, scalability and security of the different SDN solutions offered by the different vendors. This study proved that this is a top inhibitor to SDN adoption. The results obtained in this research were similar to the ones collected on the survey result obtained by Metzler et al, completed by 246 IT professionals where they ranked with a 29% of the votes the Immaturity of current products to be the number one concern when implementing SDN. (Metzler, et al., 2015)

3rd - Immaturity of the enabling technologies (OpenFlow).

OpenFlow, currently in version is 1.4, but with its first standard version, OpenFlow 1.1, released the 28th of February 2011 is still considered a new network protocol. The data obtained during this research proves that, at present, the immaturity of Openflow is still generating distrust or reluctance among the network professionals to deploy SDN solutions.

The top three inhibitors uncovered during this research are to be considered inherit inhibitors to any new technology and are expected to dissipate over time. Therefore this inhibitors should not represent a threat for the continuously increasing adoption of SDN initiatives.

5.2.3 Impact of SDN Technologies on the Network Engineer Role

From a perspective of the impact on network engineer role and based on the data analysed in this research, it is safe to assume that SDN will bring changes to the traditional role of network engineers.

Participants surveyed expected a moderate impact on the nature of their roles already during the next two years as they will continue to be involved in SDN initiatives. There is a strong current of opinion among the network engineers predicting a shift of skills from networking to programming and scripting. Further evidence supporting that current may lie in the fact that half of the respondents to the survey acknowledged that they would need to be trained to be able to support the SDN initiatives. Around that same idea, the future network engineer by using programming languages to configure the network will modify its daily work tasks. Configuration time and mundane manual tasks are expected to decrease, and more proactive tasks such as network design, capacity planning, network innovation and network automation will increase.

From the aspect of the impact of SDN on the organisation's organisational structure and based on the research performed in *Section 4.3.4*, it is safe to say that SDN will bring

some structural changes to the organisations that get involved in SDN initiatives. A majority of SDN stakeholders asked during this research predicted some impact on the organisational structure of their organisation. In order to be able to maximise the benefits provided by a programmable network deployment, Organisations will need to add a new role often mentioned in the literature as network programmability engineer, *Section 2.6.5*. This new role will be added to the traditional network design and network operations role. The network programmability engineer will be responsible for programming the new network releases designed by the design teams and operation teams to deploy new network solutions or automate operational tasks. The fact that half of the network engineers surveyed foresaw an increase in cross-functional teams and projects and a move to a DevOps model within the network teams supports this idea.

5.3 SWOT Analysis to Integrating SDN

As proven by the results in *Section 4.2.1* of this study, most organisations are currently either in early states of adopting SDN or foresee adopting it within the next two years. To be able to maximize the benefits of SDN and mitigate the top challenges uncovered by this study, *Section 4.2.2*, organisations should set clear objectives for implementing SDN and should acknowledge and assess weaknesses and threats that SDN integration implies.

SWOT analysis is a comprehensive way of assessing, positive and negative factors both internal and external to an organization. Correct SWOT analysis helps organisations build on their strengths, minimize their weaknesses, seize opportunities and counteract threats. (Dealtry, 1992)

A framework for SDN-SWOT analysis has been built based on the results of this study to help organisations identify strengths, weaknesses, opportunities and threats of SDN implementation. This analysis can help organizations make strategic plans and decisions.

Internal Factors: Strengths and Weaknesses

Strengths and weaknesses are determined by organization’s resources. The factors listed in the following list will fall under strength or weakness category depending on each

organisation characteristics defined below. Common internal factors to consider for SDN analysis include:

- Human resources. Organisations should assess SDN proficiency of their engineers.
- Technology resources – Organisations should assess their network equipment and identify outdated network equipment that needs to be upgraded.
- Financial resources– A study of the cost, value and feasibility of implementing an SDN should be done by any organisation.
- Implementation processes – Organisations should assess if there are strong processes in place, i.e. change management, knowledge transfer, risk assessment, to help guide the deployment of SDN initiatives.

External Factors: Opportunities and Threats

This study identified a broad range of Opportunities and Threats that SDN technology brings to an organization. Organizations should consider the following Opportunities and Threats before implementing SDN.

Opportunities

- Simplification of network provisioning and configuration
- Opportunity to perform traffic engineering
- Better utilisation of network resources
- Opportunity to reduce OPEX
- Opportunity to reduce CAPEX
- Opportunity to support network virtualisation

Threats

- Risks of Integrating SDN with existing network
- Immaturity of current products
- Immaturity of the enabling technologies (OpenFlow)
- Potential inability of SDN to scale up for organisations requirements
- The need to significantly train staff

- Lack of definition in strategies provided by vendors
- Possible security threats

Following *Table 5.1* represents the framework for SDN-SWOT analysis to be considered by any organisation undertaking an SDN initiative. The elements in Strengths and Weaknesses columns, in lighter grey, can be defined as either Strength or Weakness depending on characteristics of each organisation. On the other hand, the elements in Opportunities and Threats are constant. The most important elements in these fields according to this study are in bold.

STRENGTHS	**WEAKNESSES**
• SDN savvy network team • SDN Ready network hardware • Strong financial environment • Strong SDN migration processes	• SDN knowledge gap in network team • Outdated / Not SDN ready hardware • Uncertain financial environment • Weak or absent SDN migration processes
OPPORTUNITIES	**THREATS**
• **Simplification of network provisioning and configuration** • **Perform traffic engineering** • **Better utilisation of network resources** • Reduce OPEX • Reduce CAPEX • Support network virtualisation	• **Concerns about Integrating SDN with existing network** • **Immaturity of current products** • **Immaturity of the enabling technologies (OpenFlow)** • Concerns about the ability of SDN to scale for organisations requirements • The need to significantly train staff • No real business case for it • Lack of definition in strategies from vendors • Possible security threats

Table 5.1 SDN SWOT Framework

5.4 The Roadmap to Integrating SDN

IT organisations considering adoption of SDN should keep in mind the top three challenges of SDN uncovered by this research in section 5.2.2. Some organisations might not be ready to move to SDN at present for a number of reasons, such as SDN knowledge gap in their workforce or a lack of best-practice migration processes for migrating from their legacy network to SDN. However, their network hardware should be ready when these issues are addressed. Newly purchased network equipment should be able to be programmed by a controller or a script rather than CLI interface requiring direct human interaction.

Moreover, SDN will reallocate the spend from equipment toward controllers and software. Network provisioning processes will change and network engineers will need to learn programming skills to provision and manage new SDN network deployments. All of this implies organisational disruption, however implications can be minimised if correctly assessed beforehand. As explained in section 5.2.3, organisations may need to reassess their respective IT organisational structures by realigning IT teams from siloed teams, such as application, storage, virtualization and networking teams to cross-functional teams. This will enable open communication between technology specialists.

This section presents the roadmap for SDN adoption to help organisations seeking to implement SDN. The roadmap defines the following 6 different phases of SDN integration.

1. Study the value that SDN can bring to the organisation
2. SDN-SWOT analysis
3. Definition the SDN strategy
4. Study of the different SDN vendors' solutions
5. SDN solution testing
6. SDN integration in production network

Successful completion of each phase will help organisations maximise the benefits and overcome the pitfalls of an SDN deployment

Phase 1; Study the value that SDN can bring to the organisation

This research results, in *Section 4.3.2*, show that currently 90% of organisations are involved in SDN initiatives. Neither these figures nor the current hype should make any engineering team or CIO doubt the benefits of studying the value of SDN implementations. A clear vision of the value of implementing SDN will help the organisation navigate to a clear goal. Therefore, it helps the organisation to successfully complete Phase 2 and Phase 3 of this roadmap. Contrarily, if no value has been identified, the following activities around SDN implementations should cease. Activities shall be re-activated if value derived from SDN adoption is identified in future iterations of Phase 1.

Phase 2; SWOT analysis for the SDN effort

If the organisation is certain that SDN will bring value, the next step will be to assess internal and external factors that affect the organisation's ability to successfully complete an SDN deployment. In order to do that, the organisation's SDN stakeholders group should complete a SWOT analysis using the framework provided in section 5.2.1 of this research.

Phase 3; Define the SDN strategy

Once the SWOT analysis has identified the current state of the organisation, the next step is to develop the SDN strategy to follow when adopting SDN. The right strategy should build on the organisation's strengths, minimize its weaknesses, seize opportunities and counteract threats. SDN adoption strategy should cover areas such as:

- SDN functionalities to be implemented;
- Network environments affected by SDN implementation;
- SDN hardware and software procurement guidelines;
- Organisations' SDN-training plan for staff;
- Organisational structure.

Phase 4; Study SDN vendor solutions

Once the strategy for the adoption of SDN has been decided upon, the organisation should evaluate which vendors' SDN product and strategy is more aligned with its SDN adoption strategy. Companies surveying different vendors should consider the following list.

- **Vendor support.** SDN allows organisations to develop their own code. It is crucial to have an understanding of how a vendor will support the self-developed code.
- **Programming language**. It is key to understand what languages are supported by the vendor solution so that they match organisations' developers' skills. The goal is to reduce the need for knowledge transfer and training required.
- **Avoid vendor lock-in.** Organisations will always benefit from the freedom to be able to choose the best vendor in the market at any time.
- **SDN applications availability.** For organisations searching for a vendor-supplied and vendor-supported SDN application that provides particular solutions, it is paramount to understand what applications run today, and what is on the vendor's applications roadmap.
- **Licensing mode.** Organisations should examine exactly how the vendor licenses its technology and what that means for their network design.
- **Past use cases.** Organisations should ask vendors to supply white papers and customer references that prove how its technology solves recent challenges to understand how a particular solution fits their needs.
- **Vendor roadmap for OpenDaylight support.** As OpenDaylight develops, it could form a standard of interoperability used by all SDN products.

Phase 5; SDN testing

Since adopting SDN technology implies a significant change to the network platform for any organisation, it is recommended to perform the following minimum testing to the selected SDN solution;

- **Proof of Concept Testing** evaluates that the chosen SDN solution contains the necessary capabilities to drive the value expected
- **Interoperability Testing** evaluates the interoperability of the preferred solution with future cross-vendor SDN deployments and, more importantly, with the current legacy network.
- **Performance Testing** evaluates if the performance capabilities of the SDN solution can fulfil the organisations' network requirements.

A thorough evaluation of the tests above will help verify that the capabilities of the implemented SDN solution match the initial requirements drafted in Phase 1 and 2 and will help mitigate the impact of the challenges presented in Section 5.2.2 when implementing SDN later on in production environment.

It is important to stress that this phase is an excellent opportunity for vendor's and organisations' technical teams to obtain a profound technical knowledge about the chosen SDN solution and to become familiar with its possible challenges while there is no risk of incidents in the network.

Phase 6; SDN integration in production network

Integrating SDN solutions with legacy networks always represents a risk. As seen in *Section 4.2.2* in this research, SDN integration with legacy network represents the biggest challenge to overcome by organisations today.

The correct execution of Phases 1 to 5 of this roadmap should resolve into a clear SDN strategy and a thorough tested SDN vendor solution. Also, organisations' technical teams should have acquired enough proficiency with the SDN solution to be leveraged in production. Simultaneously, organisation's processes should have been reviewed to support the adoption of SDN. All this should help organisations mitigate possible impacts during the process of integrating SDN solutions into their production network.

As seen in Section 5.2.2 of this document, there are different approaches when it comes to integration SDN to legacy networks. These are, legacy-to-greenfield, legacy-to-mixed, and legacy-to-hybrid. (ONF, 2016) A study on what approach suits better for a particular organisation or particular network environment should be discussed in Phase 4 of this framework. Strong vendor support, a tuned monitoring system and a robust change process will be critical for the smooth integration of SDN.

- **Strong vendor support** to help plan and resolve incidents derived from SDN network implementation changes.

- **Tuned monitoring systems** to alert support teams at any time of any impact on the network infrastructure before, during and after an SDN implementation change has occurred.
- **Robust change process** to ensure that all changes are correctly documented, peer reviewed, executed and have a rollback strategy. It should also keep a database of the changes completed for possible future reference and standardisation efforts.

As organisations continue to be involved in SDN efforts and SDN solutions continue to be developed, the ones that recognise the potential of SDN and achieve its adoption will be the ones that will gain a competitive advantage.

5.5 Contribution to the Body of Knowledge

This research presents the current adoption state of Software-Defined Networking technology. As this new paradigm for network engineering has gained traction, it has become relevant for network engineers to gain familiarity with this technology and be aware of the value that SDN can bring to their organisations.

The study pinpoints the top three benefits provided by SDN that are driving its adoption and the top three challenges slowing it. Network engineers today need to be aware of what these benefits and these challenges are to be able to use this knowledge to their advantage when adopting present and future SDN initiatives. This knowledge will also be useful for them to stay relevant on the market. Moreover, this paper provides an insight into what is the expected impact that SDN is going to have in the nearest future on the nature of the network engineer role and its team organisational structure inside its organisation.

This research culminates with a proposed framework for SDN-SWOT analysis and a roadmap to help organisations overcome the challenges identified in integrating SDN whilst maximising the benefits. Practitioners and researchers may decide to use these frameworks as a base for further research efforts.

5.6 Limitations of the Research

This research has several limitations. These limitations are a direct consequence of the limited time cycle and the nature of this analysis. The size of the sample population was smaller than initially desired and even though the population sample covered all the different profiles that wanted to be covered by this research, a larger sample population would have been more representative. Therefore, a bigger sample population would have strengthened the validity of the conclusions derived from this research.

On top of that, a mixed research approach where qualitative data obtained through interviews engaging major SDN stakeholders would have been combined would have been very relevant to the study. Qualitative data would have had incorporated specialists' opinions to the evidence gathered through the quantitative data collected from the survey, thus helping to reaffirm the conclusions of this study. Qualitative data collection was waived due to time restrictions.

5.7 Recommendations for Future Work

This section introduces compelling directions for future research related to the areas study around SDN technologies.

This study proposes further research on the challenges faced by practitioners when integrating SDN implementations with legacy networks. Ranked as the primary inhibitor for SDN implementations, any development or progress in this ambit would be very beneficiary to the adoption of SDN. On the same issue, a deeper study of the evolution of the different vendors SDN solutions and SDN enabling technologies would also be of great aid to researchers and practitioners.

This study also identified several areas of impact of SDN on the network engineers' workforce. It unveiled future impact on the shift of skills that network engineers need to make to stay relevant and the different reorganisation their teams might be subject to. Therefore, this study proposes a deeper analysis on what specific new programming skills would be more beneficial for the network engineers to learn. It would also be interesting to find which programming languages and what SDN certifications would be more relevant

in the upcoming years. SDN has opened a door to open source networking challenging the status quo of traditional networking vendors.

Moreover, the evolution of SDN should be continuously monitored as one thing is certain: the increase in volume, variety and velocity of data is unprecedented and networks are becoming larger and more complex each day. SDN initiatives are developing fast to keep networks manageable and flexible to the data flow changes, and such initiatives are only going to become more relevant to the future of networking than they are already today.

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Appendices

Appendix 1 Ethics Application Form

.

Research Ethical Application Form

Part A

Project Title: Software Defined Networking movement in Ireland, current status and adoption factors

Name of Lead Researcher (student in case of project work): Alberto Martinez

Name of Supervisor: Paula Roberts

TCD E-mail: martia12@tcd.ie Contact Tel No.: 0852775994

Course Name and Code (if applicable): M.S.c in Management of Information Systems

Estimated start date of survey/research: 19th June

I confirm that I will (where relevant):

- Familiarize myself with the Data Protection Act and the College Good Research Practice guidelines http://www.tcd.ie/info_compliance/dp/legislation.php;
- Tell participants that any recordings, e.g. audio/video/photographs, will not be identifiable unless prior written permission has been given. I will obtain permission for specific reuse (in papers, talks, etc.)
- Provide participants with an information sheet (or web-page for web-based experiments) that describes the main procedures (a copy of the information sheet must be included with this application)
- Obtain informed consent for participation (a copy of the informed consent form must be included with this application)
- Should the research be observational, ask participants for their consent to be observed
- Tell participants that their participation is voluntary
- Tell participants that they may withdraw at any time and for any reason without penalty
- Give participants the option of omitting questions they do not wish to answer if a questionnaire is used
- Tell participants that their data will be treated with full confidentiality and that, if published, it will not be identified as theirs
- On request, debrief participants at the end of their participation (i.e. give them a brief explanation of the study)

- Verify that participants are 18 years or older and competent to supply consent.
- If the study involves participants viewing video displays then I will verify that they understand that if they or anyone in their family has a history of epilepsy then the participant is proceeding at their own risk
- Declare any potential conflict of interest to participants.
- Inform participants that in the extremely unlikely event that illicit activity is reported to me during the study I will be obliged to report it to appropriate authorities.
- Act in accordance with the information provided (i.e. if I tell participants I will not do something, then I will not do it).

Signed: ..... Date: 7/6/16
Lead Researcher/student in case of project work

Part B

Please answer the following questions.		***Yes/No***
Has this research application or any application of a similar nature connected to this research project been refused ethical approval by another review committee of the College (or at the institutions of any collaborators)?		No
Will your project involve photographing participants or electronic audio or video recordings?		No
Will your project deliberately involve misleading participants in any way?		No
Does this study contain commercially sensitive material?		No
Is there a risk of participants experiencing either physical or psychological distress or discomfort? If yes, give details on a separate sheet and state what you will tell them to do if they should experience any such problems (e.g. who they can contact for help).		No
Does your study involve any of the following?	Children (under 18 years of age)	No
	People with intellectual or communication difficulties	No
	Patients	

School of Computer Science and Statistics Research Ethical Application Form

Details of the Research Project Proposal must be submitted as a separate document to include the following information:

1. Title of project
2. Purpose of project including academic rationale
3. Brief description of methods and measurements to be used
4. Participants - recruitment methods, number, age, gender, exclusion/inclusion criteria, including statistical justification for numbers of participants
5. Debriefing arrangements
6. A clear concise statement of the ethical considerations raised by the project and how you intend to deal with them
7. Cite any relevant legislation relevant to the project with the method of compliance e.g. Data Protection Act etc.

Part C

I confirm that the materials I have submitted provided a complete and accurate account of the research I propose to conduct in this context, including my assessment of the ethical ramifications.

Signed: ..... Date: 7/6/16
Lead Researcher/student in case of project work

There is an obligation on the lead researcher to bring to the attention of the SCSS Research Ethics Committee any issues with ethical implications not clearly covered above.

Part D

If external or other TCD Ethics Committee approval has been received,
please complete below.

External/TCD ethical approval has been received and no further ethical approval is required from the School's Research Ethical Committee. I have attached a copy of the external ethical approval for the School's Research Unit.

Signed: ..... Date: 7/6/16
Lead Researcher/student in case of project work

Part E

If the research is proposed by an undergraduate or postgraduate student, please have the below section completed.

I confirm, as an academic supervisor of this proposed research that the documents at hand are complete (i.e. each item on
the submission checklist is accounted for) and are in a form that is suitable for review by the SCSS Research Ethics Committ

Signed: Date:
.....7/6/16.....
Supervisor

Completed application forms together with supporting documentation should be submitted electronically to research-ethics@scss.tcd.ie Please use TCD e-mail addresses only. When your application has been reviewed and approved by the Ethics committee hardcopies with original signatures should be submitted to the School of Computer Science & Statistics, Room F37, O'Reilly Institute, Trinity College, Dublin 2.

Appendix 2 Information for prospective participants

INFORMATION FOR PROSPECTIVE PARTICIPANTS AND INFORMED CONSENT FORM

BACKGROUND OF RESEARCH:

Conventional networks are not only complex but are difficult to manage as well. One reason revolves around the fact that data and control planes are vendor-specific and vertically integrated. Secondly, typical networking devices are also closely linked to line versions and products. Simply put, each product line might have a specific management interface and configuration that imply long production cycles for product upgrades (i.e., new device versions) or updates (i.e., new firmware). All the issues mentioned above have caused vendor-lock- in challenges for owners of network architecture, and those presenting serious impediments towards innovation and change. Software-defined-networking (SDN) offered an opportunity of addressing such long-term concerns. Some critical concepts regarding SDN revolve around the incorporation of dynamic programmability within forwarding devices via open southbound interfaces, data and control plane decoupling, and global network visibility through network brain logical centralization.
SDN solutions promise to ease network provisioning, management and troubleshooting using a centralised view of the network. At the same time, through network virtualization and dynamic performance routing, SDN can better utilise the network resources available, reducing CAPEX. On the other hand, its adoption is being delayed or stopped due to different challenges such as technical reliability and scalability issues or the immaturity of the different vendor solutions. On top of that, it has been observed that sometimes there is a knowledge gap in the workforce that should be implementing the transition from legacy networks to SDN.

This research tries to answer what is the current status of SDN implementations, in which network environments it is being implemented and what are the top benefits and inhibitors affecting its deployment. The research also tries to understand what impact SDN might have in the future of the network engineer role and the organisational structure of the companies adopting it.

PROCEDURES OF THIS STUDY:

I, **Alberto Martinez** as part of the fulfilment of the **M.Sc. In Management of Information Systems dissertation in Trinity College**, am asking you to devote **10 minutes** to complete an online survey that will focus on the study of the current status of the SDN movement in Ireland, it's adoption factors and its impact on network administrators and organisations structure.

The survey includes questions related to your current role in your organisation and SDN specific questions including; Primary business of your organisation Years of experience Size of the network you manage Your knowledge around SDN technology Specific SDN adoption factor questions Your perception of the impact that SDN might have in your role and your company organisational structure

The results will be **confidential** and **anonymous**. They will be analysed, they will be presented in a report and they will be the base of statistical conclusion to help IT professionals understand the current panorama around SDN implementations.

PUBLICATION:

This information is being gathered for the completion of a dissertation as part of the **M.Sc. In Management of Information Systems**. Individual results will be aggregated anonymously and research reported on aggregate results.
This dissertation along with the gathered anonymous data may be published in **Trinity College Dublin Library** along with all other theses and dissertations.
In keeping with standard professional practice, your data may be retained for 10 years, during which time only the researcher on this project, Alberto Martinez, will have access to them. The data will be stored in a password protected folder (WiSER folder). The identity of you and all participants will be **totally confidential**.

CONFLICT OF INTEREST

This survey is being undertaken by the researcher, Alberto Martinez, and it is acknowledged that this represents a possible conflict of interest because some of the survey participants might have some personal or professional relationship with him. In respect of this acknowledgement, he asks them to act with integrity and he undertakes to do the same as the researcher. This research does not aim to obtain any confidential information from any company but seeks to obtain data purely from an expert point of view from Network engineers and SDN stakeholders. The **information** provided is **strictly confidential** and all responses will be used **solely for the purpose of this research**.

The researcher will **NOT benefit**, directly or indirectly (through giving advantages of market research knowledge to an employer) from the research findings separate to the role of the research in the researcher's course.

DECLARATION:

I am 18 years or older and I am competent to provide consent. I have read, or had read to me, a document providing information about this research and this consent form. I have had the opportunity to ask questions and all my questions have been answered to my satisfaction and understand the description of the research that is being provided to me. I agree that my data is used for scientific purposes and I have no objection that my data is published in scientific publications in a way that does not reveal my identity. I understand that if I make illicit activities known, these will be reported to appropriate authorities. I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights. I understand that I may refuse to answer any question and that I may withdraw at any time without penalty. As this research involves viewing materials via a computer monitor, I understand that if I or anyone in my family has a history of epilepsy then I am proceeding at my own risk. I understand that my participation is fully anonymous and that no personal details about me will be recorded. I have received a copy of this agreement.

STATEMENT OF INVESTIGATOR'S RESPONSIBILITY:

I have explained the nature and purpose of this research study, the procedures to be undertaken and any risks that may be involved. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent.

RESEARCHER CONTACT DETAILS:

Alberto Martinez Aranda, martia12@tcd.ie

CONSENT STATEMENT

I have read the INFORMATION FOR PROSPECTIVE PARTICIPANTS AND INFORMED CONSENT FORM. I am 18 years or older and I am competent to supply consent. I wish to proceed and I consent to participate in the study that has been described above

Yes, I would like to proceed with the questionnaire

No, I would not like to proceed

Appendix 3 Ethics consent form

TRINITY COLLEGE DUBLIN

INFORMED CONSENT FORM

LEAD RESEARCHERS:
Alberto Martinez, School of Computer Science and Statistics, Trinity College Dublin

BACKGROUND OF RESEARCH:

Conventional IP networks, which connect most of today's organisations, are usually highly complex and challenging to manage. In conventional networking control and data planes are bundled together in each network device. This condition makes network reconfiguration to respond to faults, load, and changes a manual and highly time and resource consuming task.
Software-defined networking (SDN) is an emerging paradigm that overcomes this challenge by splitting the packet forwarding functionality, known as the data plane, from the control intelligence factor, known as the control plane, promoting centralization of network control. Central network control eases network provisioning, management and troubleshooting. At the same time, through network virtualization and dynamic performance routing, SDN can better utilise the network resources available, reducing CAPEX.

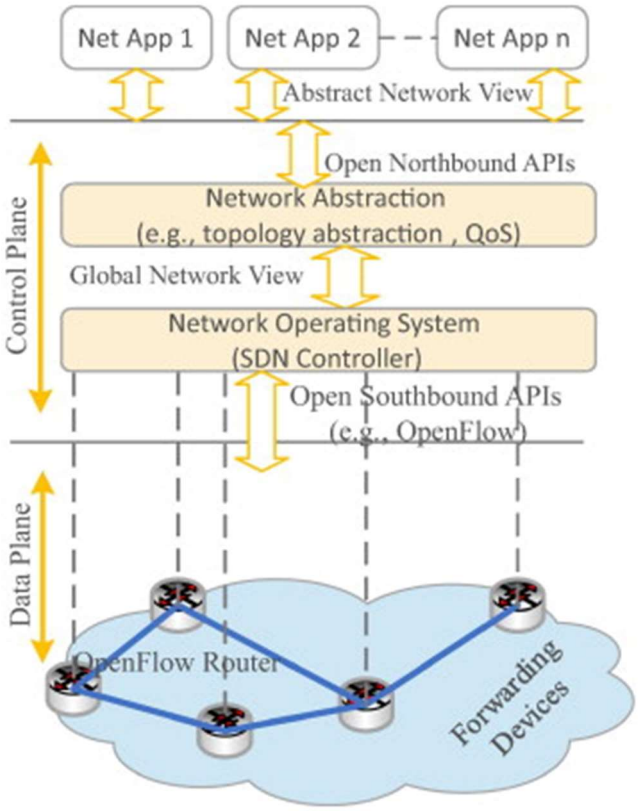

Fig. 1.
Simplified view of an SDN architecture.

Despite the obvious benefits of implementing SDN, its adoption is being delayed or stopped due to different technical challenges including reliability and scalability issues and network engineers and SDN stakeholders often complain about the immaturity of the different vendor solutions or their lack of a clear SDN strategy. On top of that, it has been observed that sometimes there is a knowledge gap in the workforce that should be implementing the transition from conventional networks to SDN.
This research tries to answer what is the current status of SDN implementations, in which network environments it is being implemented and what are the top benefits and inhibitors affecting its deployment. The research also tries to understand what impact SDN might have in the future of the network engineers roles and what organisational structure changes of the companies adopting it.

The data required to be able to perform this research will be obtained only from network engineers and IT professionals who possess the necessary technical knowledge about SDN. A positivist approach was adopted where anonymous quantitatively data will be obtained using an online survey hosted in Qualitrics platform.

CONFLICT OF INTEREST

This survey is being undertaken by the researcher, Alberto Martinez, and it is acknowledged that this represents a possible conflict of interest because some of the

survey participants might have some personal or professional relationship with him. In respect of this acknowledgement, he asks them to act with integrity and he undertakes to do the same as the researcher. This research does not aim to obtain any confidential information from any company but seeks to obtain data purely from an expert point of view from Network engineers and SDN stakeholders. The information provided is strictly confidential and all responses will be used solely for the purpose of this research.

The researcher will NOT benefit, directly or indirectly (through giving advantages of market research knowledge to an employer) from the research findings separate to the role of the research in the researcher's course.

METHODS AND MEASUREMENTS

The first draft of the survey was sent to a small group of peers to review the logic and viability of the survey. It was then modified according to their feedback, in order to create a survey that would be easier for the respondents; therefore more meaningful for the dissertation.

This online survey will be sent via email to several groups of network engineers such as the meetup group INOG (Irish network operators group) http://www.meetup.com/Irish-Network-Operators-Group/ and other network engineers that the researcher has met during his professional career as an I.T professional. The analysis will be conducted using Qualitrics, which includes research information and consent sheet. (Please see the document Survey.pdf. The researcher has attached an export of the survey and the survey flow)

https://scsstcd.qualtrics.com/SE/?SID=SV_0w88qzvtXOYAfU9

Phase Description Anticipated Timeline

1 - Email invite from me to all employees	**27th June (Or as soon as Ethics approval will be confirmed)**
2 - Reminder email invite	**3rd July**
3 - Close of survey	**11th July**
4 - Analisis of survey data	**11th to 24th July**
5 - Report on findings	**25th July to 7th August**

We do not anticipate any risks to the participants as it will be a self-selecting questionnaire outlining details of the study and allowing for participants to opt in or out of participation. Also, participants can opt out of the study at any stage of the questionnaire.

PUBLICATION:
The results when analysed, will be presented in a Report and they will be the base of a statistical conclusion.

Statement of Ethical consideration raised by the project and how you intend to deal with it.
This project does not raise any ethical issues. The participant will be informed that in the extremely unlikely event that illicit activities are reported I would be obliged to report them in turn to appropriate authorities.

Relevant legislation relevant to the project with the method of compliance.
The data will be stored on a password protected folder (WiSER folder). Access to the data will be confined to the researcher who will be responsible for the subsequent analysis. The only holders of the password will the researcher, Alberto Martinez.
Data collection, analysis and retention will be undertaken in full compliance with the Data Protection Acts 1988 and 2003.

Statement of investigator's responsibility:
I have explained the nature and purpose of this research study, the procedures to be undertaken and any risks that may be involved. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent.

RESEARCHER CONTACT DETAILS:
Alberto Martinez Aranda, martia12@tcd.ie

RESEARCHER'S SIGNATURE:

Date: 08/06/2016

Appendix 4 Survey export

SDN movement in Ireland, current status and adoption factors

INFORMATION FOR PROSPECTIVE PARTICIPANTS AND INFORMED CONSENT FORM BACKGROUND OF RESEARCH: Conventional networks are not only complex but are difficult to manage as well. One reason revolves around the fact that data and control planes are vendor-specific and vertically integrated. Secondly, typical networking devices are also closely linked to line versions and products. Simply put, each product line might have a specific management interface and configuration that imply long production cycles for product upgrades (i.e., new device versions) or updates (i.e., new firmware). All the issues mentioned above have caused vendor-lock- in challenges for owners of network architecture, and those presenting serious impediments towards innovation and change.Software-defined-networking (SDN) offered an opportunity of addressing such long-term concerns. Some critical concepts regarding SDN revolve around the incorporation of dynamic programmability within forwarding devices via open southbound interfaces, data and control plane decoupling, and global network visibility through network brain logical centralization. SDN solutions promise to ease network provisioning, management and troubleshooting using a centralised view of the network. At the same time, through network virtualization and dynamic performance routing, SDN can better utilise the network resources available, reducing CAPEX. On the other hand, its adoption is being delayed or stopped due to different challenges such as technical reliability and scalability issues or the immaturity of the different vendor solutions. On top of that, it has been observed that sometimes there is a knowledge gap in the workforce that should be implementing the transition from legacy networks to SDN. This research tries to answer what is the current status of SDN implementations, in which network environments it is being implemented and what are the top benefits and inhibitors affecting its deployment. The research also tries to understand what impact SDN might have in the future of the network engineer role and the organisational structure of the companies adopting it. PROCEDURES OF THIS STUDY: I, Alberto Martinez as part of the fulfilment of the M.Sc. In Management of Information Systems dissertation in Trinity College, am asking you to devote 10 minutes to complete an online survey that will focus on the study of the current status of the SDN movement in Ireland, it's adoption factors and its impact on network administrators and organisations structure.The survey includes questions related to your current role in your organisation and SDN specific questions including;Primary business of your organisationYears of experience in IT rolesSize of the network you manageYour knowledge around SDN technologySpecific SDN adoption factor questionsYour perception of the impact that SDN might have in your role and your company organisational structure The results will be confidential and anonymous. They will be analysed, they will be presented in a report and they will be the base of statistical conclusion to help IT professionals understand the current panorama around SDN implementations. PUBLICATION: This information is being gathered for the completion of a dissertation as part of the M.Sc. In Management of Information Systems. Individual results will be aggregated anonymously and research reported on aggregate results. This dissertation along with the gathered anonymous data may be published in Trinity College Dublin Library along with all other theses and dissertations.In keeping with standard professional practice, your data may be retained for 10 years, during which time only the researcher on this project, Alberto Martinez, will have access

to them. The data will be stored in a password protected folder (WiSER folder). The identity of you and all participants will be totally confidential. CONFLICT OF INTEREST This survey is being undertaken by the researcher, Alberto Martinez, and it is acknowledged that this represents a possible conflict of interest because some of the survey participants might have some personal or professional relationship with him. In respect of this acknowledgement, he asks them to act with integrity and he undertakes to do the same as the researcher. This research does not aim to obtain any confidential information from any company but seeks to obtain data purely from an expert point of view from Network engineers and SDN stakeholders. The information provided is strictly confidential and all responses will be used solely for the purpose of this research. The researcher will NOT benefit, directly or indirectly (through giving advantages of market research knowledge to an employer) from the research findings separate to the role of the research in the researcher's course.DECLARATION: I am 18 years or older and I am competent to provide consent.I have read, or had read to me, a document providing information about this research and this consent form.I have had the opportunity to ask questions and all my questions have been answered to my satisfaction and understand the description of the research that is being provided to me.I agree that my data is used for scientific purposes and I have no objection that my data is published in scientific publications in a way that does not reveal my identity.I understand that if I make illicit activities known, these will be reported to appropriate authorities.I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights.I understand that I may refuse to answer any question and that I may withdraw at any time without penalty. As this research involves viewing materials via a computer monitor,I understand that if I or anyone in my family has a history of epilepsy then I am proceeding at my own risk.I understand that my participation is fully anonymous and that no personal details about me will be recorded. I have received a copy of this agreement. STATEMENT OF INVESTIGATOR'S RESPONSIBILITY: I have explained the nature and purpose of this research study, the procedures to be undertaken and any risks that may be involved. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent. RESEARCHER CONTACT DETAILS: Alberto Martinez Aranda, martia12@tcd.ie

CONSENT STATEMENTI have read the INFORMATION FOR PROSPECTIVE PARTICIPANTS AND INFORMED CONSENT FORM. I am 18 years or older and I am competent to supply consent. I wish to proceed and I consent to participate in the study that has been described above

- Yes, I would like to proceed with the questionnaire (1)
- No, I would not like to proceed (2)

NOTE: All the questions are optionalHow long have you been working in IT?

- Less than a year (1)
- 1 to 3 years (2)
- 4 to 6 years (3)
- 7 to 10 years (4)
- Over 10 years (5)

How big is the network you operate/provision/manage?

- 1 to 49 Nodes (1)

- 50 to 99 Nodes (2)
- 100 to 499 Nodes (3)
- 500 to 999 Nodes (4)
- 1000+ Nodes (5)

How much influence your opinion on adopting SDN would have in your organisation?
- I am the maximun responsible and decision maker for network design and implementations including SDN (1)
- I am part of a decision making group for network implementations including SDN (2)
- I am NOT part of a decision making group but my opinion would be considered by the decision making group in my organisation (3)
- I have no influence at all (4)

In which industry are you currently employed? (What is your company primary business)
- Information Technology / Internet / Software (1)
- Telecommunications provider (2)
- Finance or insurance (3)
- Construction (4)
- Forestry, fishing, hunting or agriculture support (5)
- Public administration (6)
- Transportation or warehousing (7)
- Real estate or rental and leasing / Accomodation (8)
- Management of companies or enterprises / Consulting services (9)
- Educational services (10)
- Health care or social assistance (11)
- Other (12)

How familiar are you with Software Defined Networking
- Very familiar (1)
- Moderately familiar (2)
- Slightly familiar (3)
- Not familiar at all (4)

Are you part of any Software Defined Networking initiative?(Check all that apply)
- We have not conducted any study of SDN yet (1)
- We will likely study SDN possibilities next year (2)
- We are studying the VALUE that SDN can bring to our organisation (3)
- We expect to have SDN running in a Lab environment within a year (4)
- We are currently studying different SDN vendors solutions (5)
- We already have SDN running in a LAB (6)
- We already have SDN running in our production network (7)

NOTE: All the questions are optionalCheck all the scenarios where you think you will deploy SDN in the next 2 years. (check all that apply)
- DevCloud/Test network (1)
- Corporate/Campus network (2)
- WAN network (3)
- Production Data Center Green field deployment (new network) (4)
- Production Data Center Brown field deployment (existing network) (5)

- I don't think I will deploy SDN in the next two years (6)

Rank the benefits that would drive you to implement an SDN solution?Drag most important (TOP) to less important (BOTTOM)
_____ Simplification of network provisioning and configuration (1)
_____ Perform traffic engineering (2)
_____ Reduce OPEX (3)
_____ Reduce CAPEX (4)
_____ Better utilisation of network resources (5)
_____ Support network virtualisation (6)

Rank the following challenges that would stop or delay you deploying SDNDrag most important (TOP) to less important (BOTTOM)
_____ Concers about Integrating SDN with existing network (1)
_____ Immaturity of the enabling technologies (openflow) (2)
_____ Lack of definition in strategies from vendors (3)
_____ Immaturity of current products (4)
_____ Possible security threats (5)
_____ Concerns about the ability of SDN to escale for organisations requirements (6)
_____ The need to significally train our staff (7)
_____ No real business case for it (8)

NOTE: All the questions are optionalHow much impact do you think an SDN implementation would have on the nature of your work within the next two years?
- Significant impact (1)
- Moderate impact (2)
- Little impact (3)
- No impact (4)
- I dont know (5)

What changes do you think the SDN movement will bring to the nature of your job?(Check all that apply)
- Skils needed will swift from networking to programming and scripting (1)
- My role will blend with application teams causing confusion (2)
- Configuration time will decrease and planning time will increase (3)
- I will need to be trained to be able to support the SDN initiatives (4)
- I don't think SDN movement will bring any change in the nature of my job (5)

How much impact do you think an SDN implementation would have on your department organisational structure in the next two years?
- Significant impact (1)
- Moderate impact (2)
- Little impact (3)
- No impact (4)
- I dont know (5)

In your opinion. what structural organisational changes do you think an SDN implementation would bring to IT organisations?(Check all that apply)
- A likely re-organisation of Network Operations team (1)

- An Increase of cross functional teams and projects (2)
- A move to a DevOps model within the Network teams (3)
- I don't think SDN will bring organisational structure changes (4)

Thank you! Would you like to submit your answers?
- Yes (1)
- No, exit without submitting answers (2)