System For Pratical Evaluations in Network Administration Courses

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Resumo

Os métodos convencionais de formação em rede de computadores, que dependem fortemente do hardware físico, são muitas vezes proibitivamente caros e não são escaláveis. As tecnologias de virtualização e emulação resolvem esta limitação, permitindo a execução simultânea de vários dispositivos simulados numa única máquina. No entanto, a avaliação da correção das configurações dos dispositivos de rede continua a ser um processo manual, propenso a erros, em que configurações incorrectas podem conduzir a falhas críticas em toda a rede.

A primeira fase deste projeto, conduzida por um estudante anterior, centrou-se na investigação da viabilidade de construir um sistema deste tipo e na produção de um conjunto de componentes soltos. Este trabalho representa a segunda fase, focando-se no desenho e implementação de um sistema para avaliação automática de topologias de rede, com suporte para um ambiente de dispositivos heterogéneos, no seguimento direto de um trabalho anterior. O sistema terá como objetivo fornecer um ambiente de trabalho completo para os alunos, uma interface Web para que tanto os alunos como os professores possam interagir com a plataforma e capacidades para automatizar a avaliação das configurações feitas pelos alunos, permitindo que os professores se concentrem no ensino e na orientação dos alunos, em vez de terem de efetuar verificações manuais repetitivas dos trabalhos dos alunos.

Os desenvolvimentos deste projeto incluem a extensão e integração do trabalho anterior, bem como o desenvolvimento de uma aplicação web utilizando FastAPI para alavancar as capacidades de comunicação assíncrona que se revelaram essenciais para garantir que o sistema pode escalar.

Palavras-chave: Proxmox VE, GNS3, automação, Nornir, FastAPI, assíncrono, comunicação, emulação, ferramenta de ensino

Abstract

Conventional computer network teaching methods, which depend heavily on physical hardware, are often prohibitively expensive and lack scalability. Virtualization and emulation technologies address this limitation by allowing multiple simulated devices to run concurrently on a single system. Nevertheless, assessing the correctness of network device configurations continues to be a manual, error-prone process, where misconfigurations can lead to critical failures across the network.

The first phase of this project, conducted by a previous student, focused on investigating the viability of building such a system and producing a set of loose components. This work represents the second phase,centered on designing and implementing a system for automated assessment of network topologies, designed to support a diverse range of network devices. Building upon previous research, the system aims to deliver a complete, web-based working environment where both students and instructors can interact with the platform. Its key feature is the automation of configuration assessments made by students, which reduces the manual workload for instructors, allowing them to focus more on teaching and guiding rather than repetitive checking of assignments.

The developments of this project include the extension and integration of previous work as well as the development of a web application using FastAPI to leverage asynchronous communication capabilities which proved essential to ensure the system can scale.

Keywords: Proxmox VE, GNS3, automation, Nornir, FastAPI, asynchronous, communication, emulation, teaching tool

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1. Introduction

Network administration remains a fundamental discipline within Computer Science (CS), given the central role that networked systems play in the functioning, scalability, and security of modern digital infrastructures.

Modern organizations require professionals who can design, configure, and troubleshoot increasingly complex network environments. Effective education must therefore bridge theoretical knowledge with practical implementation, particularly through hands-on learning that simulates real-world scenarios. Yet current training and assessment methods fail to meet these needs at scale, creating a growing gap between academic preparation and professional requirements.

This project aims to build an initial version of a system capable of assisting training in the topic of network administration, building upon previous work of Santos [1] which solved a series of individual problems relevant to this topic, without building a system out of them.

1.1. Need for Automated Assessment

Practical assessments are essential to prepare students for real-world challenges, enabling them to apply theoretical knowledge and develop hands-on skills. However, traditional assessment methods face significant limitations.

Creating a physical network environment for practical assessments is sure to be costly and challenging to scale for large student populations. While emulation and virtualization technologies offer cost-effective alternatives for creating flexible practice environments, they lack built-in automated assessment capabilities. Instructors must manually review each students' network assignment configuration—a process that is:

- **Time-consuming**: Manual checks grow linearly with class size.
- **Error-prone**: Human reviewers may overlook misconfigurations.
- **Risk of inconsistency**: Automated assessment ensures fully deterministic and consistent evaluation.

Automating assessments would reduce instructor workload, freeing time for student support as well as ensure consistent, objective grading and simultaneously enable immediate feedback for learners.

Previous work by Santos [1] has shown that it is possible to automate the validation of basic network commands, such as verifying the output of a ping command between a specific machine and a target IP address. This demonstrates that connectivity checks can be automated, paving the way for network automated assessment.

1.1.1 Limitations of Current Solutions

Existing approaches to network education suffer from two critical gaps:

1. **Single-vendor focus**: Most tools (e.g., Cisco's Packet Tracer) are designed for specific vendor ecosystems, failing to prepare students for heterogeneous real-world networks where multi-vendor interoperability is essential.

2. **Missing assessment component**: Some education institutions' curricula, such as our case in FCUP-Department of Computer Science (DCC), forgo practical assessments entirely, meaning students complete networking exercises without getting feedback or validation. This lack of feedback can lead to students having gaps in their knowledge, hindering their performance when they join the workforce, as they may not have acquired sufficient practical skills in the identification and solving of common problems.

1.2. Aims and Objectives

Designing and implementing a system that can automatically evaluate network administration assignments is one of the aims of this work. It will be utilised as a tool in classes and tests, allowing instructors to spend more time directly helping and guiding students.

One of the objectives needed to accomplish this, is to have such a system be able to perform assessments whenever requested by a student, in a fully automated manner. To have a wide range of support for vendors and device types is also highly desirable as exposing students to as much variety as possible will better prepare them for more heterogeneous environments of the real world. It will also be important to have assessment for configurations as well as connectivity.

Another aim of this project is to create a modular and cohesive back-end system out of the components created by Santos [1]. Achieving this will require further development of the components as well as creating capabilities to communicate between them.

1.3. Organization

Besides the Introduction, this work includes 6 more chapters:

1. **Chapter 2** presents an overview of the system components and underlying technologies.
2. **Chapter 3** reviews related work, highlighting lessons learned and how this project differentiates itself from existing solutions.
3. **Chapter 4** provides a detailed description of the system architecture and its layers. It also outlines the project's functional use cases.
4. **Chapter 5** focuses on implementation details, emphasizing design decisions and their realization.
5. **Chapter 6** discusses performance evaluation results, demonstrating the scalability of solutions introduced in this work.
6. **Chapter 7** gives an overview of met aims and objectives, reviews lessons learned throughout, and goes over ideas for future work.

2. Background

This chapter lays the technical groundwork for our project, with the aim to provide the reader with the necessary background to understand the context and technical foundations of this project. The goal of the system is to automatically evaluate network assignments by validating configurations and executing tests across various devices within a virtual network. Achieving this will require the coordination of several components and services in order to support an automated solution capable of providing each student with a correctly provisioned environment.

While a more detailed architecture will be presented in Chapter 4, here we will introduce the concepts and technologies that make this project possible. These include virtualization technologies to host students' work environments as well as the network devices in them, technologies that support our orchestration needs, web frameworks for user interaction and asynchronous technologies to enhance scalability.

2.1. Virtualization

Virtualization is the process of creating a virtual version of physical resources, such as routers, switches, or even entire computers. In the context of this project, it is used to create Virtual Machine (VM)s to provide students with a work environment consisting of a virtual network, itself comprised of various types of virtualized devices. This approach enhances scalability and reduces costs, as it allows multiple VMs to be run on a single physical machine.

In our project we will utilize **emulation** and **simulation**.

- **Emulation** is the process of replicating the exact behavior of a hardware or software system in a virtual environment, reproducing even its bugs and limitations. This is useful for various things like testing software on different platforms, running legacy software on modern hardware and even running potentially harmful software in a safe isolated environment. Emulation will be used wherever possible to provide students with a work environment that resembled the real world as much as possible to best develop their network skills.
- **Simulation** models aspects of the behaviour of a device, without replicating the underlying hardware or software. This results in a simpler, less resource intensive

model, though it may not fully capture the real devices' behavior. Simulation will be used to simulate the behaviour of certain, simpler and generic, network devices and PCs.

This project relies on both, as they enable the use of the the devices in the virtual work environments students will use to complete their assignments. These environments are hosted within VMs that run on a virtualization platform. These will be discussed in further detail, in Section 2.2 and Section 2.3.

2.1.1 Virtualized Work Environments

Creating a physical lab for students to learn and practice networking skills can be labor and time intensive as well as costly for larger student populations. To tackle this challenge we devised virtualized work environments wth existing tools and technologies, where a student can interact with a unique instance of a virtualized network, consisting of multiple devices. Then, by virtualizing these work environments, we can host several instances simultaneously over a single physical machine, increasing the number of students supported without an increase of hardware requirements.

This approach offers significant benefits over physical lab infrastructures:

- **Resource Efficiency**: Single physical host can support multiple concurrent student environments, each with multiple devices.
- **Operational Characteristics**:
  - Fast environment provisioning through template VMs.
  - Possibility of state preservation via Proxmox Virtual Environment (Proxmox VE)'s snapshot/restore functionality.
  - Support for diverse operating systems through virtualization technologies.

The combined use of Proxmox VE as a virtualization platform and Graphical Network Simulator-3 (GNS3) for network emulation presents a flexible and cost-effective solution for scalable networking education.

2.2. GNS3

GNS3 is an open-source graphical network emulator software that allows the user to create complex network topologies and interact with the various devices in it. It is widely used for educational purposes and is often used in preparation for professional network certifications like the Cisco Certified Network Associate (CCNA).

GNS3 employs a simple drag and drop interface to allow users to add new devices, make links between them and even add textual annotations. The software allows users to interact with the devices by way of a console or even a Graphical User Interface (GUI) if the device supports it. It also allows users to export their topologies to be shared with others, which can be useful for teachers to provide students with a pre-configured assignment to work on.

Additionally, there is support for packet capturing, which is essential for students to develop their debugging and troubleshoting skills. Finally, it can also be interacted with via a Representational State Transfer (REST) Application Programming Interface (API), which exposes its functionality through a set of standardized Hypertext Transfer Protocol (HTTP) endpoints. This allows external applications to perform actions such as retrieving information or triggering operations by sending structured requests. The stateless and language-agnostic nature of REST makes it well-suited for integration into automated systems, which is particularly relevant for this project.

2.2.1 Architecture

GNS3 has a modular architecture [2] that separates the user interface from the backend components responsible for simulation. The two main interfaces are the desktop-based gns3-gui and the web-based gns3-web, both of which act as front-ends. These interfaces communicate with the gns3-server, which handles the actual emulation of network devices. A central controller component coordinates communication between the server and the user interface. A diagram showing all the components can be seen in Figure 2.1. This separation allows for distributed deployments, where the GUI can run on a different machine than the server, enabling flexible use cases such as remote labs or headless setups.

2.2.1.1 Controller

The controller is integrated in the gns3-server project and is responsible for communicating with all the other components of the software. The controller is a singleton, meaning there should only be one instance of it running at any given time, and it does not support concurrent requests. The controller can manage multiple compute instances, which

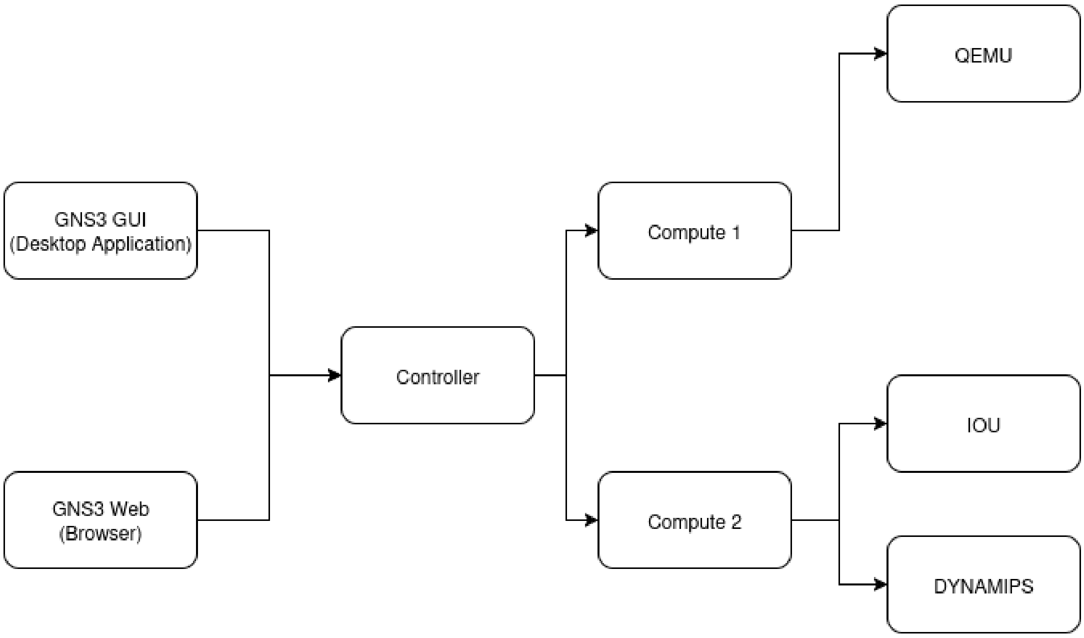


Figure 2.1: A simple diagram showcasing the architecture of GNS3. Recreation of architecture shown in GNS3's official docs.

are parts of the gns3-server project responsible for launching and managing emulators. These compute instances may run locally (in the same node as the controller) or remotely on different machines running their own instances of gns3-server if so desired, each capable of hosting one or more emulator instances, varying depending on their complexity. The controller also exposes a REST API providing the ability to interact with the software programatically. All communication is done over HTTP in JavaScript Object Notation (JSON) format and there is support for basic HTTP authentication as well as notifications via WebSockets.

2.2.1.2 Compute

The compute is also integrated in the gns3-server project and controls the various emulators required to run the nodes in the topology. The list of currently supported emulators is:

- **Dynamips** - Used to emulate Cisco routers and their hardware, as well as basic switching.
- **IOS on Unix (IOU)** - Used to emulate Cisco Internetworking Operating System (IOS) devices, it is faster than Dynamips as it does not perform hardware emulation.

Supported but not recommended as it is deemed inferior when compared to Virtual Internet Routing Lab (VIRL) Cisco's official simulation platform.

- **Quick Emulator (QEMU)** - Used to emulate a wide variety of devices, including virtual routers, switches, and Linux-based VMs.
  - **VIRL** To use VIRL IOS images on QEMU it is required to purchase a licence from Cisco. These images are created specifically for simulation and are recommended if newer version of IOS are desirable.
- **Virtual PC Simulator (VPCS)** - A program meant to simulate a basic PC.
- **VMware/VirtualBox** - Used to run VMs with nested virtualization support.
- **Docker** - Used to run docker containers.

2.2.1.3 GUI

The GUI is composed of two separate entitites with mostly identical functionality, namely the gns3-gui and the gns3-web projects. The gns3-gui project is a desktop application that is used to to interact with a local or remote gns3-server instance. It is written in Python and uses the Qt framework for the graphics. The gns3-web, seen in Figure 2.2, is a web interface that is accessible via web browser and, even though it is still in a beta stage, it has all the necessary features that students will need, as well as enough stability to be used as a substitute for the gns3-gui.

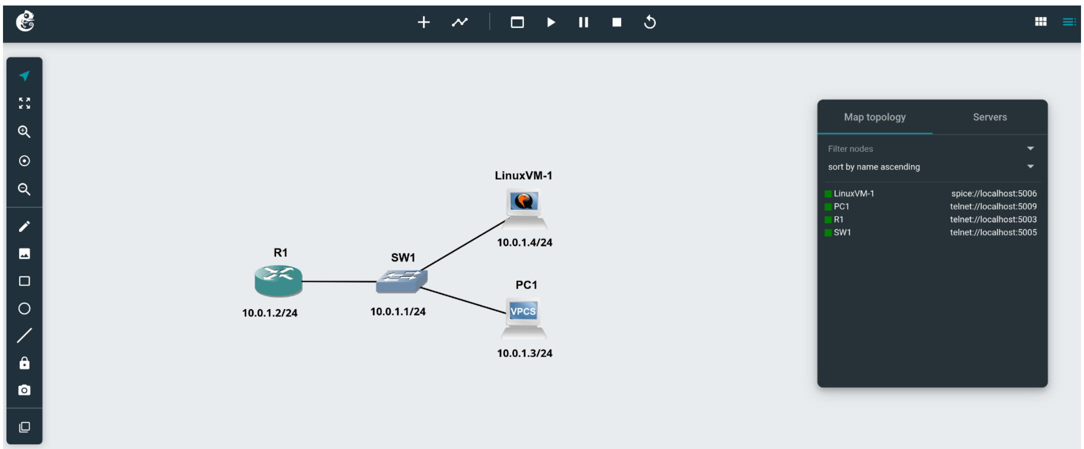


Figure 2.2: A simple network topology example in the GNS3 Web UI

The gns3-web UI, accessible via a browser, serves as the platform where students can complete their assignments, by interacting with the virtualized devices in a pre-configured

GNS3 remote host. This ensures students can focus on doing their assignments without having to set up software on their own or interact with the underlying host VM.

2.3. Proxmox VE

Proxmox VE is an open-source platform designed for enterprise-level virtualization [3]. It is based on the Debian distribution of Linux and provides a web-based interface for managing VMs and containers. It is widely used in data centers and cloud environments, as it provides a scalable and reliable solution for virtualization.

Proxmox VE bundles several core services that can be interacted with via shell commands, a web interface or by using the Proxmox VE REST API. These allow the user to interact with every service provided by Proxmox VE, in a plethora of ways, depending on the user's needs, skills and preferences. The web interface is the most user-friendly way to interact with the platform, as it provides a GUI for managing the cluster. The shell commands provide a more direct way to interact with the platform, allowing for more complex operations to be performed and opening the doors to scripting and automation. Finally, the Proxmox VE REST API allows for programmatic and remote interaction with the platform, enabling users to create custom applications that can interact with the platform.

Proxmox VE will be used to host all the VMs running GNS3 that students will complete their assignments on.

2.3.1 Supported Virtualization Technologies

Proxmox VE supports the the deployment and management of two distinct types of virtualization, namely, Kernel-based Virtual Machine (KVM) and Linux Containers (LXC).

Users can interact with these virtualized environments via NoVNC, a web-based client for Virtual Network Computing (VNC), a graphical desktop-sharing system that transmits keyboard and mouse input from one computer to another and relays the graphical screen updates back over a network. Alternatively, Simple Protocol for Independent Computing Environments (SPICE) may be used — a more advanced remote display protocol offering better performance and enhanced features compared to VNC. Both of these protocols support the use of a console-based interface, as well as a full desktop GUI.

2.3.1.1 KVM

KVM is a virtualization solution provided by the Linux kernel. It leverages the hardware virtualization extensions of modern processors to provide a full virtualization experience at near-native speeds. Supports a wide range of guest operating systems making it a good choice for general purpose virtualization.

In Proxmox VE, KVM is used as the core component for running VMs and is used alongside QEMU.

2.3.1.2 LXC

Containerization is an operating system-level virtualization method that packages an application and its dependencies together into an isolated environment. Contrary to traditional VM solutions, containers dont emulate hardware or require a guest operating system relying instead on the host's kernel. This approach leads to a faster and more lightweight virtualization solution, as they consume less memory and Central Processing Unit (CPU) resources.

LXC creates full system containers, capable of simulating a complete Linux distribution providing users with an environment that behaves like a traditional VM but with the speed and efficiency of a container. LXC start much faster than VMs making them ideal for scenarios requiring rapid deployment and/or scaling.

However, it's important to note that while containers offer a degree of isolation, they do not provide the same level of security as VMs. They also dont support all features that VMs do, which will be discussed more in-depth in Chapter 4. This means that they may not always be a suitable replacement for VMs.

2.4. Authentication with LDAP

Lightweight Directory Access Protocol (LDAP) is the foundation of user and device management in many institutions and enterprise environments. In universities, it is common for LDAP directories to be used for authentication. LDAP can be to used to provide access control for students, faculty, and staff across a wide range of services from logging into campus computers to accessing library resources or online learning platforms. In DCC, LDAP is used to authenticate labs' users.

One of LDAP's most popular implementations, OpenLDAP, had its initial release in 1998. The protocol's longevity stems from its efficiency at handling large-scale authentication so much so that despite newer alternatives existing, LDAP remains in academic environments due to its reliability. For our project, LDAP integration enables students access to the system using their existing university credentials. This avoids the need to create and manage a separate set of usernames and passwords for the system, which not only reduces administrative overhead but also aligns with standard institutional practices. Furthermore, group-based permissions can be derived directly from the directory, streamlining role-based access control.

Two key factors make LDAP particularly valuable for this project: its standardized approach to user management and pre-existing deployment in our target educational environments. Given the extensive use, it's desirable for our system to have the capability to interact with LDAP in order to correctly authenticate users.

However, it is also important to ensure that our system remains flexible and accessible in a wider range of contexts. Not all institutions have an LDAP deployment, or may have a preference for alternative identity providers. For this reason, LDAP support in the system is designed as an optional integration. When enabled, it provides direct authentication against an existing LDAP server; when disabled, the system falls back to local user management.

When LDAP based authentication is desired, the proper authentication realms must be configured in the Proxmox VE cluster. This has multiple benefits, such as not overbearing the yet to be introduced web application component of the project with functionalities and responsibilities, as well as providing a better logging experience, as it will be possible to see who interacted with the cluster and what was done, providing accountability.

2.5. Python Web Frameworks for API-Based Systems

Python is a high-level, interpreted programming language renowned for its readability and versatility. It supports multiple programming paradigms, including procedural, object-oriented, and functional programming, making it suitable for a wide array of applications. In the context of this project, Python serves as the primary programming language, as its extensive standard library and supportive community contribute to efficient development and maintenance of the project's codebase. In the case of building Python web APIs there are 2 big standards in active use today, Web Server Gateway Interface (WSGI) and Asynchronous Server Gateway Interface (ASGI).

2.5.1 WSGI

The WSGI is a standard for Python web application deployment, defining a consistent interface between web servers and Python web applications/frameworks.

Prior to WSGI's introduction [4], Python web frameworks were typically written against various server-specific APIs such as CGI, FastCGI, or mod_python. This diversity led to compatibility issues, limiting developers' choices of web servers and frameworks, as not all frameworks supported all web servers and vice-versa. To address this fragmentation, WSGI was created as a standardized interface, promoting portability and flexibility in deploying Python web applications.

WSGI serves as a bridge, as can be seen in Figure 2.3, enabling web servers to communicate with Python applications. It specifies a simple and universal interface for web servers to forward requests to Python applications and for those applications to return responses. This standardization allows developers to choose from a variety of web servers and Python frameworks without compatibility concerns.

Introduced in 2003 as PEP 333, WSGI was later updated to PEP 3333 in 2010 to accommodate Python 3. These specifications outline how web servers and Python applications should interact, ensuring a consistent and reliable deployment environment across different platforms.

The WSGI standard consists of two main components:

- **Server/Gateway Side** - Responsible for receiving HTTP requests from clients and passing them to the Python application. Then receives the response from the application and forwards it to the client.
- **Application** - A Python callable (usually a function or class) that follows the WSGI specification. It receives request data from the server, processes it, and returns a response in a specific format that the server can forward to the client.

Additionally WSGI has support for middleware components. WSGI middleware is a Python callable that wraps another WSGI application to observe or modify its behavior. Middleware can perform various functions, including request preprocessing, response

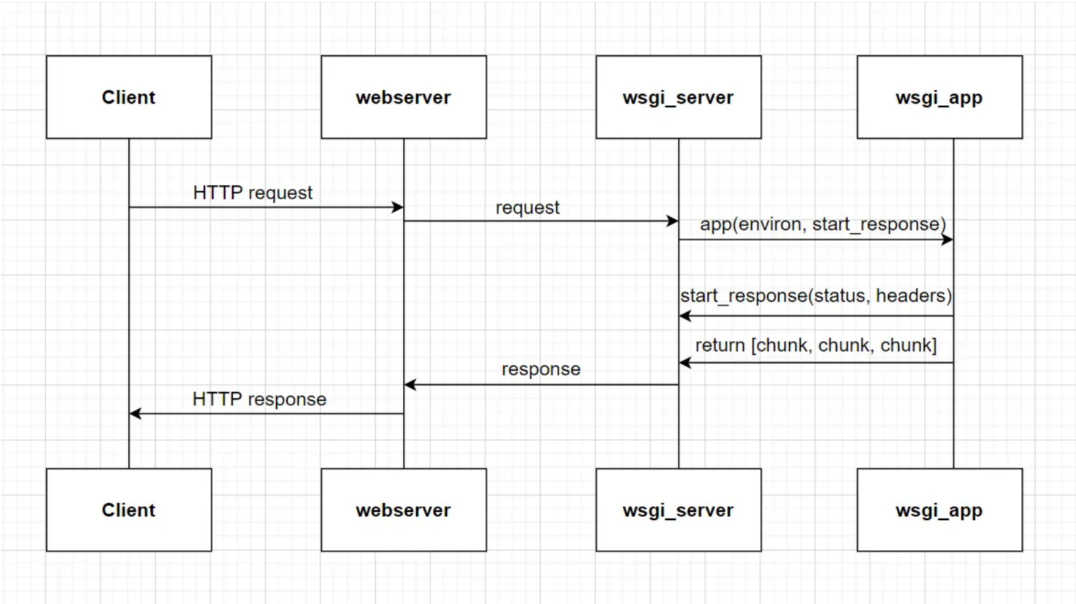


Figure 2.3: A figure showcasing the deployment of a WSGI application. Illustration by Reena Kamra

postprocessing, session management, and security checks. This modularity allows developers to add functionality to their applications in a reusable and maintainable manner.

The separation defined by WSGI allows for flexibility and scalability in deploying Python web applications.

Python WSGI applications often use built-in servers, during development, provided by frameworks like Flask. However, these servers typically aren't fully featured and aren't suitable for production environments, as they are optimized for running Python code instead of other tasks typical of web servers, such as serving static assets. In production, WSGI servers act as intermediaries between web servers (e.g. NGINX or Apache) and Python applications, handling incoming requests and serving responses efficiently.

2.5.1.1 Flask

Flask is a web application micro framework written in Python, and the most popular one adhering to the WSGI standard, designed to facilitate the development of web applications by providing essential tools and features. Classified as a microframework, Flask does not require particular tools or libraries, instead choosing to focus on simplicity and extensibility [5].

An example of how easy it is to develop a basic web application with flask is provided in Sample Code 1.

Sample code 1 Flask Hello World

```
from flask import Flask
app = Flask(__name__)

@app.route('/')
def hello_world():
    return 'Hello, World!'

if __name__ == '__main__':
    app.run()
```

2.5.1.2 Requests

Requests [6] is a popular and user-friendly HTTP library for Python, used to send HTTP requests to web services. It simplifies interactions with APIs by simple to use methods for the various HTTP verbs, as well as providing support for cookies, sessions, authentication, JSON and exception handling for network failures and invalid responses.

Requests was initially used in the project to handle all HTTP requests to the various services, such as GNS3 and Proxmox VE. Its simplicity and ease of use made it a natural choice for the initial implementation, allowing for quick development and testing of the various endpoints. An example of a GET request and subsequent processing can be seen in Sample Code 2.

Sample code 2 Making a Synchronous HTTP Request Using Requests

```
import requests

url = "https://api.example.com/data"
response = requests.get(url)

if response.status_code == 200:
    data = response.json()
    print(data)
else:
    print("Request failed with status code", response.status_code)
```

However, as the project evolved and the need for alternative non-blocking I/0 became more apparent, with Requests being a synchronous blocking library only, there was a need to transition to an alternative that supported different programming paradigms.

2.5.2 Long running task processing approaches

Modern API-driven applications may benefit from programming paradigms made to handle concurrent operations efficiently. Traditional synchronous execution models, where each request blocks thread execution until completion, prove inadequate for systems requiring high throughput and responsiveness. This limitation becomes particularly apparent in projects like ours, which relies heavily on HTTP calls to various devices and services.

2.5.2.1 Celery

Celery is an open source distributed task queue focused on real-time processing but also offers support for task scheduling. It is implemented in Python, but the underlying protocol can be implemented in any language. It requires a message broker to function, such as Redis or RabbitMQ, which are responsible for queuing and distributing tasks from producers (clients) to consumers (workers). Celery's workers are processes that can be distributed among different machines

When integrating Celery into their projects developers must mark functions they want to be processed as tasks with Celery provided decorators (e.g. `@app.task`) which allows workers to then execute them. The system shines in projects requiring heavy computational or scheduled jobs, but brings with it non-negligible operational, developmental and resouce overhead, doubly so if the project didn't already include the use of message brokers.

2.5.2.2 Asyncio

`asyncio` is Python's built-in library for writing concurrent asynchronous code. It serves as the foundation for asynchronous operations in many Python frameworks, enabling high-performance networking, web servers, database connections, distributed task queues, etc.

The asynchronous model, implemented through Python's `async`/`await` syntax, offers several critical advantages:

- **Improved Resource Utilization**: A single thread can manage multiple concurrent I/O operations by yielding control during waiting periods.
- **Enhanced Scalability**: Systems can handle higher concurrent user counts with the same hardware resources.
- **Responsive Performance**: The application remains reactive even during long-running operations.

Asynchronous I/O can be useful in cases of time-consuming operations, as while awaiting the finish of said tasks, it relinquishes control so that other code can run in the meantime. This approach is particularly well-suited for I/O-bound operations, such as network communication, file access, or database queries, where tasks would otherwise spend a significant amount of time waiting for external operations that are outside of our control to complete. Rather than blocking the entire application during such waits, `asyncio` allows other tasks to execute in the meantime, leading to more efficient resource utilization and improved throughput.

Overall, `asyncio` provides the concurrency model that underpins efficient I/O performance. By embracing this model, the project benefits from improved responsiveness, lower latency, and better scalability, during workloads that involve heavy interaction with services external to the web application, such as Proxmox VE.

Although Python has native asynchronous capabilities, libraries must be written with these in mind, meaning some may have limited or even no support for these capabilities.

Frameworks that leverage these capabilities natively, provide the foundation for building responsive, scalable API services.

2.5.3 ASGI

ASGI is an interface specification for Python web servers and applications. It is considered a spiritual successor to WSGI, designed to provide a standard interface for asynchronous communication. ASGI was developed to address the limitations of WSGI, which was primarily designed for synchronous applications. Unlike WSGI, ASGI supports handling multiple requests concurrently, making it suitable for modern web applications that require real-time features such as WebSockets, long-lived connections, background tasks or the use of Python's async features.

As development progressed, asynchronous task handling became a more central requirement, initially addressed by integrating task queues. However, due to resource overhead and deployment complexity, they were phased out. This shift prompted an evaluation of frameworks that offered native support for asynchronous operations.

2.5.3.1 FastAPI

FastAPI is a modern, high-performance web framework adopting the ASGI standard. It leverages open standards, such as OpenAPI Specification (OAS), for defining path operations, parameters, and more, which in turn is based on the JSON schema. FastAPI relies entirely on Python type declarations, making it more intuitive and lowering the barrier to entry to new developers. This approach also simplifies the understanding and maintenance of the codebase.

Built on top of Starlette, a lightweight ASGI framework, and Pydantic, a data validation library, FastAPI combines the strengths of both to provide a powerful and flexible framework for building APIs with automatic data validation, serialization and documentation generation, all of which significantly enhance developer productivity.

Another key feature of FastAPI, being ASGI-compliant, is its built-in support for asynchronous programming, allowing developers to write non-blocking code using Python's `async/await` keywords. This is particularly useful for I/O-bound operations, such as database queries or network requests, as it allows the application to handle multiple requests concurrently without blocking the application. This is essential in projects such as this one where multiple concurrent HTTP calls are made to interact with multiple devices and services concurrently, such as GNS3 and Proxmox VE.

Another powerful feature of FastAPI is its dependency injection system, that is very easy to use as it is automatically handled by the framework itself. This allows for a clean and modular codebase, as dependencies that need to be reused often (e.g. have a need for shared logic repeatedly or sharing database connections) can be easily injected into the various components of the application reducing code repetition. This is especially useful in larger applications, where managing such dependencies can become complex and cumbersome.

A change from Flask to FastAPI laid the groundwork for more efficient handling of I/O-bound operations—such as network interactions with Proxmox VE or GNS3, which will be of importance in future iterations of the project while also streamlining development thanks to FastAPI's built-in request parsing, background task support, and integrated dependency injection system.

2.5.3.2 HTTPX

HTTPX [7] is a modern HTTP client library for Python. HTTPX retains a similar structure to Requests, while providing built-in support for asyncio.

In contrast to Requests, which blocks the current thread while waiting for a response, HTTPX enables non-blocking HTTP communication when used in asynchronous mode. This is particularly beneficial in scenarios involving multiple concurrent network operations, such as querying multiple GNS3 devices or cloning VMs in Proxmox VE, where synchronous requests would otherwise serialize execution and lead to performance bottlenecks.

An example of a basic asynchronous GET request with HTTPX is provided in Sample Code 3.

Sample code 3 Making an Asynchronous HTTP Request Using HTTPX

```
import httpx
import asyncio

async def fetch():
    url = ”https://api.example.com/data”
    async with httpx.AsyncClient() as client:
        response = await client.get(url)
        if response.status_code == 200:
            data = response.json()
            print(data)
        else:
            print(”Request failed with status code”, response.status_code)

asyncio.run(fetch())
```

HTTPX was adopted in the project to replace Requests for both asynchronous and synchronous use cases. Thanks to its full support for `async` and `await`, HTTPX integrates seamlessly into the FastAPI application, allowing concurrent HTTP requests to be awaited collectively using constructs like `asyncio.gather()`. This significantly improved the application's throughput under concurrent workloads.

Overall, HTTPX provides a robust and flexible foundation for asynchronous networking in Python, making it an ideal fit for the needs of this project.

Using these technologies, a web application will be built to offer a solution where students can interact with the system as a whole.

2.6. System administration automation tools

Modern system administration increasingly relies on automation tools to manage complex infrastructure while maintaining reliability and reproducibility. In our context, these tools serve as the foundational layer for ensuring well-configured device states across network environments.

2.6.1 Ansible

Ansible is a widely adopted open-source automation platform that simplifies configuration management, application deployment, and task automation through a declarative YAML Ain't Markup Language (YAML)-based approach. YAML is a human-readable data serialization format commonly used for configuration files due to its simplicity and clarity. Unlike imperative scripting solutions, Ansible employs playbooks to define system states, making automation accessible to both developers and operations teams while maintaining robust capabilities for complex workflows.

The platform operates on an agentless architecture, utilizing Secure Shell (SSH) for connectivity, which eliminates the need for persistent software on managed nodes. This design choice significantly reduces deployment overhead while maintaining secure communication through standard protocols. Ansible's push-based execution model allows for immediate task execution across entire device inventories without requiring pre-installed clients.

Ansible remains a valuable tool in task automation and orchestration but, as was already discussed in [1] there are several barriers to the adoption of Ansible in this project, mainly the difficulties encountered by utilizing the Telnet protocol for communications with network devices that dont support the SSH protocol .

Ansible remains a valuable tool for task automation and orchestration. However, as discussed in [1], its adoption in this project is limited due to challenges in communicating with network devices that only support the Telnet protocol as it is not well-supported by Ansible's core modules.

2.6.2 Nornir

Nornir is an open-source automation framework written in Python, designed to provide a flexible and efficient approach to network automation tasks [8]. Unlike other automation tools that utilize customized pseudo-languages, Nornir leverages pure Python code, offering developers the full power and versatility of the Python ecosystem.

Nornir supports multi-threaded task execution, allowing operations to run parallel across multiple devices. This capability enhances efficiency and reduces the time required enabling easy scaling to a large number of devices.

The framework provides a robust inventory management system, enabling the organization of devices into groups and the assignment of specific tasks to these groups. This structure facilitates targeted automation and simplifies complex network operations.

Finally, thanks to Nornir's architecture, it is highly extensible through its plugin system, allowing users to create custom plugins for inventory management, task execution, and result processing. This modularity ensures that Nornir can adapt to a wide range of network automation scenarios. Similarly to Ansible, Nornir also employs an agentless architecture.

Nornir makes it easy to write reusable tasks for configuration management and state validation which makes it highly desirable in the context of this project. Its ability to handle concurrent operations will also ensure it can scale alongside the rest of the project.

Nornir will be used as the main tool to interact with the virtualized devices in students' assignments in order to run commands on them and retrieve the respective output for analysis.

3. Related Work

This chapter focuses on placing our project within the context of existing solutions and related work. The primary goal of this project is to develop a system capable of automatically assessing network topologies by validating device configurations and executing tests across a virtual network.

While automated assessment systems are well established in the field of programming education, receiving student-submitted code and running it against predefined test cases, equivalent systems for network exercises are far less common. Tools like Mooshak [9] and similar platforms have proven effective for evaluating programming assignments and are widely adopted in academic settings.

At first glance, adapting automated assessment approaches to network topologies may seem straightforward. However, network assessment introduces a set of challenges like validating the configuration of multiple devices in a distributed and stateful environment. These devices may differ in type, vendor, or firmware version, requiring tailored communication methods and output validation strategies for each case.

This chapter explores existing tools, in particular, Mooshak and Packet Tracer, highlighting their capabilities, limitations, and how our project builds upon or diverges from them.

3.1. Automated Assessment Systems

While not directly related, programming assessment systems are the main inspiration for this project. They are widely deployed in universities and other educational institutions. These systems receive, as input, code from students and subsequently run tests on it, outputting a score and even being configurable to provide students the first test case that they failed in, guiding students to the solution without handing it out.

A key differentiator of the proposed system is its support for multiple valid configurations across several devices to achieve a correct solution to a network exercise. In contrast, many existing automated assessment systems, particularly those used in programming, assume a single expected output for a given input, which does not accommodate the variability and flexibility often found in networking scenarios.

One key difference is that automated assessment systems dont always provide a working environment for the students to test their code, owing to the fact that students might prefer to user their own development environment for initial development and testing. However setting up a networking lab can be a daunting task for students, especially when they are just starting out. By providing a pre-configured environment, students can focus on learning the concepts and skills they need to succeed in their studies, rather than spending time troubleshooting their setup. Another key difference is that automated assessment systems dont have to interact with distributed systems or deal with matters of concurrency as is the case in a network administration assignment, as to validate it, it will be necessary to interact with multiple devices, even if they are virtually hosted on the same physical machine.

3.1.1 Mooshak and lessons learned

In our context, in the DCC, Mooshak is commonly deployed to be used in the context of classes, exams and even programming contests.

Mooshak is a web-based system for managing programming contests and also to act as an automatic judge of programming contests [9]. It supports a variety of programming languages like Java, C, etc. Under each contest, students will find one more problem definitions each containing varying sets of test cases in input-output pairs. After submiting their solution, the system will compile and run the code against an instructor-provided solution and compare the outputs obtained for the same inputs giving a score based on the the amount of test cases passed.

Mooshak provides a structured approach to test coding and problem solving skills. It begins by offering a problem statement coupled with an optional image and an example test case, in the form of input and expected output, as can be seen in Figure 3.1

Users can submit their proposed solution by uploading a file with their code. The system then evaluates the provided solution against multiple pre-defined test cases, validating the output of the submitted code against the output of a known-good code solution, giving feedback in the form of a score based on the number of test cases passed. The system may also be configured to have time and/or memory constraints, to ensure that temporal and spatial complexity are also taken into account.

All of these, serve to provide a thorough evaluation of the student’s solution, which can help guide a student to better their coding and problem solving skills.

Figure 3.1: A screenshot of a mooshak exercise page

The system can also differentiate between differing types of errors, such as not giving the expected output, poorly formatted output, failure to compile or even exceeding the time limits. Mooshak also includes some features designed to drive competition between students, like a real time leaderboard and the ability to have more than 100% of the score for a given contest.

However, the system has limitations. It relies on plain text files for test cases and performs character-by-character output comparison. This strict matching can result in false negatives when a student's output is functionally correct but formatted differently than expected.

3.2. Cisco Packet Tracer

Cisco Packet Tracer is a network **simulation** tool developed by Cisco Systems, widely used in academic environments to teach networking concepts and prepare students for certifications such as the Cisco Certified Network Associate (CCNA). It offers a visual interface, seen in Figure 3.2, for building and simulating virtual network topologies using a variety of Cisco devices, including routers, switches, and end devices.

Packet Tracer includes an ”Activity Wizard”. This feature allows for the creation of assignments with automated assessment. To use this, two topologies must be provided, namely a starting network, used as a starting point, and an answer network, containing

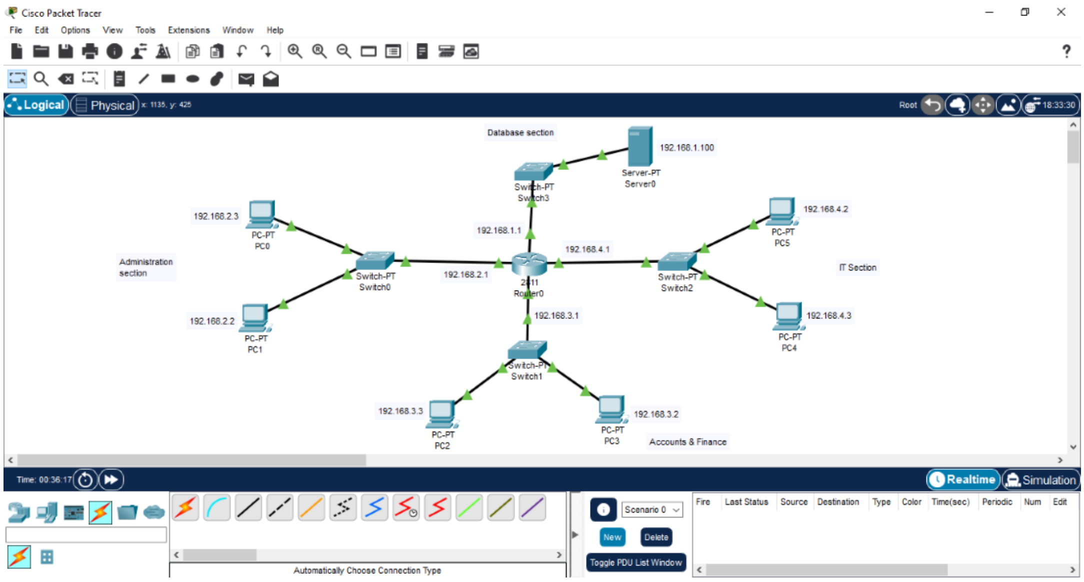


Figure 3.2: A screenshot of a Packet Tracer exercise

the intended configurations. From this a list of all the settings applied to the answer network can be toggled for validation and a custom amount of points can be assigned to each validation, as can be seen in Figure 3.3.

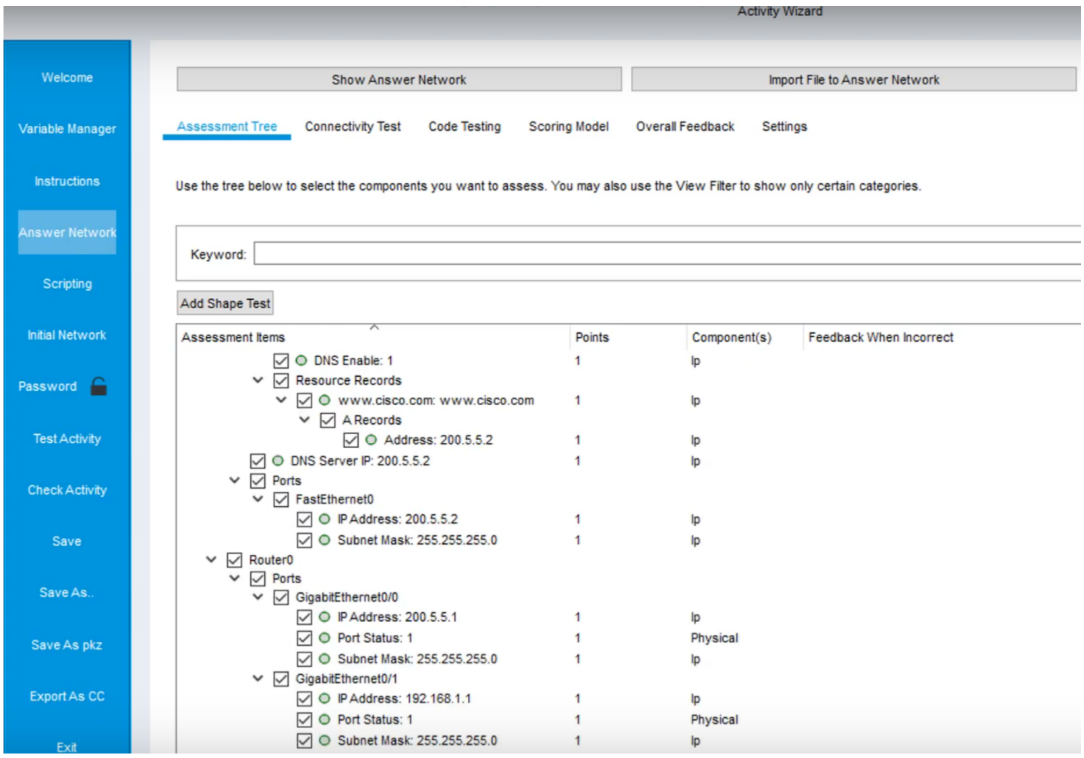


Figure 3.3: A screenshot of a Packet Tracer's Activity Wizard

Apart from the settings validation, it also provides the ability to perform connectivity tests between devices by sending a simple message between them.

Additionally, through the Activity Wizard, instructions can be included via HTML or a rich text editor which students can then use as a guide. After configuration is finished a file will be obtained. This file can then be used by students to obtain the starting network, the necessary instructions and real-time scoring, as points will be added when each of the correct settings are inserted.

Packet Tracer also offers a separate interface for applying configurations or services on devices, allowing students to completely skip the devices' native interface seen in Figure 3.4.

This feature can be seen as valuable in very early stages of teaching, but quickly becomes counter-productive as students should grow accustomed to navigating the devices' native interfaces to properly configure them, better preparing them for professional environments.

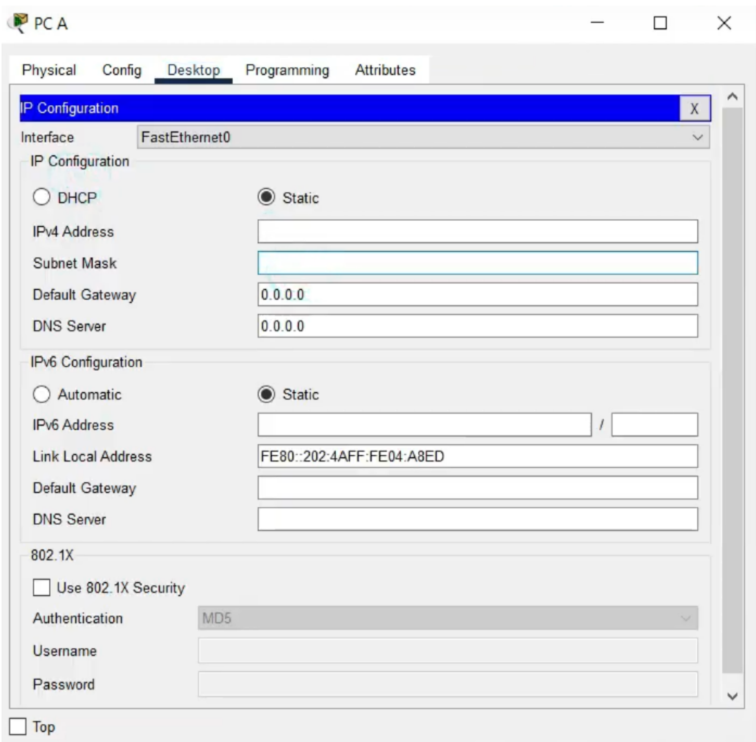


Figure 3.4: A screenshot of a Packet Tracer's configuration

While Packet Tracer is highly accessible and effective for introducing basic networking concepts, it is a closed-source, proprietary tool designed primarily for Cisco hardware simulation. Its feature set is tailored for entry-level instruction and lacks the extensibility, platform flexibility, and integration capabilities required for more advanced or automated assessment workflows. For example, Packet Tracer does not support running custom operating system images or integrating external automation tools via APIs, which limits its applicability in more complex or open-ended environments.

In contrast, this project aims to allow for a more realistic and extensible lab environment. The use of real operating systems and support of a wide range of vendor platforms for routers and switches, as well as Linux-based VMs is highly desirable.

Therefore, while Cisco Packet Tracer remains a valuable educational tool, the needs of this project called for a more flexible and open architecture.

4. System Architecture & Design

This chapter outlines the architecture of the proposed system, detailing the key components and how they interact to enable evaluation of student-submitted network exercises.

The system is designed to provide each student with a working environment where custom virtual network topologies can be deployed, configured, and tested. To achieve this, the platform integrates several technologies—such as for network emulation, virtualization, and configuration testing—alongside an asynchronous web-based API layer for user interaction and system communications.

The chapter begins by introducing the architectural building blocks of the platform, including the rationale behind selecting core technologies such as Proxmox VE and GNS3. It examines the trade-offs of using virtualization, the limitations of Proxmox VE, and resource usage considerations such as the potential role of containers. The VM lifecycle is described to illustrate how environments are provisioned, managed, and recycled in a scalable manner.

Next, the chapter presents a high-level architectural breakdown, identifying major components such as the user interface, back-end logic, virtualization infrastructure, evaluation pipeline, and persistent storage. Each component is analyzed for its responsibilities and how it contributes to overall system performance, reliability, and modularity.

Finally, the chapter presents a functional overview of the system by defining the key actors and use cases that drive interaction. From authentication and exercise creation to VM interaction and automatic solution validation, these use cases form the operational backbone of the platform and validate the system design against its original requirements.

Together, these sections provide a detailed, layered understanding of the system's structure and the trade-offs made during development.

Note: While it is common to present system architectures in a generic and technology-agnostic manner, this chapter deliberately includes specific details about Proxmox VE and GNS3. This is justified by the fact that the project follows on the work by Santos [1] who already carried out research into what could potentially be used to build this system. This directly shaped design decisions and so, discussing these elements explicitly allows for a more accurate and useful description of the system as implemented.

4.1. System Architecture Overview

The architecture is divided into several key components, seen in Figure 4.1, each responsible for a specific aspect of the system's functionality. The main components of the system architecture are as follows:

- **Web Application:** The web application serves as the main interface for users to interact with the system. In the context of this component two types of users exist, students and teachers, with the latter having access to more features than the former. This component provides endpoints for, amongst others, evaluation, creation and viewing available exercises. It is designed to be asynchronous where possible, allowing for efficient handling of multiple requests simultaneously. This is important for our system as it can be expected to have multiple interactions students simultaneously, all working on their own assignments and interacting with the web application.

- **Proxmox VE:** Responsible for creating and managing VMs that host the network devices used in the exercises. This component interacts with the web application and all communication is done asynchronously through its REST API, which allows for efficient communication, keeping the web application responsive, while also keeping the components decoupled.

- **GNS3:** Used to emulate all the components of the virtual networks to be configured by students, using various types of virtualization detailed earlier. Communication with GNS3 is done asynchronously through the GNS3 REST API by the web application.

- **Nornir:** This automation framework is used for validating device configurations. It connects to the virtualized devices, executes commands, and compares the output to expected results to determine correctness. Currently, this component is integrated into the web application.

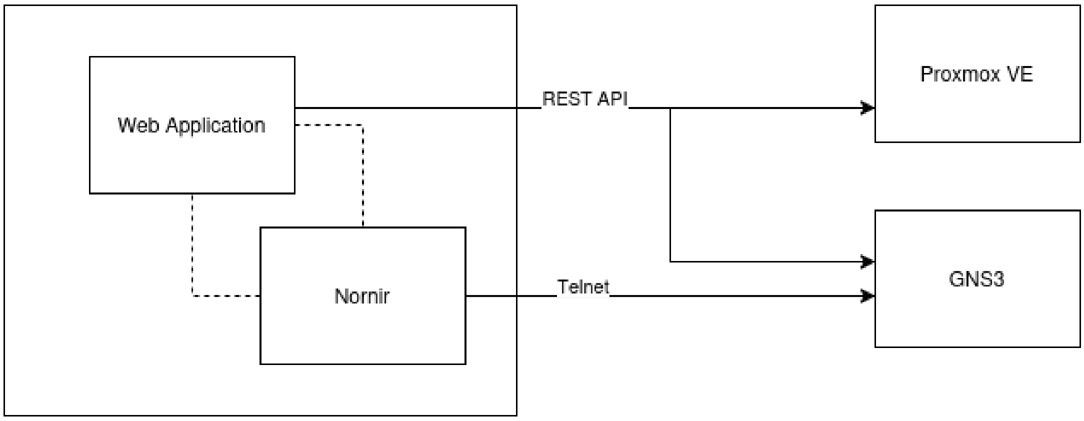


Figure 4.1: A diagram showcasing how components interact with each other on a high level

4.2. Proxmox VE

Proxmox VE functions as the virtualization backbone of the system, enabling the creation and management of VMs which in turn host services for use by students. Each students' VM runs a headless Linux-based operating system, meaning it operates without a GUI, serving as a host to an instance of the GNS3 server. This setup provides a self-contained environment in which students can deploy and configure virtual network topologies using virtual devices. The environment is meant to be used by only a specific students, ensuring that each student can work independently without affecting others.

All Proxmox VE-related operations, such as cloning, starting, templating, and deletion, are fully automated and triggered by the web application. Under normal operating conditions, no manual intervention via the Proxmox VE web interface or shell utilities is required once the initial setup is complete. Such intervention should only be necessary when the system's error handling mechanisms aren't capable of automatically resolving errors. To securely execute these operations, the application authenticates to the Proxmox VE API using token-based authentication, ensuring that only authorized and properly configured processes can interact with the Proxmox VE infrastructure.

For future expansion, the system can be deployed on a machine with a higher core count and larger memory capacity to support more users. Additionally, it can be expanded horizontally by adding more physical nodes to the VM cluster. In this context, horizontal expansion refers to scaling the system by distributing workloads, specifically student VMs, across multiple servers within the cluster, thereby increasing the total available compute resources.

However, implementing this form of scalability will require enhancements to the current orchestration logic. Since Proxmox VE does not provide automatic load balancing of VMs, the system must be extended to include custom mechanisms for monitoring resource usage across nodes and intelligently placing new VMs on less-loaded hosts to optimize performance and ensure fair resource distribution.

4.2.1 Why Proxmox VE?

Proxmox VE was chosen for several compelling reasons that make it ideal for it to be choosen as our virtualization platform. First, it's completely free to use for all core functionality, with no hidden costs or licensing traps. Unlike proprietary solutions that charge per CPU core or socket, Proxmox VE lets us scale up our infrastructure without worrying about licensing fees.

The platform's support for both containers and VMs within a single management interface gives us tremendous flexibility. We can run lightweight LXC for applications that dont require a full VM while using full VMs where required seamlessly. This hybrid approach would not be as straightforward with other solutions, like VMware ESXi.

We also value storage system's flexibility with LVM-thin provisioning allows efficient snapshotting of student environments while maintaining good performance.

Looking ahead, Proxmox VE's built-in support for technologies like software-defined networking and a robust role-based access control system means our project still has room to grow into Proxmox VE. The active open-source development community ensures continuous improvements without vendor lock-in.

4.2.2 Proxmox VE Limitations

During development, we encountered some challenges when interfacing programmatically with Proxmox VE.

One of the most significant limitations encountered was the lack of visibility into long-running operations on the platform, particularly during tasks such as VM cloning, where the Proxmox API did not return task IDs in the HTTP responses. As a result, custom polling mechanisms had to be implemented to monitor and determine the completion status of these operations reliably. This limitation introduced delays and added complexity to the automation logic, as operations could not be tracked directly through standard API responses and had to be inferred through periodic status checks.

A more critical limitation emerged in Proxmox VE REST API's resilience characteristics. During stress testing, we discovered that even moderate request volumes done using a single machine running sequential code could overwhelm the single-node cluster's management daemon, triggering frequent HTTP 500 errors. These reliability constraints necessitated the development of protective measures to ensure stable interaction with Proxmox VE. Specifically, an exponential backoff retry mechanism was implemented, where failed API requests are retried after progressively longer wait times (e.g., 1s, 2s, 4s, 8s), reducing the risk of overwhelming the server during transient failures. Additionally, the web application enforces strict limits on concurrent requests sent to Proxmox, preventing spikes in API traffic that could degrade performance or cause timeouts

One final limitation discovered during performance testing was that, on occasion, some VM disks would fail to be removed. This issue could not be detected through HTTP responses alone and was only observable by inspecting the Proxmox VE logs. As more disks failed to be removed, they accumulated as unused entries in storage, eventually leading to a noticeable performance degradation. This specific limitation will be discussed in more detail in Chapter 6.

4.2.3 Proxmox VE Firewall

Proxmox VE comes bundled with an iptables-based firewall implementation that can be enabled and configured at different levels.

The Proxmox VE host-level firewall plays a crucial role in preserving the integrity of examinations by restricting student VMs and the virtual devices within them from accessing external networks. This isolation helps prevent unauthorized communication or access to online resources during assessment periods.

This is done by adding firewall rules at the host level, meaning to each relevant student VM, that disable communications in both directions, with the exception of the machine that is responsible for configuration validation and the machine the student is working from.

By default this behavior is not active and must be enabled on an as-needed basis, such as when a controlled assessment environment is required for more rigorous situations such as examinations.

In future iterations it may also be valuable to develop this further and making this feature less rigid as it may be interesting to have exercises that communicate with devices on the internet, outside of the virtual network environment.

4.2.4 Maximing resource usage

During development, we attempted to minimize resource usage where possible to achieve higher levels of scaling potencial. The introduction of the GNS3 web interface removed the need for students to interact with VMs directly, allowing for operation in a headless manner. This eliminated the need for a desktop environment reducing memory overhead which improved scalability.

4.2.4.1 Exploration of containers as a full substitute for VMs

We considered replacing VMs entirely with containers to reduce resource usage and improve deployment efficiency. However, this approach introduced significant technical and security challenges that prevented its adoption in the current iteration of the platform.

A core requirement for effective network emulation, especially when using QEMU-based devices, is access to KVM acceleration. In containerized environments, this leads to two main challenges. First, unprivileged containers do not have access to KVM, which results in a substantial drop in performance, rendering this setup not ideal for realistic emulation workloads. Second, enabling KVM passthrough within containers typically requires either privileged containers or relaxed security profiles, both of which weaken the isolation guarantees of the container runtime and potentially expose the host system to security risks.

Despite these limitations, container-based deployments remain viable for specific scenarios. Assignments that rely solely on IOU , VPCS and a few others, which do not depend on KVM for performance, can still benefit from containerization, allowing for more efficient resource usage. Moreover, the restricted scope of student access (limited to the virtual network environment rather than the full container) could help mitigate some of the security concerns associated with privileged containers.

Nevertheless, due to limited time for a thorough analysis, such as evaluating the risk of container breakout or privilege escalation, this alternative was not pursued further.

4.2.5 VM Lifecycle

The lifecycle of a VM begins when a new exercise is created by a priviledged user through the web application. Upon exercise creation, the platform automatically clones a pre-configured base template VM stored in Proxmox VE. This new instance undergoes a configuration process where the provided GNS3 project file is imported and a series of user-defined commands are executed across the provided network topology. Once the setup is finalized, the configured VM is converted into a new template VM, one that is tailored to that specific exercise.

When students are enrolled in an exercise, the system generates individual work environments, by creating linked clones from these exercise-specific templates. Each student receives their own VM instance that precisely mirrors the original template's configuration. This cloning approach ensures both consistency across student environments and rapid provisioning, as linked clones avoid the overhead of full disk copies while maintaining the template's baseline configuration. The use of linked clones significantly reduces both storage requirements and deployment time compared to traditional full cloning methods. However, once the base VM is converted into a template, it can no longer be modified. As a result, any changes to the base environment require creating a new template and redeploying all student VMs from scratch.

4.3. GNS3

GNS3 serves as the core network virtualization component in our system, providing the capability to emulate various network devices and topologies. The platform was selected for several key advantages: its remote web-based interaction, the intuitive drag-and-drop interface simplifies usage, and its broad device support accommodates both terminal-based and GUI network equipment and full computers. Additionally, GNS3's API allows for programmatic interaction, which proves essential for automation within our environment.

Currently, the system requires manual preparation of the base GNS3 template VM, used as the basis for all subsequent student VMs. This process begins with creating and configuring a new VM on the virtualization infrastructure. The administrator must then install the GNS3 software along with supported emulators such as QEMU and Dynamips. Additionally, the GNS3 server must be configured to start automatically upon system boot. The final step involves importing all required device images—including routers, switches, and other equipment that will be used in student exercises—directly into the template VM. This template serves as the base image from which all student work environments are deployed.

This base template VM then serves as the source for all subsequent student instances through Proxmox VE's cloning functionality. While this manual setup process adds initial configuration overhead, it ensures complete control over the base environment and allows for careful curation of the included device images.

Showcased in Figure 4.2, we can see how we can scale one physical machine to accommodate multiple users.

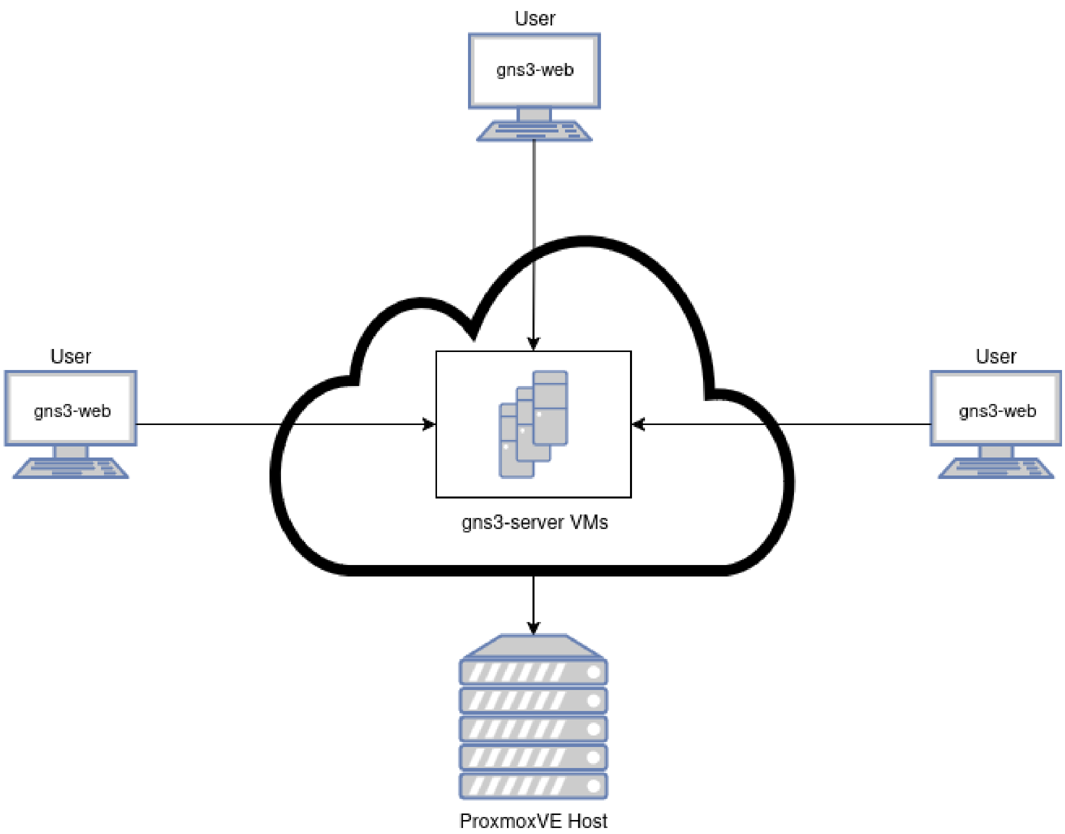


Figure 4.2: A diagram showcasing how one node hosts various students

4.4. High-level architecture

The system architecture is divided into five main components: the user interface component, which provides user access via both server-side rendered pages and the network emulation User Interface (UI); the web application component, responsible for back-end orchestration and API handling; the virtualization components, which manage VMs;

the evaluation component, which validates user configurations through a modular Nornir-based framework; and the storage component, which covers both VM storage and the application database. Together, these elements form a scalable platform for interactive networking exercises.

4.4.1 User Interface Component

This component is comprised by two distinct UIs accessible via standard browsers. For administrative functions and exercise management, users interact with server-side rendered HTML pages delivered by the web application. These handle all developed features, like user authentication, VM interaction etc.

When working on networking exercises, users are redirected to the network emulation interface. This dedicated environment provides direct access to the user's virtual network devices, as required by each exercise scenario. This ensures users experience a cohesive workflow from exercise selection to practical implementation without needing multiple authentication steps.

4.4.2 Web Application Component

The web application serves as the primary interface through which users interact with the system. It follows an asynchronous-first, modular architecture to interact with other system components. Asynchronous I/O is employed to prevent blocking during operations such as API calls to Proxmox VE.

The application exposes a REST API that supports endpoints for user authentication, exercise creation, virtual machine management, and configuration validation. It acts as the coordinator for the entire system, triggering operations in Proxmox VE, GNS3, and Nornir based on user actions.

Internally, the application is designed to be as stateless as possible. Essential information, such as user accounts, defined exercises, and student-to-VM mappings—is persisted in a relational database rather than stored in memory. Configuration parameters such as the cryptographic secret key, the Proxmox VE host IP address, database connection, as well as LDAP-specific realms and distinguished names, are injected through environment variables. This approach ensures that deployment-specific settings are decoupled from the application logic, promoting flexibility, portability, and security.

To ensure maintainability and modularity, interactions with external services like Proxmox VE and GNS3 are isolated in dedicated modules. These serve as abstraction layers between the application logic and third-party APIs, exposing clean, reusable interfaces while hiding low-level implementation details. For example, Proxmox VE-related operations such as VM creation and deletion are handled in separate modules, which themselves interface with lower level implementations as are all GNS3-related tasks. This separation of concerns improves the structure of the codebase and simplifies future maintainability by being more readable.

To help with development and testing, the application automatically generates OpenAPI-compliant documentation, a feature of FastAPI, allowing developers to explore and interact with available endpoints. This self-documenting behavior streamlines integration testing and encourages a more agile development process.

Finally, to safeguard user data and infrastructure control points, the application enforces secure authentication mechanisms using JSON Web Token (JWT) ensuring that only authorized users can trigger actions on shared resources.

4.4.3 Virtualization Components

The system employs a dual virtualization approach using Proxmox VE as the foundational platform. The usage of containers was explored but it was found unsuitable, at this stage, for our main use case of virtualization, GNS3 instances. Even so there remains one valid usage for containers for the project, which is hosting the web application. Nevertheless this component may also be optionally hosted in a separate physical machine.

For network emulation, the system utilizes full KVM-based VMs, each hosting a GNS3 instance. These VMs provide the necessary hardware virtualization support for nested device emulation, particularly crucial for fast virtualization. Finally, the use of linked clones and storage-efficient backing filesystems, allows the system to rapidly provision VMs while minimizing storage usage.

4.4.4 Evaluation component

The system employs a modular evaluation framework built on Nornir to validate configurations across virtualized network devices. At its core, this component utilizes specialized Python classes called ”modules” that encapsulate platform-specific validation logic. Each module is responsible for three key functions: identifying the target device’s platform (such as Cisco IOS, Linux, or VPCS), executing the appropriate validation commands for that platform, and interpreting the command output using regular expressions to determine configuration correctness. As an example, we can look at a case where we would like to verify connectivity between two devices using a `ping` command. One of these devices is a Linux host, while the other is a Cisco IOS device. Before interacting with either, it is essential to determine the appropriate syntax for the commands we intend to run. For instance, in Linux, the `ping` command requires the `-c` argument followed by a number to specify the number of packets to send; otherwise, it will run indefinitely. In contrast, the Cisco `ping` command typically expects only an IP address and terminates on its own. Furthermore, the output format of each device differs significantly. Since we rely on parsing this textual output to extract relevant information, we must account for these differences to ensure correct and consistent interpretation.

The architecture follows an object-oriented design paradigm with a base `CommandModule` class that handles common functionality. This parent class manages the Nornir inventory initialization and provides essential methods like platform detection and command execution. Specific validation logic is delegated to child classes that inherit from `CommandModule`, with each subclass tailored to a particular type of network test or validation scenario. These subclasses implement platform-specific command variants and output interpretation logic, allowing support for a wide range of configuration checks. This architecture can be seen in Figure 4.3. For example, the included `Ping` Module implements platform-specific variants of the `ping` command and corresponding response interpretation methods. This design promotes code reuse while allowing easy extension for new test types, as developers can create additional modules by simply extending the base class and implementing the required platform-specific methods for command input and output validation.

Configuration validation occurs through a multi-stage process. When a test is initiated, the system first identifies the target device's platform through Nornir's inventory system. It then dispatches the appropriate platform-specific command variant, such as the Cisco IOS-style `ping` command for cisco routers versus the Linux `ping -c` syntax for Linux hosts, as was exemplified earlier. The module captures and sanitizes the raw command output, removing terminal control sequences and other artifacts before applying regular expressions to assess the results. For connectivity tests like `ping`, the interpretation logic can be configured to allow some tolerance, such as classifying a `ping` test with 80% success rate as valid.

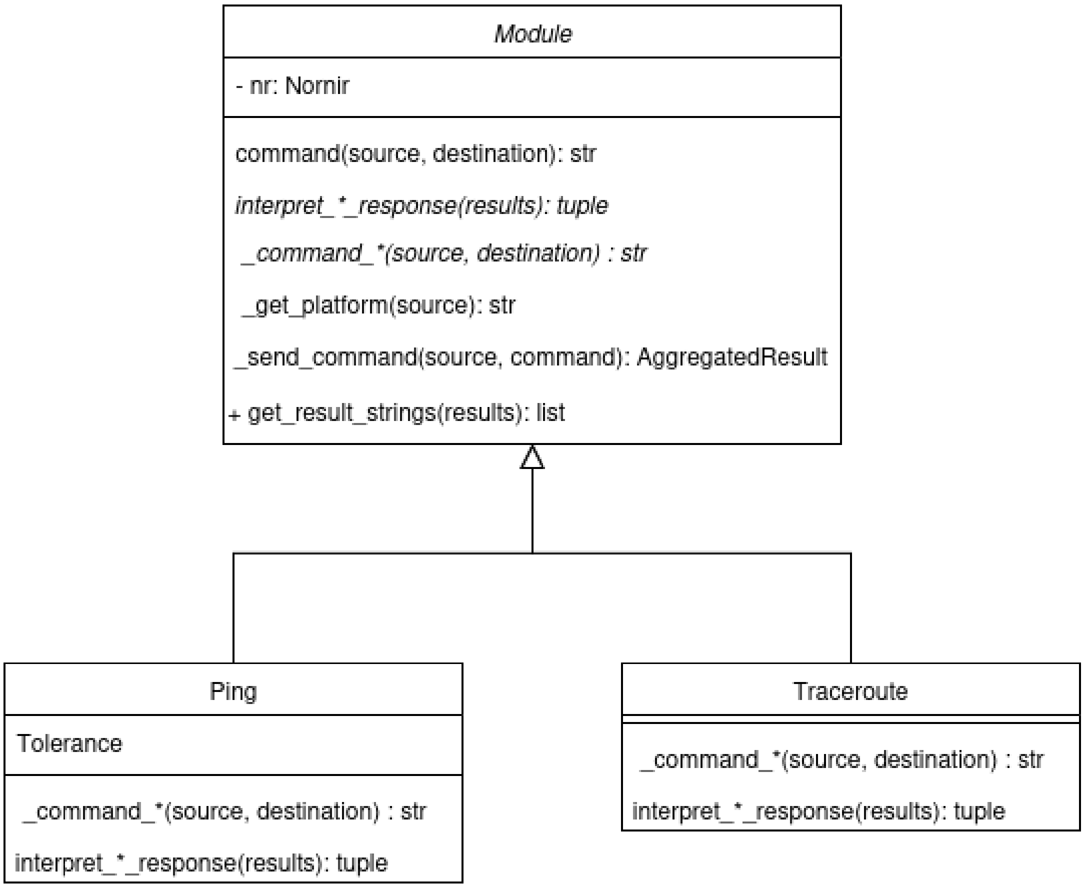


Figure 4.3: A diagram showcasing the module structure

The evaluation framework supports several advanced features to enhance reliability and debugging. Command timeouts are managed to prevent hanging operations, with a default window that can be tuned as needed. Future extensions could incorporate snapshot functionality, allowing the system to capture and compare device states at different points during an exercise, though this capability is not currently implemented in the base version. The modular architecture ensures such enhancements can be added without disrupting existing validation workflows.

Figure 4.4 illustrates how the previously discussed components interact, along with their respective physical locations. The system comprises three distinct physical components: the LDAP instance, the Proxmox VE host, which runs both the web application containers and GNS3 VMs and the users' machines.

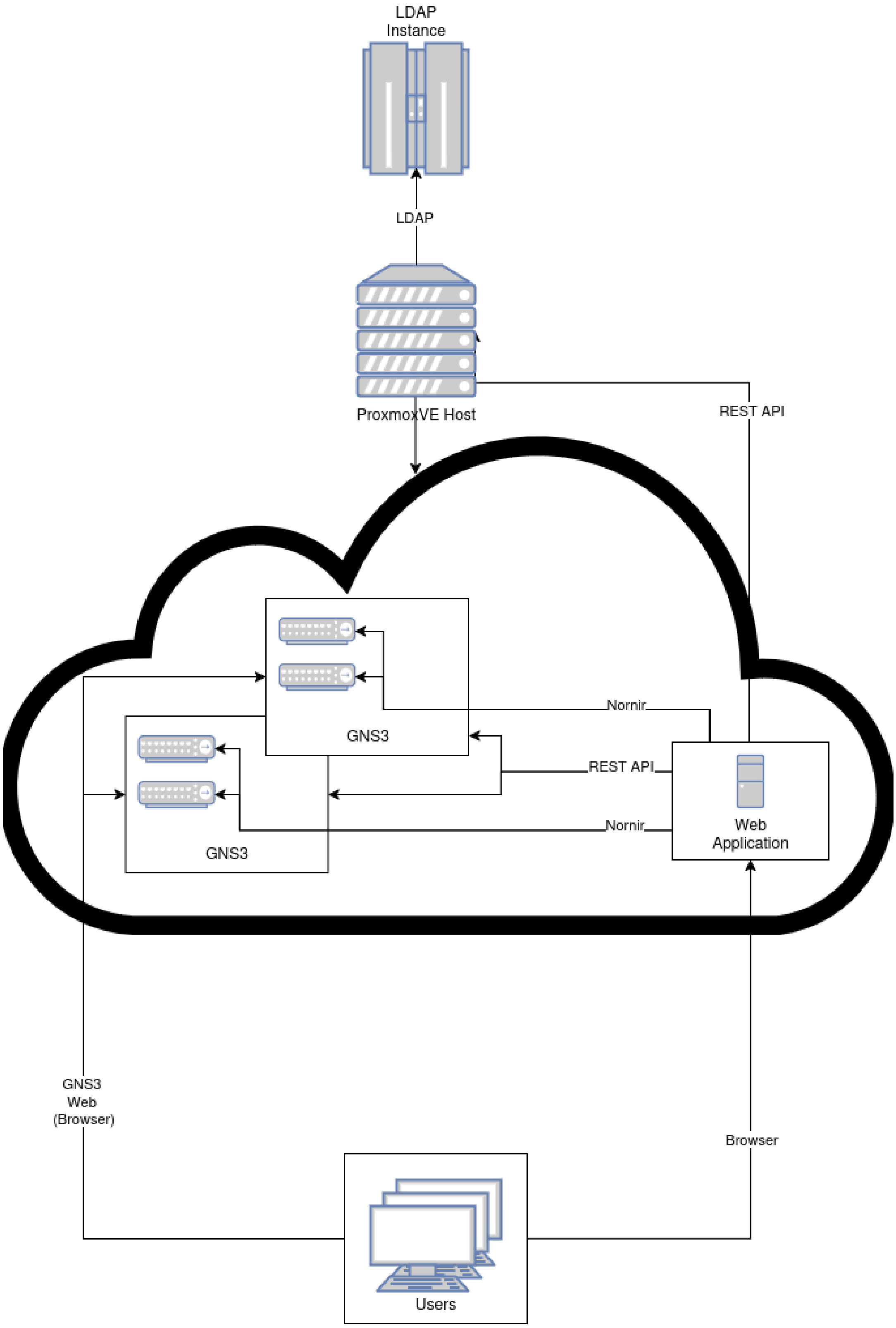


Figure 4.4: A diagram showcasing a high level overview of the system's main components

4.4.5 Virtual machine storage

LVM Thin Provisioning (LVM-Thin) is an efficient solution for creating and managing VMs by optimizing storage usage and improving performance. Unlike traditional Logical Volume Manager (LVM), which pre-allocates disk space, LVM-Thin allows dynamic allocation, meaning storage is consumed only as the VM writes data—ideal for environments like ours where multiple VMs share the same storage pool. When combined with Copy-on-Write (CoW) snapshots, LVM-Thin enables rapid VM cloning and backup operations. For instance, a base VM image can serve as a template, and new VMs are created as linked clones that initially share all data blocks with the original. Only when a VM modifies its disk does LVM-Thin allocate new blocks, significantly reducing storage overhead. This approach not only saves disk space but also speeds up VM deployment, making it a great choice for our project.

Additionally, since snapshots are space-efficient, in the future, we can maintain multiple VM checkpoints without worrying about excessive storage consumption—as long as the thin pool is monitored to avoid overprovisioning. Overprovisioning occurs when the system allocates more virtual storage than the underlying physical storage can support, under the assumption that not all VMs will use their full allocated capacity simultaneously. While this is generally safe with proper monitoring, it can lead to data loss or system instability if actual usage exceeds available physical space.

Overall, LVM-Thin provides a scalable, high-performance storage for virtualization with minimal waste.

4.4.6 Web application database

The database serves as the central repository for all application data and is directly interacted with by the web application.

The database schema, seen in Figure 4.4.6, organizes information across several interrelated models. All model creation builds upon a base `CustomBase` class that automatically tracks creation timestamps, with the `User` model storing authentication credentials, administrative privileges, and relationships to both submissions and VM instances. The `Exercise` model captures lab configuration details, including JSON-serialized validation rules and device configurations stored as text fields due to SQLite's native type limitations. VM provisioning is managed through the `TemplateVm` and `WorkVm` hierarchy, where template instances maintain the base GNS3 project configurations and spawned work environments link back to both users and exercises. The `Submission` model completes the core data structure by tracking student attempts, scores, and evaluation outputs while maintaining referential integrity through SQLModel relationships.

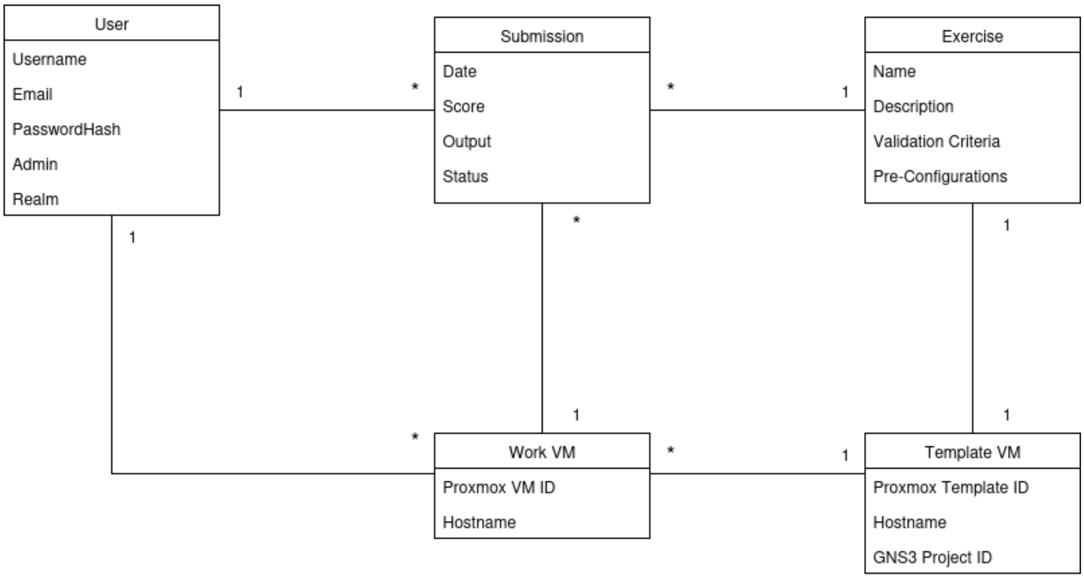


Figure 4.5: A diagram of the database

The schema encodes several cardinal relationships that reflect how the system components interact. Each `User` can have multiple `Submission` and `WorkVm` records, establishing one-to-many relationships in both cases. Similarly, each `Exercise` is linked to a single `TemplateVm` instance (a one-to-one relationship), but can also be associated with many `Submission` records, forming another one-to-many connection. The `TemplateVm` model, while tied to at most one `Exercise`, may serve as the basis for multiple `WorkVm` instances, capturing the concept of student-specific virtual lab environments derived from a common template. The `WorkVm` model itself is tied to exactly one `User` and one `TemplateVm`, but may be associated with multiple `Submission` entries as students can make repeated attempts. Finally, the `Submission` model acts as a junction point that binds a specific user, exercise, and work environment into a coherent record of interaction and evaluation.

4.5. System Functional Overview

This section presents the core functional use cases that define the interactions between users and the system. These use cases were derived from the system's intended objectives and help illustrate how the platform is expected to behave under various scenarios. By breaking down the system into user-centered tasks, we provide understanding of its functional requirements and the responsibilities of each actor. These scenarios not only guide the system's implementation but also serve as a reference point for validating correctness and completeness during testing and future development.

4.5.1 System Actors

The system is primarily used by three types of actors:

- **System Administrator:** Responsible for configuring authentication methods, setting up and managing the system as a whole.
- **Teacher:** A privileged user who creates, manages and enrolls users onto exercises via the web application.
- **Student:** A user enrolled in one or more exercises. Students interact with an assigned VM, work within the network emulation environment, submit solutions, and view assessment feedback generated by the system.

Each of the following use cases is defined in terms of a specific actor and the steps they follow to accomplish a task. Preconditions and postconditions are also described to clearly establish when the use case can be triggered and what outcomes it produces.

4.5.2 Functional Use Cases

The system's functional requirements can be effectively illustrated through a use case diagram, seen in Figure 4.5.2, which provides a high-level representation of the primary interactions between users (actors) and the system. This diagram identifies the main use cases supported by the platform and the specific roles that initiate them.

By capturing these interactions visually, the use case diagram helps clarify the system's intended behavior and supports the overall understanding of how user-driven workflows are handled. It also serves as a foundational artifact to guide the subsequent specification and implementation of each use case in detail.

Additionally, this section outlines the key functional use cases that the system must support to fulfill its intended requirements. Functional use cases describe the interactions between the users (actors) and the system, detailing the expected behavior and workflow for each core functionality. These use cases serve as a foundation for understanding the system's design and implementation, as well as assess if it complies with system requirements.

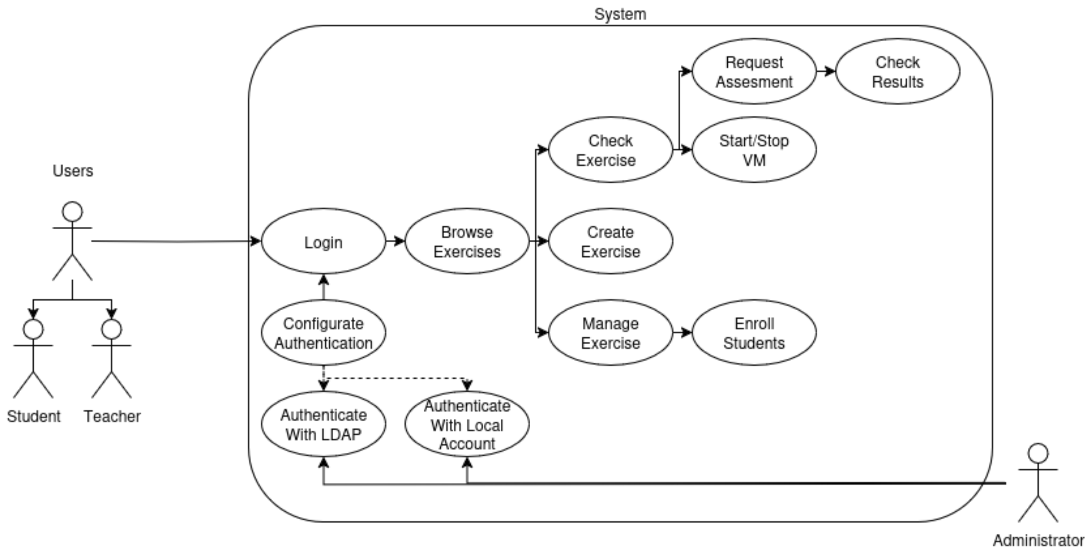


Figure 4.6: A diagram of the database

4.5.2.1 System Supports Both Directory Integration and Local Authentication

Actor: System Administrator

Main Flow:

1. The administrator configures the authentication method.
2. If directory integration is enabled, LDAP or similar service becomes responsible for credential validation.
3. If local authentication is selected, user credentials are stored and verified in the web application.

Postconditions: Users can authenticate via the configured method: directory service or local credentials.

4.5.2.2 Teacher Creates a New Exercise

Actor: Teacher

Preconditions: A teacher account is authenticated in the web application.

Main Flow:

1. The teacher fills out an exercise creation form with the exercise metadata.
2. The teacher enters a template VM ID into the form.

3. The teacher submits the form.
4. The system clones the selected template.
5. The system uploads the GNS3 project file provided in the form to the newly cloned VM.
6. (Optional) The system performs form-defined pre-configurations to the GNS3 topology.
7. The system transforms the new VM into a template ready to be cloned for use by students.

Postconditions: The exercise and related specific VM are created and stored in the system and become visible to enrolled users.

4.5.2.3 System Supports Enrollment of Users into Exercises

Actor: Teacher

Preconditions: Atleast one exercise exists in the system.

Main Flow:

1. The teacher selects an exercise.
2. The teacher navigates to an enrollment interface.
3. The teacher uploads a list of users.
4. (Optional) The system checks the list of users against existing directory services.
5. If necessary, new users are registered automatically in the database.
6. The system validates if the list contains already enrolled users.
7. The system creates VMs for non-enrolled users.
8. The system creates associations between the users, the VMs and the exercise.

4.5.2.4 Student Starts Their Exercise VM

Actor: Student

Preconditions: Student is enrolled in selected exercise.

Main Flow:

1. The student logs in and navigates to the assigned exercise.
2. The student clicks the `Start VM` button.
3. The system sends an API request to the Proxmox server to start the VM..

Postconditions: The VM is started and its GNS3 instance becomes accessible to the student.

4.5.2.5 Student Submits Solution

Actor: Student

Preconditions: The student's VM and its its GNS3 instance are running.

Main Flow:

1. The student clicks the `Submit` button for the exercise.
2. The system (via Nornir) connects to the necessary virtual devices hosted in the student's VM.
3. Commands are executed and their output is validated.

Postconditions: The validation feedback is made available.

The architectural design laid out in this chapter defines the foundation upon which the system was implemented. However, translating this design into a functional platform required addressing real-world constraints, technology limitations, and performance considerations. The next chapter moves from architectural blueprints to concrete implementation details, exploring the project's technical evolution, codebase organization, and how the selected technologies were integrated to realize the envisioned system.

5. Implementation

This chapter will expand on topics introduced in the last chapter, while going more into implementation specifics and providing more details.

This chapter presents the practical realization of the system, detailing the technology stack and internal structure of the codebase. It begins by recounting the iterative evolution of the back-end framework, starting with Flask and progressing through Celery and Quart, ultimately arriving at FastAPI as the final choice. Each transition reflects specific technical needs uncovered during development, particularly around asynchronous execution.

Following this, the chapter provides a breakdown of the project's modular structure, highlighting how responsibilities are split across directories . The integration of technologies like SQLite, GNS3, and Proxmox VE's REST API is also addressed, alongside considerations for error handling, VM orchestration, and asynchronous task execution.

Together, these sections provide a clear view into how the architecture translates into a working system, one emphasizing modularity and scalability as guiding principles throughout the implementation.

All source code developed as part of this project is publicly available at: `https://github.com/ICWeiner/FCUP-DissertationProject`

5.1. FastAPI Adoption: Overcoming Flask's Shortcomings

As the web application matured, demand for concurrency and responsiveness increased. This will be discussed further in Chapter 6. While Flask offered a lightweight and productive starting point, its synchronous foundations and lack of native asynchronous support became a bottleneck for I/O-heavy workloads. This section outlines the successive iterations of the back-end framework, beginning with Flask, transitioning through solutions like Celery and Quart, and culminating in the migration to FastAPI.

5.1.1 Initial setup: Flask

Initially, Flask served as the framework for the web application, providing the necessary infrastructure to handle HTTP requests, render Jinja2 HTML templates, and manage application routing. Its flexibility and minimalistic approach allow for the integration of various extensions and libraries as needed, ensuring the application remains lightweight yet functional. Flask's comprehensive documentation and supportive community further enhance its suitability, via the creation and support of community-driven extensions, speeding up development and reducing the need to reinvent the wheel.

However, as we progressed, the need for better I/O performance became increasingly apparent. Early on, it was clear that leveraging Python's native `asyncio` would benefit the project, but a significant portion of the existing codebase, including Flask itself, relied on non async-compatible libraries. This limitation stemmed from Flask's foundation on WSGI, a synchronous standard developed long before Python's asyncio was introduced. WSGI operates strictly in a blocking request-response model, requiring each request to complete fully before processing the next.

Traditional workarounds like multi-threading or multi-processing can mitigate some of WSGI's limitations, they are generally more suitable for CPU-bound tasks. Both approaches introduce additional complexity such as synchronization issues, race conditions, and increased memory overhead. For I/O-bound tasks—such as handling concurrent HTTP requests or interacting with remote APIs—these traditional models are often inefficient, as threads or processes may remain idle while waiting for external operations to complete.

In contrast, Python's `asyncio` framework is specifically designed for I/O-bound concurrency. It uses an event loop to manage multiple tasks cooperatively within a single thread. This makes `asyncio` more efficient and scalable in web applications where responsiveness and concurrency are essential, and where tasks spend most of their time waiting on I/O rather than performing computation.

To address these constraints, several approaches were considered:

- **Gevent/Eventlet:** These libraries use monkey-patching to emulate asynchronous behavior in synchronous code. However, they are not true `asyncio` and can lead to unpredictable behavior. Given the project's early stage, this option was deemed too risky.
- **Flask + Celery:** Offloading long-running tasks to Celery workers helps avoid blocking Flask but introduces operational overhead, requiring additional infrastructure like Redis or RabbitMQ for message brokering, as well as resource overhead, as Celery worker pools take up resources even when idle.

- **Quart (ASGI Flask):** A Flask-compatible ASGI reimplementation with native `async/await` support. However, Quart lacks Flask's mature ecosystem and still relies partially on monkey-patching, raising concerns about long-term stability.
- **FastAPI (Full ASGI migration):** Built on ASGI, FastAPI was designed with async-first principles, enabling efficient handling of concurrent connections. Its native `async/await` support and modern tooling offer a cleaner solution without the need for workarounds, at the expense of having to reimplement some features already implemented in Flask.

While Flask remained suitable for early development, emerging requirements—particularly those involving asynchronous communication for more scalable I/O operations—eventually led to a need to explore architectural shifts, due to Flask's limited async support and WSGI heritage. While recent versions allow defining `async def` routes, the framework does not provide full asynchronous request handling out of the box. This means that Flask cannot handle multiple concurrent requests as fully asynchronous frameworks like ASGI-compliant frameworks. Additionally, many Flask extensions and middlewares are not designed to work in an asynchronous context, which can lead to unexpected behavior or performance bottlenecks when attempting to use async features in more complex applications. All these downsides led to the exploration of alternatives, as the project was still in earlier development stages, so the cost of migration would not be as significant as in later stages.

5.1.2 Second setup: Flask + Celery

As the limitations of Flask's synchronous WSGI model became more apparent, we explored Celery as a potential solution for handling asynchronous tasks. Celery, a distributed task queue system, allows offloading blocking I/O to separate worker processes. Celery operates by decoupling task execution from the main application flow. When a time-consuming operation is required, Flask dispatches it to a Celery worker via a message broker (typically Redis or RabbitMQ). The worker processes the task asynchronously, while Flask remains free to handle incoming requests. While this approach mitigated some of Flask's blocking I/O issues, it introduced new challenges in complexity and system overhead.

Celery operates through worker processes that listen to the message broker for tasks. These workers run as independent processes, executing tasks marked with Celery's

`@app.task` decorator. The system's concurrent processing capability comes from multiple workers operating in parallel, each handling different tasks from the queue. Tasks are Python functions that are decorated with provided Celery decorators such as `@app.task`, causing them to be registered as Celery tasks within the Celery application. This design is particularly valuable for operations like batch processing or scheduled jobs that would otherwise block Flask's synchronous request handling.

Sample code 4 Calling a Celery Task and Getting the Result

```
from celery import Celery

app=Celery('tasks',broker='redis://localhost:6379/0',backend='redis://localhost:6379/0')

@app.task
def hello():
    return 'hello world'

result = hello.delay()
print(result.get())
```

To execute a task, a Celery task function must be called using the *delay()* method, which will return a result object. This result object can be used to check the status of the task and to retrieve the result once it is available. This pattern is shown in Sample Code 4

Celery supports horizontal scaling by design, allowing multiple worker pools to run on separate physical or VMs. This makes it especially effective for handling growing workloads—for example, processing email newsletters for an expanding user base.

Celery's advanced features, including task retries, chaining, and prioritization, while powerful, further increased the system's complexity. We found ourselves managing not just our application logic, but also the reliability of the message broker, persistence of results, and supervision of worker processes. This architectural overhead seemed increasingly disproportionate to our actual needs as the project evolved.

Furthermore, Celery clients and workers introduce a non-negligible overhead in terms of CPU and memory usage, even when idle, as they must maintain persistent connections to the broker and periodically perform health checks or heartbeats. This can be a concern in resource-constrained environments or during development.This overhead became especially evident during early integration tests.

As tests were performed, it became increasingly clear that Celery's benefits lend themselves better to CPU-bound workloads, as opposed to our I/O-bound ones, for reasons that were already detailed in Subsection 5.1.1 and they did not outweigh the resource and architectural costs, for our workloads. This realization prompted an exploration of more lightweight asynchronous alternatives, eventually culminating in an investigation into ASGI-compliant frameworks with native async capabilities and simpler concurrency management.

5.1.3 Third setup: Quart, an ASGI-compliant Flask reimplementation

Quart emerged as a promising candidate during our exploration of async solutions, offering a unique combination of Flask syntax with ASGI compliance. As a near-drop-in replacement for Flask, Quart theoretically allowed for an easy migration while providing all the benefits of native `async/await` support. The framework's design promised seamless execution of asynchronous code alongside familiar Flask patterns, making it particularly attractive for existing Flask projects that would benefit from asynchronous capabilities.

However, after evaluation it was revealed that there are significant limitations in Quart's ecosystem, namely its lack of maturity. While Quart itself required minimal changes to code orignally written for Flask, many critical Flask extensions we relied on - including ones that provided authentication capabilities, database integration, among others - either lacked Quart equivalents or had poorly maintained implementations. We discovered many Quart-specific packages were either abandoned, documented only through sparse READMEs, or failed to match their Flask counterparts in functionality. For instance, the Flask-Login equivalent for Quart was one such unmaintained extension that would require reimplementation efforts. This gap would require us to reimplement this and other substantial portions of our web application instead of using existing, known-good solutions.

While Quart offers the possibility to use monkey patching on Flask extensions, deeper evaluation revealed this compatibility came with significant trade-offs. This approach could make some Flask extensions work in the async environment, but we found this to be an unstable foundation for long-term maintenance. Additionally, recent Quart releases have started to moved away from this approach - the framework now treats these compatibility layers as optional extras rather than core features, signaling a deliberate shift in architectural direction. Quart's smaller community and limited production adoption made it difficult to assess long-term viability, raising concerns about framework maintenance and the availability of future support.

Ultimately, while Quart's technical merits as an ASGI Flask alternative were sound, the ecosystem risks and migration costs outweighed its benefits for our project. The framework's current state appears best suited for teams that can commit to Quart's entire stack, rather than as a migration path for existing Flask applications with extension dependencies. This realization steered us toward more mature ASGI alternatives, despite requiring some reimplementation, that could provide robust `asyncio` support without sacrificing ecosystem stability.

5.1.4 Final Decision: FastAPI Migration

To better evaluate the trade-offs between different architectural approaches for supporting asynchronous workloads, we compared our current Flask-based setup with an enhanced Flask + Celery configuration and the FastAPI framework. Table 5.1 summarizes key differences across aspects such as async support, concurrency models, complexity, and suitability for various types of workloads.

Table 5.1: Comparison of Flask, Flask + Celery, and FastAPI

Aspect	**Flask**	**Flask + Celery**	**FastAPI**
Async Support	Limited; WSGI-based, synchronous by design	Background tasks offloaded to Celery workers	Native ASGI support; fully async with `asyncio`
Concurrency Model	Can implement Multi-threading or Multi-processing (Manual)	Task queues; good for parallel background work	Non-blocking I/O using async/await
Best Fit For	Simple, low-load synchronous applications	CPU-bound and/or deferred workloads	I/O-bound, high-concurrency APIs
Architecture Complexity	Minimal, single-process app	High: requires workers, message broker, and Flask app coordination	Moderate, single-process app with async flow
I/O-bound Task Handling	Poor; threads block on I/O	Offloaded to background workers	Efficient via async handlers
CPU-bound Task Handling	Possible with multi-processing	Good with multiple Celery workers	Possible with multi-processing
Data Validation	Manual or with external libs (e.g. WTForms)	Same as Flask	Built-in via Pydantic models
API Documentation	Manual or using Flask-RESTX / Swagger tools	Same as Flask	Automatic OpenAPI documentation
Learning Curve	Low	Moderate; adds inter-process complexity	Moderate; async model + modern Python features
Operational Overhead	Very low	High; needs message brokers and task monitoring	Very Low

5.2. Project structure

This section provides a detailed overview of the project's structure, focusing on the key directories and modules that make up the application. It begins with the core technologies used, Python and SQLite .The following subsections describe the purpose and contents of each major directory, including `app/`, `inventory/`, `logger/`, `nornir_lib/`, `proxmox_api/`, and `gns3_api/`. Attention is given to how components interact, with a focus on modularity and clarity. Where relevant, error handling mechanisms and implementation considerations are highlighted to illustrate design decisions.

```
Code
├─ app
├─ inventory
├─ logger
├─ nornir_lib
├─ gns3_api
└─ proxmox_api
```

5.2.1 Technologies

The architecture emphasizes separation of concerns through several key design choices. A modular package structure organizes code into logical components, while the use decorators and dependency injection promote code reuse. Strict interface boundaries between components maintain clear contracts, and repository patterns abstract data access details. This approach adheres to Don't Repeat Yourself (DRY) principles while ensuring maintainability as the project scales.

5.2.1.1 Python

All application components were developed in Python 3.10+, chosen for its mature `async/await` implementation and robust type system. FastAPI serves as our web framework, having replaced earlier Flask + Celery-based prototypes due to its superior native async support. External API communications are handled through HTTPX for asynchronous HTTP REST interactions, while network device configuration validation is managed via Nornir.

5.2.1.2 SQLite

For our database, we adopted SQLite during development, accessed through SQLModel - an Object-Relational Mapping (ORM) built on top of SQLAlchemy that incorporates Pydantic's validation capabilities. This combination provided type-safe queries through Python type hints while maintaining SQLAlchemy's powerful query syntax, along with seamless FastAPI integration for automatic OpenAPI schema generation. The use of SQLModel ensures an easy future transition to production-grade databases like PostgreSQL when needed. All database related code is written using SQLModel's capabilities, meaning no SQLite-specific code is present anywhere in the project, meaning any future database change, such as to PostgreSQL is hassle-free.

5.2.2 app/

The `app/` directory contains the complete implementation of our web application, organized to promote maintainability and clear separation of concerns. The root level includes several key files that form the application foundation:

- `main.py` - The ASGI entry point to run with any ASGI-compliant server.
- `database.py` - Manages database connections and session handling.
- `models.py` - Defines all database tables and their relationships using SQLModel.
- `decorators.py` - Contains reusable decorators for route handling and logic.
- `config.py` - Centralizes application settings loaded from environment variables.

You will also find the following folder structure

```
app
├─ alembic
├─ dependencies
├─ repositories
├─ routers
├─ services
├─ templates
├─ uploads
└─ utils
```

`alembic/` is responsible for database creation and migrations, as well as seeding a small amount of dummy data.

`dependencies/` contains all FastAPI dependency injections, including shared resources like model repositories, along with authentication and authorization utilities. These components are reused across multiple endpoints.

`repositories/` implements the database abstraction layer using SQLModel/SQLAlchemy, following the repository pattern. This directory houses all database queries and data access operations, providing a clean interface to access required data.

`routers/` organizes API endpoints by domain (authentication, exercises, vms etc.). Each router file contains related route definitions with minimal logic, delegating complex operations to the services layer.

`services/` forms the core logic layer, processing data between repositories and routers. This directory contains the complex workflow of some functions and offers a clean interface.

`templates/` stores Jinja2 templates for front-end interfaces, along with related static assets. The templates follow a consistent layout system.

`uploads/` stores all files uploaded by priviledged users, mainly `gns3project` files.

`utils/` provides shared utility functions and classes that don't belong to specific domains.

5.2.3 inventory/

The `inventory/` directory contains YAML configuration files that store static device information for each topology. These files serve as a device registry, enabling Nornir to immediately access device specifications without runtime type checking. This approach significantly improves automation performance by eliminating redundant device discovery operations. This information is derived from the `gns3project` files that define the topology of the emulation environment.

Table 5.2: Example inventory file contents

Device	Groups	Hostname	Port	Username	Password
`linuxvm-1`	linuxvm	192.168.57.143	5005	`<username>`	`********`
`pc1`	vpcs	192.168.57.143	5007	–	–
`r1`	cisco_router	192.168.57.143	5000	–	–
`sw1`	cisco_switch	192.168.57.143	5002	–	–

Key Fields Explanation:

- **Device Name**: Unique identifier within the topology (e.g., `linuxvm-1`, `r1`).
- **Device Class**: Specifies the device type/role (determines connection handlers):
  - linuxvm: Linux hosts
  - cisco_router: Cisco IOS Router
  - cisco_switch: Cisco IOS Switch
  - vpcs: Virtual PC simulator
- **Hostname**: Shared IP indicates all devices are virtual instances on the same host.
- **Port**: Unique port for each device's management interface.
- **Credentials**: Shown here as placeholders.

Implementation Notes:

1. The YAML structure enables easy integration with Nornir's inventory plugins
2. Port assignments do not follow any specific order
3. Credential fields use `null` values for unauthenticated devices like VPCS

5.2.4 logger/

The `logger/` directory implements the application's centralized logging system with consistent configuration across all components. This module provides:

- Pre-configured log formatting with timestamps, log levels, and module names.
- Simultaneous output to both file (`app.log`) and console.
- Easy integration via `get_logger()` factory function.

The logger module enforces standardized logging practices across the entire application, featuring a consistent log format that includes timestamps, severity levels, and module identifiers for all log entries. Configuration is centralized in `logging_config.py`, which automatically creates and manages the `app.log` file in the project root directory while simultaneously outputting to the console. By default, the system logs messages at INFO level and above, with built-in flexibility to adjust verbosity for debugging purposes through simple configuration changes. This approach ensures uniform logging behavior while maintaining adaptability for different runtime environments.

The implementation follows Python best practices while allowing for future extensions such as log rotation or remote logging services. All application modules should obtain their logger instance through the provided `get_logger()` function to maintain consistent logging behavior.

5.2.5 nornir_lib/

The `nornir_lib/` directory implements the evaluation system that interfaces with various virtual devices. This component executes commands across network topologies and analyzes the responses to determine operation success.

Configuration requires three key files in the `app/` directory:

- `config.yaml` - Specifies paths to host/group files and Nornir runner settings.
- `host_file` - Contains device credentials (IP, username, password in plaintext).
- `group_file` - Defines device group parameters (must maintain `fast_cli: false`).

Developers can implement new test modules by extending the base `CommandModule` class. This requires implementing device-specific command methods (`_command_vpcs()`, etc.) and corresponding response interpreters (`interpret_vpcs_response()`, etc.) with the benefit of not having to worry about anything about nornir and its inventory system. The system currently includes `ping` and `traceroute` implementations, with the modular design. Developers can use the bundled `ping` module that demonstrates this pattern, taking parameters and evaluating success based on configurable packet loss tolerance.

The architecture emphasizes:

- Consistent device communication through standardized interfaces.
- Flexible test creation via module inheritance.
- Centralized response interpretation logic.

In the past iteration of this project, it was noted that communication with devices could be less than reliable, with no apparent reason. After some testing and research it was found that disabling the `fast_cli` increased reliability and we have not experienced the communication failure since disabling this feature.

5.2.6 proxmox_api/

The `proxmox_api` library provides direct, lightweight wrappers around the Proxmox VE REST API, offering simplified interfaces for common virtualization management tasks while maintaining close correspondence with the underlying API endpoints.

Design Philosophy The philosophy behind the design of this API can be summarized by the following aspects:

- **Transparent Wrapping**: Each method maps clearly to a specific Proxmox VE API endpoint.
- **Minimal Abstraction**: Preserves the API's native behavior with light conveniences.
- **Consistent Error Handling**: Uniform approach across all operations.
- **Asynchronous Communication**: Use async methods where possible to maximize performance.

5.2.6.1 Error Handling

The library implements a consistent error handling approach through the `@handle_network_errors` decorator, which manages network-related exceptions while preserving application-level errors. This decorator specifically intercepts basic connectivity issues (host unreachable, timeouts) and HTTP 404 responses, causing it to return `False`, signaling a failure, and maintaining detailed error logging. All other HTTP errors and programming exceptions propagate unchanged, ensuring callers receive complete error context for non-network failures.

The implementation preserves function signatures through Python's `@wraps` decorator and maintains type safety via generic type variables. Designed specifically for async operations, and with comprehensive diagnostic logging.

Table 5.3: Error Handling Behavior

Case	Behavior
Network Connectivity	Returns `False` with error logging.
HTTP 404 (Not Found)	Logs and re-raises with request details.
Other HTTP Errors	Propagates with original status code.
Application Exceptions	Unmodified propagation.

The system adopts three distinct implementation patterns to interact with external APIs, each suited to the complexity of the task being performed.

Simple Wrapper functions encapsulate a single API call along with basic error and status checking. These are used for straightforward operations such as starting or stopping VMs in Proxmox VE, where a single HTTP request is sufficient to complete the action.

Chained Operation handlers manage more complex workflows that require multiple API calls to complete a task. An example is the `create` operation, which may involve steps such as VM instantiation. These functions ensure that all steps are executed in the correct order, and can handle intermediate failures gracefully.

Special Case Handlers are designed for non-standard workflows or endpoints with unique behavior, such as `check_free_id`, which requires custom logic to interpret status codes or handle API quirks. These patterns are employed where simple wrappers or standard chaining would not provide sufficient control or reliability.

As an example, under `proxmox_api/` there exists `proxmox_vm_actions.py`. This file contains various methods whose only responsibility is to send an HTTP call to a specific endpoint, extracting the result from the response.

For the **Simple Wrapper** case, we can exemplify with the `astart` function. This sends a POST request to endpoint `/nodes/<node>/qemu/<vmid>/status/start`

In the case of **Chained Operation** we can look at `acreate` function. In this case, two POST requests must be made sequentially, one to create a VM and the other to disable the protection flag in Proxmox VE allowing the VM to be later destroyed, as this function is used to create VMs related to exercises that will be later destroyed.

Finally in the case of **Special Case Handlers** such as `acheck_free_id`. This function is used to check if a given ID is not assigned to any VM or container. This is required, as to create a new VM or container, a valid ID must be included in the body of the message. This is considered a special case, as the response will not contain the answer in the body if an ID is specified in the request, instead the only indicator of success or failure will be codes 200 OK or 400 Bad Request, which is different behavior from most other Proxmox VE endpoints.

5.2.7 gns3_api/

The `gns3_api` wrapper provides essential operations for managing GNS3 projects through its REST API, following similar design patterns to the `proxmox_api` wrapper but tailored for GNS3-specific tasks. The library handles project operations including verification, import/export, as well as collecting node information to generate inventory files.

The wrapper shares several architectural traits with the `proxmox_api` implementation, like using the same error handling approach, being asynchronous and maintaining similar logging pratices.However, it differs in usage as it focuses on two main use cases, alongside some smaller tasks, rather than virtualization layer operations such as the creation and deletion of VMs. The first case is importing a project into the GNS3 instance running on a given VM. This is performed when creating a new exercise, as part of preparing the template VM from which student-specific clones will be generated. The second one is generating an inventory file for a specific exercise instance hosted on a given VM, which is required to enable automated assessment using Nornir.

This second use case starts by verifying if a given project exists, retrieving its Universally Unique Identifier (UUID) as these are used by GNS3 to identify projects, from the database to the `acheck_project` function. Being valid, function `aget_project_nodes` is used to generate the inventory file for that specific project. Finally, before Nornir is used for assessment, function `astart_project` would be used to make sure the virtual nodes in the project are running. As this function is idempotent there is no harm in sending it before each assessment.

The implementation similar handling of network operations `proxmox_api` with additional handlling for local file I/O, in the import/export methods where it manages binary data transfer and local filesystem interactions. The UUID-based project identification is used to identify projects contained in GNS3 instances during operations.

5.3. Web Application Components

Web application is structured to offer the following capabilities:

1. Login with institutional or local credentials - Used by both students and administrators. Students log in to access exercises, while teachers log in to create or manage them.
2. Selection from available exercises - Relevant to students, who choose exercises to work on. Teachers may also access this view to test or verify exercises.
3. Automated environment preparation - Triggered by teachers after enlisting students into exercises. The system provisions a dedicated VM from the prepared template.
4. Practical work in GNS3 web interface - Used by students to complete the networking tasks within the virtual lab environment.
5. Validation feedback - Requested by students at any time when working on their configurations.

To accomplish that, it comprises three core modules that work in concert to manage networking exercises while abstracting the underlying virtualization infrastructure:

5.3.1 Authentication Module

The authentication module establishes user identity and access control through JWT tokens issued upon successful login. It ensures that each request is authenticated and verifies resource ownership before allowing actions such as VM control. To achieve this, the module integrates with the database to check account privileges and VM ownership relationships.

User accounts support both institutional and local credentials. Institutional login is handled by configuring the appropriate realm in Proxmox VE and sending a request to obtain a Proxmox VE authorization cookie using the LDAP credentials. Upon the first login via LDAP, the system creates a corresponding local user record in the database and stores relevant attributes (e.g., username, role) for subsequent access control. Local users can still be created even if LDAP is configured—mainly for testing or administrative access—can be created manually through the database.

Proxmox VE access is not granted directly to users; instead, all operations are executed by the back-end service account, which acts on behalf of the authenticated user. The mapping between users and the VMs they control is maintained internally within the application's database.

This approach allows us to create per-user infrastructure credentials while also performing institutional login in one single step.

5.3.2 Exercise Management Module

This module handles the complete exercise workflow from creation to validation. Instructors can upload network topologies, by providing `gns3project` files and validation criteria using the previously mentioned validation modules, namely `ping` and `traceroute`, during exercise creation. Students receive filtered exercise lists based on which they are enrolled in. The validation subsystem uses the developed modules to validate instructor defined criteria, providing automated feedback for students. All provisioning of VMs for students to work on assignments occurs automatically when students are enrolled in exercises.

5.3.3 VM Control Module

Finally this modules provides the ability to interact with VMs by exposing endpoints for, among other things, powering on/off and request exercise validation. This allows students to avoid interacting directly with the underlying infrastructure and focus on doing their exercises.

5.4. Asynchronous Processing with FastAPI

`asyncio` is Python library for writing concurrent code. It provides a foundation for asynchronous programming by enabling the creation and management of event loops, coroutines, and asynchronous tasks.

An *event loop* is a central component of asynchronous programming—it continuously runs in the background, managing the execution of asynchronous tasks. When a task reaches a point where it would normally block (e.g., waiting for a network response), it yields control back to the event loop, which can then continue running other ready tasks. This model of cooperative multitasking contrasts with traditional multithreading or multiprocessing, as it operates in a single thread and does not require locking or context switching between OS threads.

A *coroutine* is a special kind of function defined with `async def`. When called, it does not run immediately, but instead returns a coroutine object. This object can be scheduled by the event loop, and when awaited, it runs until it hits a pause point (e.g., another `await`)—at which point it yields control back to the event loop, allowing other coroutines to execute.

In FastAPI, declaring an endpoint as `async def` enables non-blocking behavior for I/O operations when using async-compatible libraries. This allows the server to handle other requests while waiting for operations like external API calls. If that logic includes `asyncio`-compatible I/O operations—such as using a library for asynchronous HTTP calls then the request can proceed in a truly asynchronous manner. This allows the web server to observe massive speedups when compared to blocking I/O when multiple HTTP calls must be made to external services.

Additionally, `asyncio` supports the orchestration of multiple tasks using constructs such as `asyncio.gather()`, which allows multiple coroutines to be executed concurrently and awaited collectively. This has been especially useful in scenarios within the project where multiple devices or services must be queried or configured simultaneously, such as when multiples students are enrolled in an exercise, which requires the creation of multiple VMs.

5.4.1 Differences Between Asyncio And Celery

In contrast, Celery operates at a higher level of abstraction, focusing on distributed task execution rather than fine-grained concurrency. Instead of relying on an event loop, Celery uses a pool of worker processes—often distributed across multiple machines—that consume tasks from a message broker such as RabbitMQ or Redis. Tasks in Celery are standard Python functions decorated with `@app.task`, which serializes their execution requests into messages sent to the broker. Workers then fetch these messages and execute the tasks in separate processes, enabling true parallelism across CPU cores or even different servers. Celery's architecture makes it particularly well-suited for workloads that require heavy computation, long-running operations, or distributed execution across multiple machines. This is unlike `asyncio`, which excels at managing many lightweight I/O-bound tasks within a single thread.

While both `asyncio` and Celery outperform traditional sequential blocking I/O code, `asyncio` proved better aligned with our project's requirements. Sequential code suffers from inherent inefficiencies: each I/O operation forces the program to idle while waiting for a response, wasting CPU cycles that could be used for other tasks. `asyncio` eliminates this waste by allowing multiple of I/O operations to proceed concurrently within a single thread, dramatically improving throughput for I/O-bound workloads. Celery, while also avoiding blocking behavior, introduces overhead from inter-process communication and task serialization, making it less optimal for high-frequency, low-latency operations. In our use case, where the system primarily handles short-lived HTTP requests, `asyncio`'s lightweight coroutines delivered the same or even superior performance with simpler structure and code. Celery remains invaluable for projects requiring background jobs, but for real-time, I/O-heavy scenarios, `asyncio` provided the speed we wanted with efficient resource usage and also being more maintainable.

5.5. GNS3 Customization and Configuration

This section outlines the configuration process for a GNS3 host VM. This setup must be performed during the initial deployment of the system, as it involves creating a base template VM that includes a properly configured GNS3 instance. All future clones used by the system will be derived from this base template.

The first step involves installing the `gns3-server` along with all its required dependencies. This provides the core back-end functionality. The installation can be done using a provided remote installation script that handles the setup of Python packages, IOU support, and necessary architecture extensions such as the i386 repository. This script can be found on the official GNS3 website.

Once installed, it is essential to configure the `gns3-server` to run as a system daemon. Running the server as a background service, ensures it is automatically started at boot time and restarted in case of crashes, and remains continuously available without requiring manual intervention. This is especially important to ensure no manual interaction is needed with the host VM.

By default, the `gns3-server` does not support launching QEMU-based devices with both an auxiliary telnet console and SPICE graphical access simultaneously. A more detailed explanation on this is available in [1]. This limitation posed a problem for the system's design, which requires console access for automated validation (via telnet) while still offering users a GUI for interactive use.

To overcome this, modifications detailed in [1] were made to the `gns3-server` source code to enable an auxiliary telnet console port while retaining SPICE support. SPICE is a remote display protocol that allows users to interact with VMs through a GUI. These source code changes enable the server to launch QEMU instances with the appropriate SPICE options, facilitating enhanced remote access and control over the virtualized devices. A more detailed explanation and rationale for these changes can be found in the first iteration of this project [1], as this is were they were developed.

The host operating system for the GNS3 host VMs during development was **Ubuntu Server** (non-minimized installation). This ensures that all necessary system tools and dependencies are available. Other operating systems such as different Linux distributions or Windows were not tested.

Note: The `gns3-web` UI for GNS3 is currently in beta and may present issues when adding templates for devices. At this point in time it is recommended to use the GUI client for this task only. Additionally, for clients to interact with SPICE enabled devices, such as virtualized linux hosts the user must install `gns3-webclient-pack` on their machine. Finally if the project includes IOU nodes, a valid IOU license is required. This file must be placed in `~/.iourc` and formatted according to GNS3's expectations.

5.6. Proxmox API Usage

Proxmox VE provides a REST API that exposes all functionality available. This includes operations such as creating, cloning, starting, stopping, and deleting VMs, as well as querying their current status. By interfacing with this API, the system gains the ability to manage VMs in an automated, repeatable, and scalable manner, which is essential for deploying work environments on demand.

In our project, the Proxmox VE API is accessed via the `proxmox_api` library, which communicates via HTTP using the HTTPX library in Python. Authentication is handled using Ticket Cookies. A ticket is a signed random text value with the user and creation time included. Additionally, any write (POST/PUT/DELETE) request must include a CSRF prevention. To obtain a valid ticket and CSRF token a POST request must be made to the appropriate endpoint with valid plaintext credentials in the body of the message, sent over. This ticket is valid for a set amount of time and itself can be sent to the correct endpoint to acquire a fresh ticket.

To avoid repeated logins, as well as avoiding storage of plaintext user credentials, and reduce overhead, tickets are stored in memory and reused for their duration, after which a new token is acquired.

Additionally, when users log into the web application, their provided credentials are sent to the Proxmox VE API authentication endpoint to obtain a ticket specific to that user. This approach offers multiple advantages. First, regular user accounts, such as those belonging to students, can be configured with limited permissions in Proxmox VE. This serves as a secondary layer of protection in case of an exploit in the authentication logic that allows an unauthorized request (e.g., attempting to delete a VM), however due to time constraints it was not possible to implement this role-based access control feature in Proxmox VE with only the web application performing a check for authorization. Second, it improves accountability, as every action taken by a user can be traced to their authenticated account, resulting in more detailed and accurate audit logs.

For this approach to work, valid user accounts must exist within the Proxmox VE system. These accounts can be created in several ways, as Proxmox VE supports a variety of authentication back-ends. For example, integration with LDAP is supported out of the box. This makes user management particularly convenient in educational institutions, where centralized identity systems are commonly used. Alternatively, local accounts managed directly within Proxmox VE can also be used, offering a simpler setup for smaller-scale or isolated environments. The use of local accounts or directory services for Proxmox VE should go in tandem with the use in the web application.

Figure 5.1 contains a diagram showcasing the process of a student's first login in the system.

Note: The Proxmox VE server is configured to use with a real certificate generated by a fake Certificate Authority, using the `trustme` Python library. This setup is suitable for internal or development environments where the server is accessed via an IP address and not a publicly resolvable domain name. Since Let's Encrypt requires a valid, publicly accessible domain and DNS or HTTP-based challenge verification, it is not applicable in this context. Using `trustme` allows for easy generation of certificates and controlled client-side trust by explicitly providing the corresponding Certificate Authority (CA) certificate during requests. Future iterations can use certificates by Let's Encrypt without changes to code.

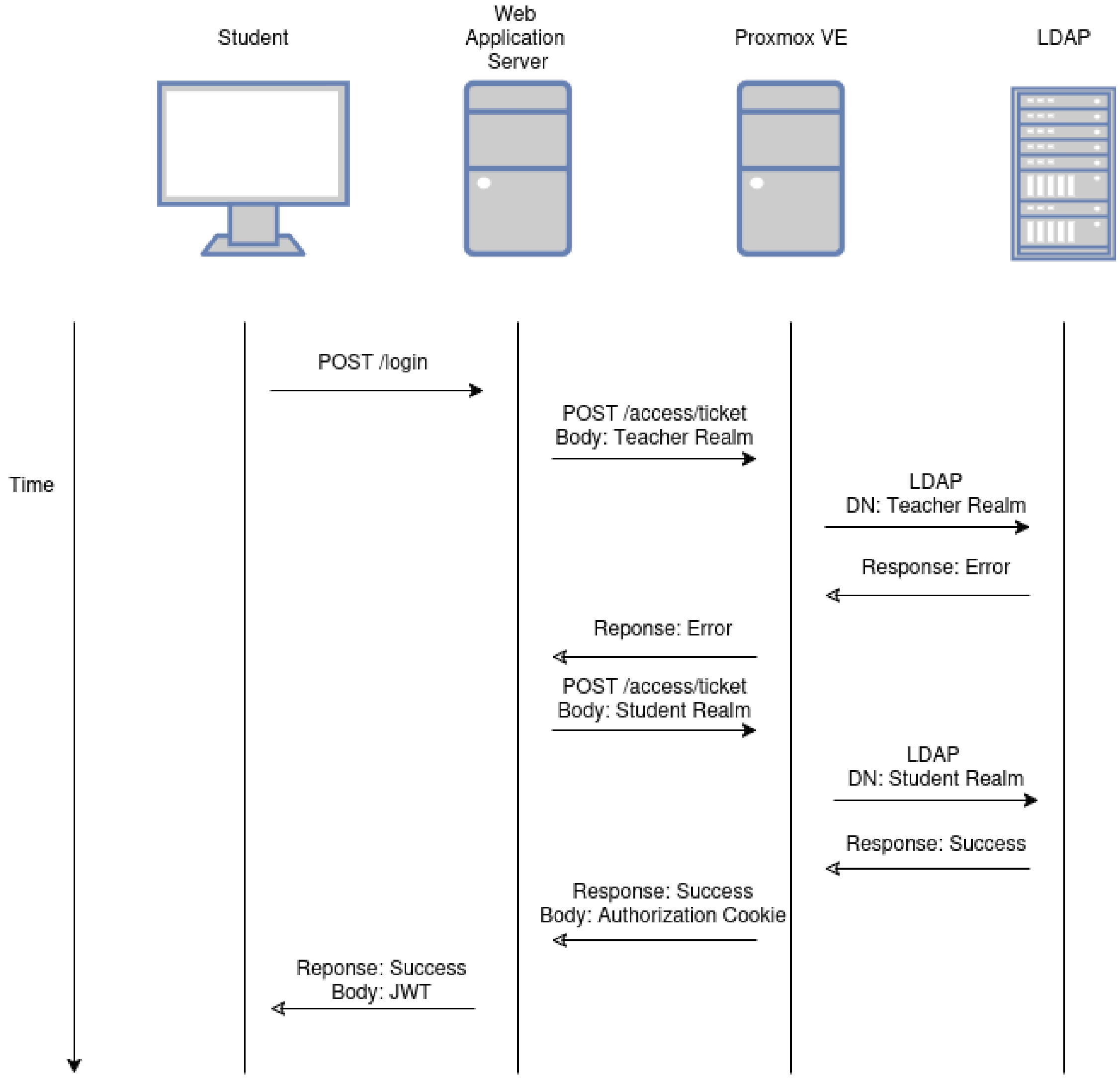


Figure 5.1: A diagram showcasing the process of login via institutional credentials

6. Testing & Evaluation

This chapter evaluates the system's performance and practical usability.

The first part of the chapter evaluates the system's performance across three implementations: Flask, Flask + Celery, and FastAPI. The aim is to assess whether transitioning to an asynchronous architecture yields measurable improvements in execution time and consistency, particularly for VM lifecycle operations such as creation, cloning, and deletion.

Benchmark tasks representative of system usage for recurring tasks are executed under controlled conditions. Results are analyzed based on average execution time and variability.

During this process, however, we also encountered infrastructure-level issues unrelated to the choice of framework. In particular, I/O bottlenecks on the Proxmox VE node emerged during intensive batch operations, prompting a closer investigation.

The second part provides a walkthrough of the main functional use cases supported by the system from an end-user perspective. Given the early-stage, prototypical nature of the user interface and the absence of structured usability testing, the focus here is on illustrating how the system is used to perform key operations. Mapping to the functional requirements described in Chapter 4, thereby serving as a practical validation of the implemented features.

It is important to clarify that the evaluation presented in this work primarily focuses on infrastructure-level operations, such as cloning, starting, and deleting VMs on Proxmox VE. While the system also automates and interacts with GNS3 instances, particularly for tasks such as topology validation athese aspects were not the primary subject of performance evaluation. The rationale is that GNS3-level interactions occur after infrastructure provisioning and are more tightly coupled to exercise-specific logic, rather than the orchestration layer itself. As such, the current analysis emphasizes the efficiency and scalability of core VM management rather than the behavior of individual emulated network devices.

Finally, Flask's synchronous request model under WSGI can become a bottleneck in disk-intensive scenarios, particularly when backed by a single Solid State Drive (SSD). While modern SSDs support parallel I/O at the hardware level, Flask processes requests sequentially per worker, preventing full utilization of this parallelism. In contrast, asynchronous frameworks allow concurrent I/O within a single thread, offering more efficient resource usage in I/O-bound workloads.

6.1. Performance Evaluation

To evaluate the impact of migrating from Flask (+ Celery) to FastAPI, we conducted a series of measurements focused on two main performance metrics:

- **Time to complete a given task**.
- **Consistency of that time**.

To collect data for analysis we divised three different tasks. Although our evaluation focused on isolated task execution, it is important to note that the use of FastAPI and the ASGI server model introduces architectural advantages beyond just concurrent task handling. In particular, it can improve response times when multiple students simultaneously interact with the system (e.g., during an exam). While this scenario was not explicitly tested, given the complexity of simulating realistic concurrent user behavior, it remains a key motivation for adopting an asynchronous framework.

6.1.1 Available Hardware

The current test environment hosts all internal system components on a single physical server with the following specifications.

Table 6.1: System Hardware Specifications

Component	Specification
Processor	Intel Core i7-9700K
Memory	32GB DDR4 @ 2666MHz
Storage	1TB Samsung 970 EVO Plus NVMe SSD
Graphics	NVIDIA GTX 1650

This machine's specifications, while capable enough for development purposes, create inherent memory constraints. With 32GB of available RAM, practical VM allocation becomes the primary bottleneck. For instance, when deploying GNS3 instances each configured with 4GB of memory, the system can maintain only seven active VMs simultaneously. This limitation accounts for Proxmox VE's own memory overhead before inducing SWAP file usage, which would degrade performance.

1. **1st task: Template VM creation:** Create a linked clone from a pre-configured template. Once the cloning process is complete, the VM is powered on and polled periodically until a valid IP address is obtained. A `gns3project` file is then imported into its GNS3 instance. After the import completes, the VM is powered off and converted into a reusable template VM.

2. **2nd task: Batch VM cloning:** Generate a specified number of linked clones from an existing template VM, each intended for assignment to a different user.

3. **3rd task: Batch VM deletion:** Remove all cloned VMs associated with an exercise, as well as the corresponding template VM.

Each batch test was conducted using different quantities of VM clones: 1, 10, 20, 100, and 200. All data is available at: `https://docs.google.com/spreadsheets/d/e/2PACX-1vRO8HiAzAyZFhjHRZl-iAnkf748y9e9-5lj-sVstbKX41DxEHpz27TJ7tb7pQBozbF6Xtq-ktSnIE5_/pubhtml`

All three implementations were deployed in the same network environment, hardware and with as minimal differences in code as possible to ensure a fair comparison. The web application in each case was hosted within the same container running on the same host machine. The container was allocated 8 virtual CPU cores and 1GB of RAM.

Time measurements were recorded from the start of a task's execution, defined as the moment the first relevant API request was issued, until the moment of successful completion, when the final API response was received.

For the first task, each implementation was run a total of fifteen times.

For the remaining two scenarios, tests were repeated three times for each implementation and batch size combination. The reported values represent the average across these repetitions. While three runs may not provide the statistical robustness of a larger sample size, they are sufficient to identify consistent trends and relative performance differences. Due to time constraints, more extensive testing was not feasible at this stage.

For the FastAPI implementation, a concurrency limit of 5 was imposed for interactions with the Proxmox VE API for reasons that will be discussed in Section 6.1.2. Other categories of tasks, such as user requests, GNS3 project handling, and Nornir automation, were allowed to proceed without any concurrency restrictions.

6.1.1.1 Task 1: Template VM Creation

This task is sequential in nature, as it interacts with only a single VM, and none of the steps can be performed in parallel, as each step depends on the previous one. As such, no significant performance uplift is expected for this particular task.

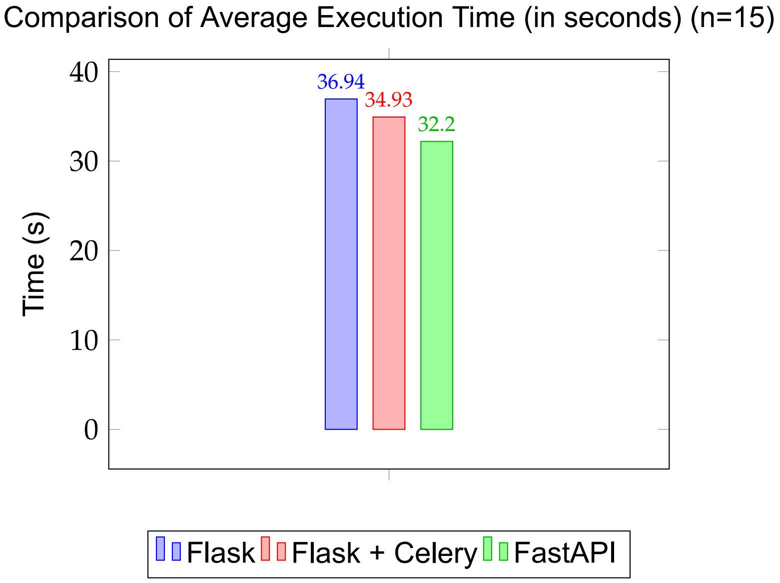


Figure 6.1: Average execution time for Template VM creation across implementations.

As can be confirmed in Figure 6.1 the average execution times are very similar across all three implementations, with the FastAPI approach showing a slight performance advantage.

However, averages alone do not tell the full story. Figure 6.2 illustrates the execution time variability. *Note: the y-axis does not start at 0.*

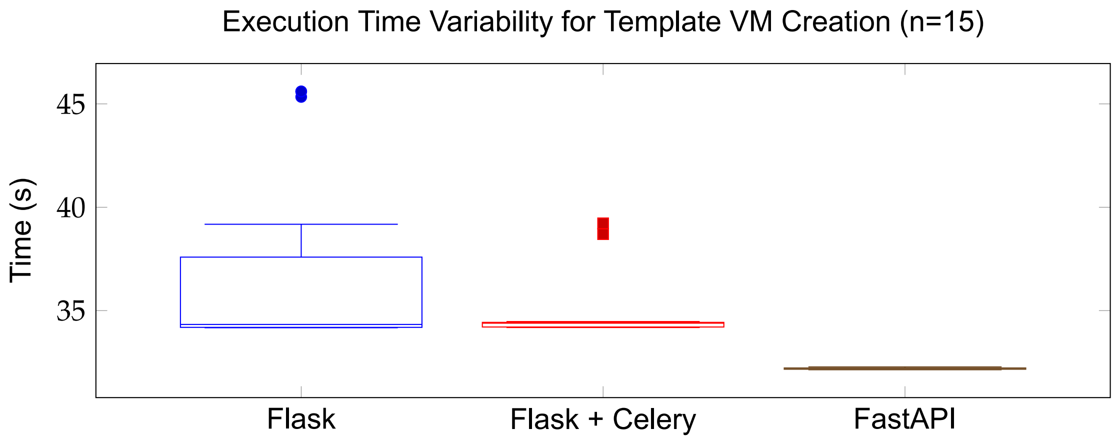


Figure 6.2: Boxplot comparison of execution time variability for Template VM creation.

From the boxplot, it is evident that the Flask implementation exhibits the highest variability in execution times, indicating inconsistency. The Flask + Celery variant improves consistency but still contains several statistical outliers. In contrast, the FastAPI implementation demonstrates significantly tighter grouping and no outliers in our tests.

This coupled with the slighty better execution time make the FastAPI implementation the more performant of the three.

6.1.1.2 Task 2: VM Cloning

Unlike the previous task, the cloning of multiple VMs can be executed concurrently, as each cloning operation consists of only two main steps and is entirely independent from the others.

For each VM, a random ID is first selected, followed by an API call to Proxmox VE to verify that the ID is not already in use. Given the large available range (100 to 999999999), and our comparatively small usage of them, collisions are rare, and the check typically succeeds immediately. In the event of a colision at any point, another random ID is generated and retried until success.

Once a free ID is confirmed, a second API call to Proxmox VE is made to clone the VM using that ID. Because these two calls are independent for each VM, the cloning process can be parallelized with minimal coordination or contention overhead.

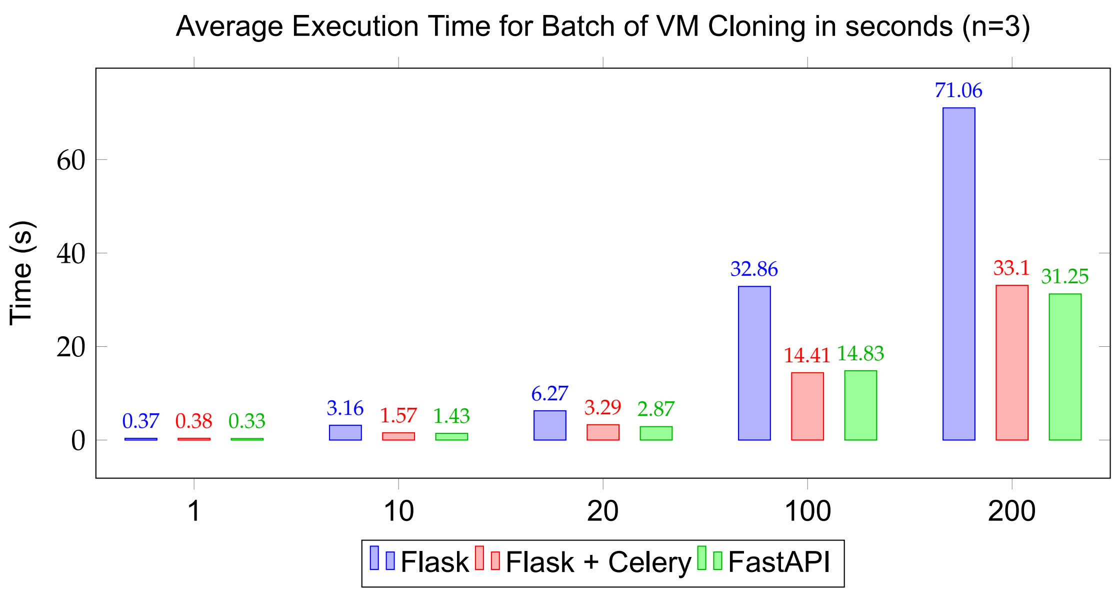


Figure 6.3: Average execution time to clone increasing number of VMs across different implementations.

From Figure 6.3, we observe that the task completion time increases linearly with the number of VMs. The purely sequential Flask implementation consistently underperforms compared to the other two approaches, except in the smallest batch size test, where no concurrency can be achieved.

To compare the consistency of different implementations (Flask, Flask+Celery, FastAPI) across batch sizes, we first normalize each run's execution time within its batch. For each combination of implementation and batch size, compute the batch mean of the run times. Then calculate each run's percentage deviation from that mean using the standard percent-change formula:

$$\text{Deviation}_i = \frac{\text{time}_i - \text{batch\_mean}}{\text{batch\_mean}} \times 100\%.$$

This normalization step effectively centers each batch's data at zero and removes scale differences. For example, if a run is 10 ms above a 100 ms mean, its deviation is

$$\frac{10}{100} \times 100 = 10\%.$$

This ensures that larger batch sizes, which naturally require more time, do not dominate the analysis. Instead, we focus on the relative fluctuations around each batch's mean.

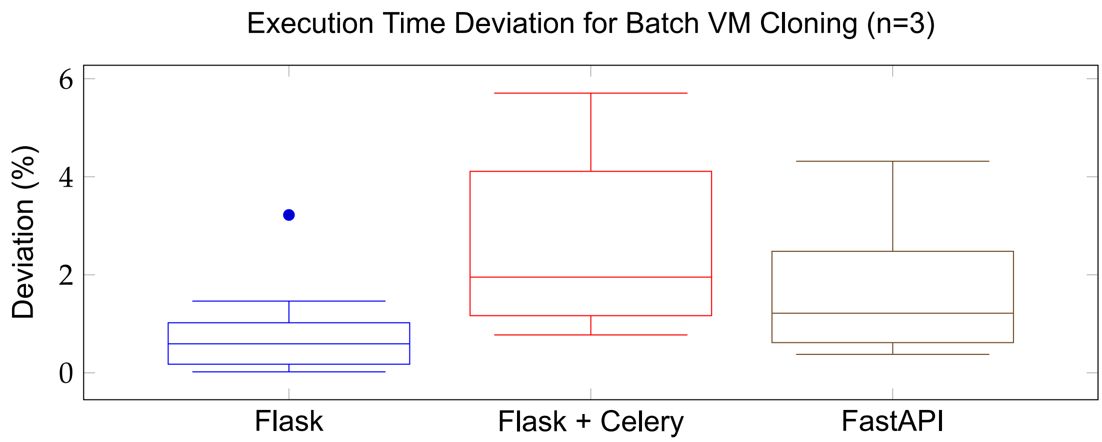


Figure 6.4: Boxplot comparison of execution time variability for VM cloning.

Once again, in Figure 6.4, we observe the same trend: the FastAPI implementation is slightly faster and more consistent when compared to the Flask + Celery approach, altought the Flask sequential implementation actually wins in this metric of deviation, being more consistent than the other two in run-to-run variation, at the cost of being two times slower than the FastAPI implementation, making the FastAPI effort the overall better performer.

6.1.1.3 Task 3: VM Deletion

This task is much more short lived than the previous ones, consisting of a single API call to Proxmox VE per VM to perform the deletion.

Since the deletion operation does not require any preliminary validation or resource allocation, each VM can be removed independently without the need for coordination. This simplicity allows for rapid execution and straightforward parallelization of the deletion process, with minimal overhead per VM.

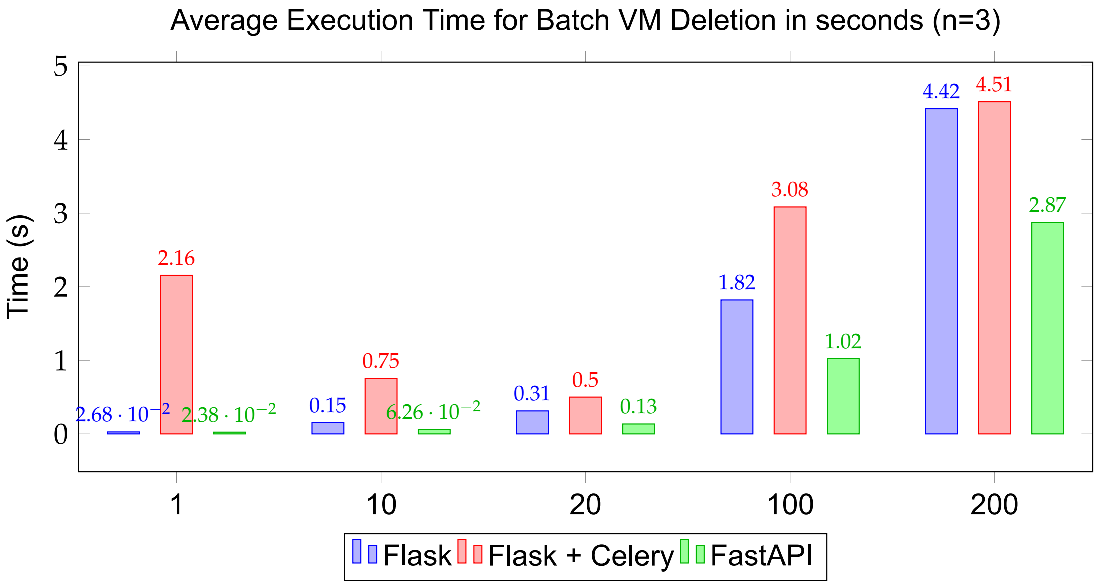


Figure 6.5: Average execution time to delete increasing number of VMs across different implementations.

In Figure 6.5 we can see a textbook example of the overhead that Celery and the message broker bring with them, and why it is not a good idea to use them for especially short-lived, non- CPU intensive tasks. The additional overhead introduced significantly impacts the overall execution time.

In this case, those two factors, the asynchronous orchestration and broker communication, have a higher influence on execution time than the VM batch size itself.

In the particular case of sample size 1, we can see that it took even more time than bigger batch sizes. While this may in part be fault of our relatively small data pool, we choose to keep it as it highlights very well the performance overhead that celery brings with it, and why it can be considered detrimental in the case of short-lived tasks

When comparing batch size 100 to 200, FastAPI exhibited a 2.8x slowdown despite only a 2x increase in workload. This disproportional latency is not due to FastAPI itself, but rather to hitting performance limits in Proxmox VE. As infrastructure resources became saturated, clone operations began failing and triggered exponential backoff retries, leading to higher cumulative delays.

The other implementations scale in a much more expected manner, with the FastAPI version being 1.84x faster on average than Flask.

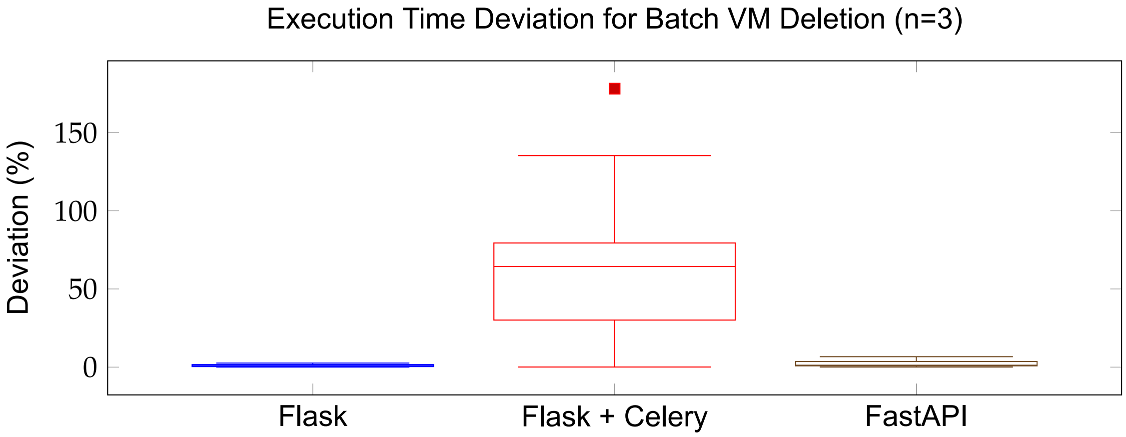


Figure 6.6: Boxplot comparison of execution time variability for VM deletion.

As shown in Figure 6.6, the Flask + Celery implementation exhibits significantly higher variability during this task when compared to the other two approaches. The presence of numerous outliers and a wide interquartile range highlight the inconsistency introduced by Celery and the message broker's overhead.

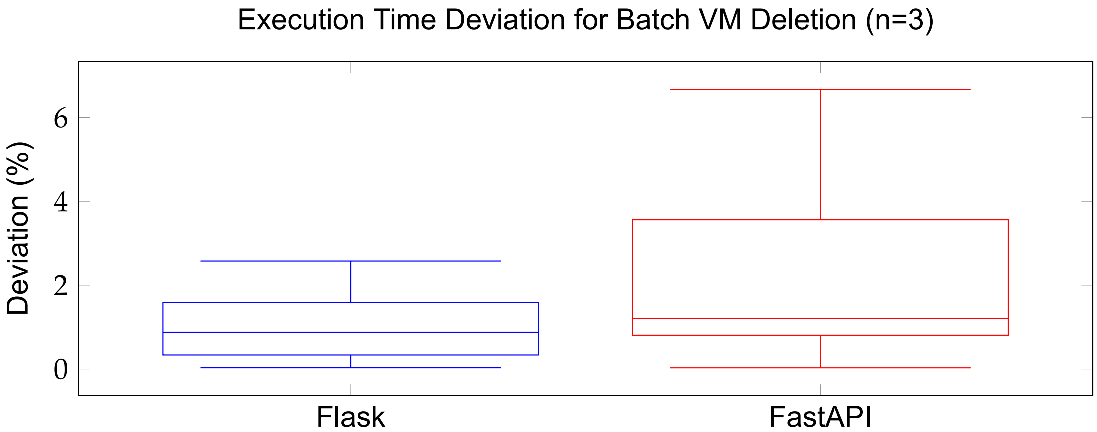


Figure 6.7: Boxplot comparison of execution time variability of Flask and FastAPI for VM deletion.

Figure 6.7 isolates the Flask and FastAPI implementations for a clearer comparison. We observe that while the Flask approach is slightly more consistent, as indicated by its tighter distribution.

6.1.2 I/O Problems during Batch VM Operations

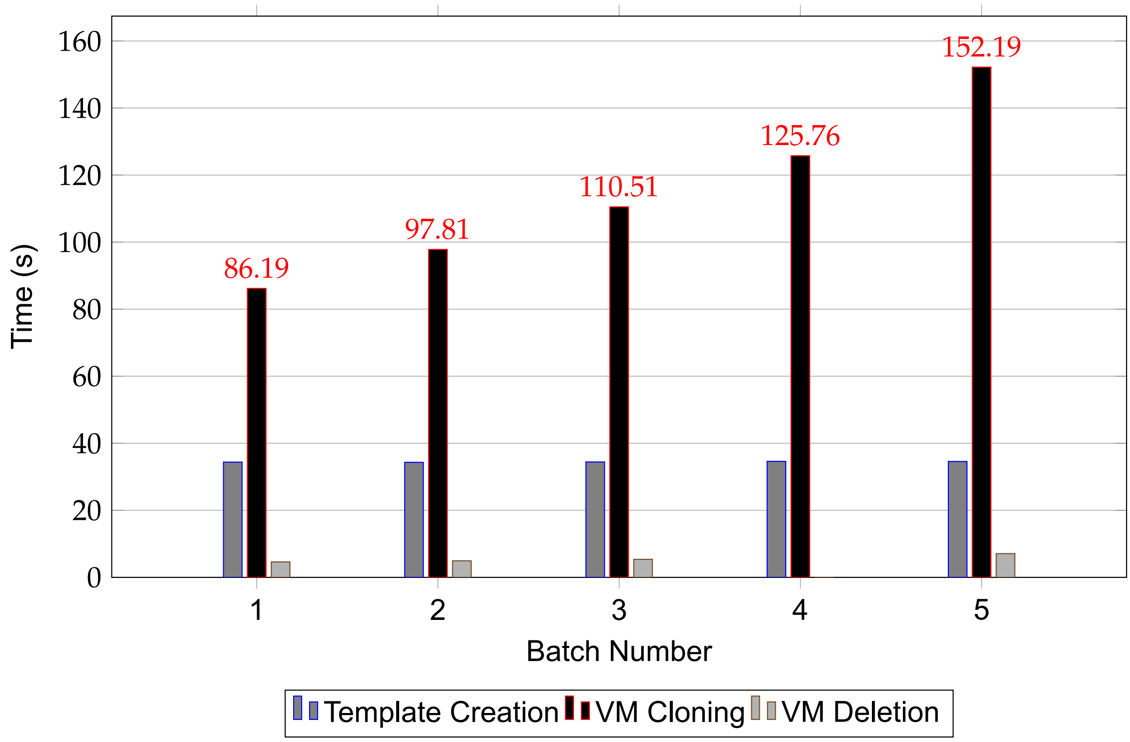


Figure 6.8: Grouped bar chart showing VM operation times. Cloning time is labeled to highlight the rising trend. Results from Flask running purely sequential code

During initial stress tests of batch cloning and deletion of VMs, 200 at a time, on our single node Proxmox VE cluster, we observed rising task times in subsequent runs, specifically for the mass cloning of new VMs, as can be seen in Figure 6.8.

It was also noted that there was an error thrown by Proxmox VE during the 4th batch of tasks, specifically during the deleting task, causing it to fail.

After some investigation it was found that there were intermittent failures to remove VM disks. These failures were *not* detectable via the Proxmox VE HTTP API responses and only appeared in the Proxmox VE server logs. As orphaned disks accumulated, overall performance degraded significantly.

Observed Task History Outputs:

1st type of output: disk removed successfully

```
trying to acquire lock...
OK
Logical volume "vm-348786940-disk-0" successfully removed.
```

```
TASK OK
```

2nd type of output: intermittent lock-timeout failures followed by disk removed successfully

```
trying to acquire lock...
Could not remove disk 'local-lvm:vm-120993831-disk-0', check manually:
can't lock file '/var/lock/pve-manager/pve-storage-local-lvm' - got timeout
trying to acquire lock...
OK
Logical volume "vm-120993831-disk-0" successfully removed.
TASK OK
```

3rd type of output: failure to remove disk

```
trying to acquire lock...
Could not remove disk 'local-lvm:vm-363495383-disk-0', check manually:
can't lock file '/var/lock/pve-manager/pve-storage-local-lvm' - got timeout
trying to acquire lock...
can't lock file '/var/lock/pve-manager/pve-storage-local-lvm' - got timeout
TASK OK
```

4th and final type of output: storage config update errors and failure to remove disk

```
trying to acquire lock...
Could not remove disk 'local-lvm:vm-5469324-disk-0', check manually:
can't lock file '/var/lock/pve-manager/pve-storage-local-lvm' - got timeout
trying to acquire lock...
can't lock file '/var/lock/pve-manager/pve-storage-local-lvm' - got timeout
trying to acquire cfs lock 'file-user_cfg' ...
TASK OK
```

This suggests Proxmox VE's locking mechanism can't keep pace with big amounts of deletion requests in quick succession.. The lock is used to ensure that two tasks dont modify the LVM's metadata simulatenously. Since there should be some underlying I/O tasks that are piling up, the system can't keep pace and eventually starts resorting to a retry mechanism to keep up, but even this is insuficient and starts failing more and more towards the end as it becomes fully congested. At the end, the system starts becoming overwhelmed and also begins having trouble updating its internal storage config file.

This, combined with other factors were the main reason that led us to implement a hard limit on the amount of concurrent requests that can be made from the web application to Proxmox VE API. Still, while this significantly reduces the chances of this problem reocurring, it does not fully remedy the problem and additional future work should look into solving this matter completely.

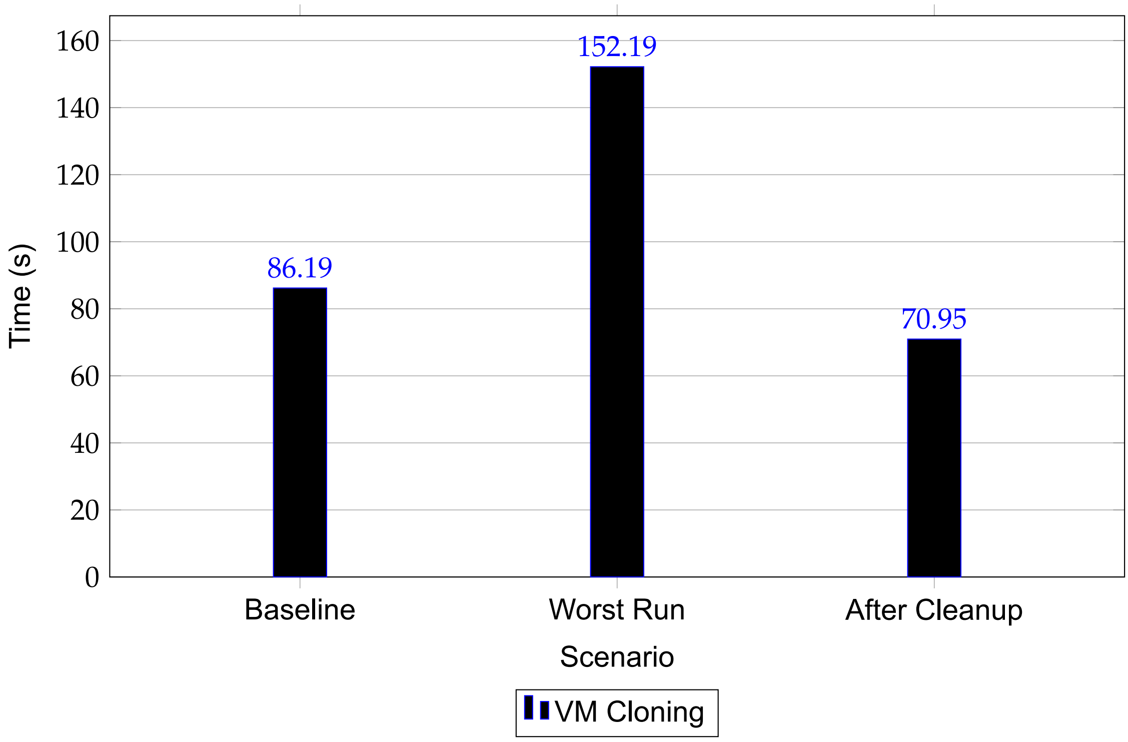


Figure 6.9: Bar chart showing VM cloning times after cleanup, at baseline, and in the worst case scenario.

After writing a small script to perform a cleanup of the orphaned disks we can see in Figure 6.9 that performance was improved from even our 1st recorded baseline test.

6.2. System Usage

Due to the very early and prototipical UI developed for the web application as well as lack of time to gather users in order to perform usability tests, this section will contain a guide on how to perform various use cases.

6.2.1 Create a new exercise and enroll students

To start, the user must provide privileged credentials using the login form shown in Figure 6.10. Without authorized credentials, the web application will not authorize the creation of new exercises.

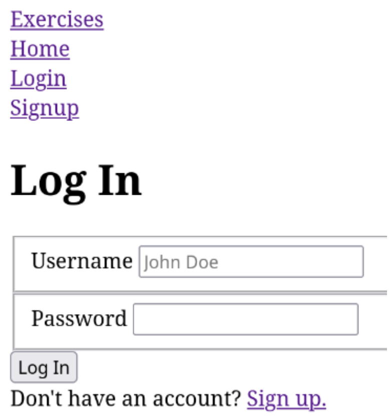


Figure 6.10: A screenshot of the login page

Next, the user should navigate to the “Exercises” page via the navigation bar, and then select “Create Exercise”. This will display the form shown in Figure 6.11.

Figure 6.11: A screenshot of the create exercise page

The form includes the following key fields:

- **Template VM Proxmox ID**: This refers to the Proxmox ID of the template VM to be cloned. The template must meet the previously defined requirements: it should have GNS3 installed and configured to start automatically after boot, and it should contain the necessary network devices.

- **GNS3 Project File**: This field accepts a file with the `gns3project` extension, which can be exported directly from GNS3.
- **Exercise validation**: This field allows the user to define one or more validation checks to be executed on the specified devices. Currently, only `ping` and `traceroute` commands are supported. These validations will be executed when a student requests automatic assessment.
- **Exercise pre-configuration**: This field enables the execution of custom commands on any supported device type for initial configuration. These commands will be executed only on the template VM before it is converted into a reusable template.

After completing this process, clearing the functional use case described in Subsection 4.5.2.2,the user should navigate to the newly created exercises' page, as shown in Figure 6.12, and click on "Manage Exercise".

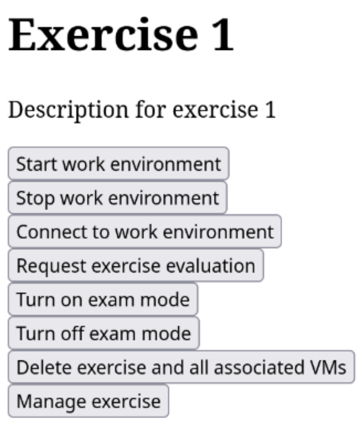


Figure 6.12: A screenshot of the exercise page

In the management interface (Figure 6.13), the user can enroll or remove students from the exercise. Enrolling a student automatically creates and assigns a dedicated VM, completing the use case in Subsection 4.5.2.3, while removing them destroys the corresponding VM. It is important to note that exercises are only visible to students who are enrolled in them.

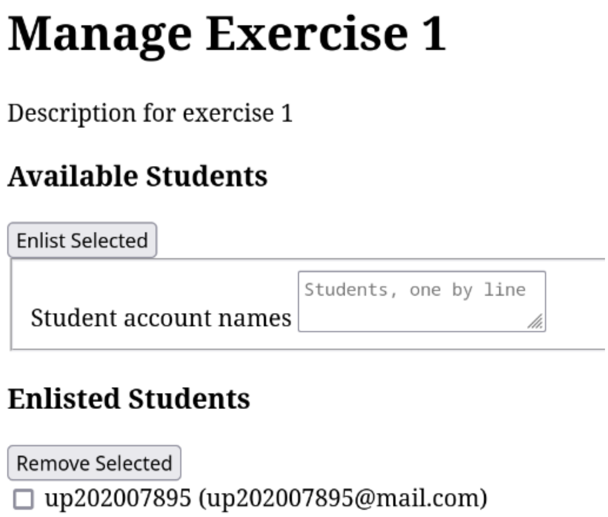


Figure 6.13: A screenshot of the exercise management page

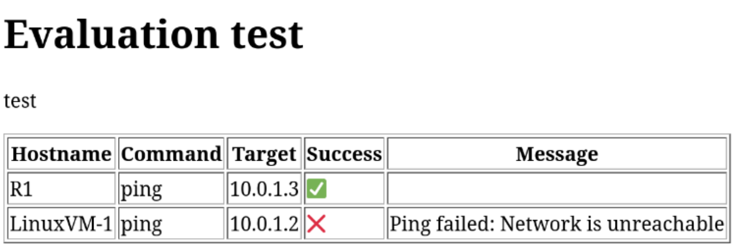
6.2.2 Complete an assignment and request an assessment

To begin, the user must log in using the form shown in Figure 6.10, ensuring the account is enrolled in at least one exercise. After logging in, the user should navigate to the exercises page (Figure 6.12) and click on ”Start Work Environment”, described in Subsection 4.5.2.4.

Once the environment has been initialized, the user can click on ”Connect to Work Environment”, which will redirect them to the gns3-web instance hosted on their dedicated VM for the selected exercise. Within the GNS3 interface, the user should configure the available devices according to the requirements specified in the exercise description.

When ready, the user can click ”Request Exercise Evaluation” to trigger the automated validation process, which checks whether the exercise has been correctly configured.

After the assessment is complete, the results are displayed on the page shown in Figure 6.14, as described in Subsection 4.5.2.5.



Hostname	Command	Target	Success	Message
R1	ping	10.0.1.3	✅	
LinuxVM-1	ping	10.0.1.2	❌	Ping failed: Network is unreachable

Figure 6.14: A screenshot of the exercise management page

7. Conclusion & Future Work

This work explored the design and implementation of an automated network assessment system, building upon the work of Santos [1]. The system was developed for the deployment and evaluation of networking assignments, with each student interacting with a dedicated GNS3 environment hosted via Proxmox VE VMs and with the intention of being used in both classroom and examination settings, allowing instructors to allocate more time toward guiding and supporting students, rather than spending it on manual evaluation.

Throughout the project, several key aims and objectives were successfully met. A modular architecture was established, enabling the creation, management, and evaluation of network assignments. Integration with Proxmox VE allowed for automated VM lifecycle management, while GNS3 provided a flexible environment for deploying practical networking scenarios. With assessment being done with Nornir, which enabled scalable and repeatable command execution across multiple devices, and a web back-end built using FastAPI that facilitated communication between all system components.

One of the central objectives was to allow students to initiate assessments on demand. This was achieved through the use of the developed modules, which input a command to a given virtual network device, determine the correct command depending of its type (e.g. Cisco router, Linux VM have different syntax for a `traceroute`). This effort was made to ensure support for a diverse range of device types and vendors, as exposure to heterogeneous network environments better prepares students for the complexity of professional settings. While the current implementations has only support for a few device types, the modular structure can easily be expanded upon for broader compatibility in the future. The modules developed during the project offer a basis for extensibility.

Another major aim of this project was also to unify and extend the components originally developed by Santos [1] into a cohesive back-end system. This required significant development effort, particularly in defining clear interfaces between components and ensuring they could operate together reliably under various conditions.

Significant progress was also made in terms of asynchronous handling and API development. The API design was iteratively refined to ensure clear boundaries between responsibilities while maintaining ease of integration with other components.

7.1. Lessons learned

This project highlighted several important lessons, one of them being the criticality of asynchronous I/O in system involving remote API calls. For this, Python's asynchronous capabilities, in conjunction with libraries that support them, proved invaluable. Additionally, it taught us key lessons in API design, particularly that modularity facilitates maintainability and integration, especially when multiple external systems are involved (Proxmox VE, GNS3).

Additionally, we learned that error handling, observability, and retry mechanisms should be devised and implemented from the the very early steps of development in networked systems, where silent failures during provisioning can propagate and lead to complex, hard-to-diagnose issues.

One more important lesson is the need to run tests periodically to ensure good system performance, as we found during our tests that our performance was decreasing with no major errors to be seen anywhere, which highlights the importance of monitoring and benchmarking.

7.2. Future Work

Building on the current system, future work should aim for several things. In terms of security and access control, the groundwork was laid for role-based authentication. However, further exploration is needed into Proxmox VE's native role and permission system. At present, Proxmox VE grants full administrative access to authenticated users, which is acceptable for development environments but poses significant security concerns in production. Currently, role-based access control is enforced solely within the web application layer, meaning that users such as students and teachers interact with the underlying Proxmox VE infrastructure using elevated privileges. A more secure and fine-grained authorization model—where roles like "student" and "teacher" are mapped to corresponding restricted scopes within Proxmox VE itself—remains a critical area for future development. Implementing this would help enforce the principle of least privilege and provide a more robust separation of concerns between the application logic and infrastructure permissions.

It would also be desirable to expand on the assignment definition model to introduce versioning, as well as introducing capabilities to create more complex grading of exercises including but not limited to adding exercise sub-lines and support for boolean expressions in lines and sublines.

Additionally improving on the UI using more modern frontend frameworks and shifting to Client Side Rendering could allow for a better UX with new features such as real time feedback and progress tracking of interactions with services external to the web application.

Developing more, but also introducing more complex modules, capable of chaining commands, and supporting a much wider range of devices is key in making sure this system can go overcome the limitations of its existing counterparts, such as Cisco's Packet Tracer, by supporting more complex, multi-step, assessment of protocols and configurations not available to them.

Furthermore, exploring the capabilities and limitations of the system in a multi-node cluster environment presents a another direction for future work. While Proxmox VE offers robust support for clustering and centralized management of multiple nodes, it does not natively include mechanisms for automated load balancing across those nodes. In the current implementation, VM placement decisions must be made manually, which can lead to inefficient resource utilization, especially under dynamic or heavy workloads. Developing an integrated load balancing feature could significantly enhance scalability, fault tolerance, and system responsiveness. This would involve monitoring node resource usage in real-time and dynamically provisioning or migrating acvms to balance CPU and memory loads more effectively across the cluster.

Another promising direction for future work lies in providing optional containerized environments for student exercises. While this was not pursued in the current implementation due to the lack of time to perform a thorough risk analysis, the potential benefits justify further investigation. Containerization could reduce resource usage and startup times for exercises that do not require full virtualization, such as those relying solely on IOU and VPCS as well as others that do not rely on KVM.

Simultaneously, as the system grows, it will be vital to integrate unit and system tests to ensure reliability and maintainability as the platform scales, to ensure the continued good functioning of older parts.

In conclusion, this system represents a promising step toward a fully automated and scalable platform for practical networking education. While there is still much work to be done before it can be fully integrated in institutions and courses, the progress made so far provides a strong basis for further growth and refinement.

References

[1] P. M. C. Santos, "Environment for practical evaluations in network administration," Master's thesis, Faculdade de Ciências da Universidade do Porto, Porto, Portugal, 2024, accessed: March 21, 2025. [Online]. Available: https://hdl.handle.net/10216/164899 [Cited on pages 1, 2, 3, 19, 27, 63, and 81.]

[2] GNS3 Documentation, "Architecture," n.d., accessed: March 15, 2025. [Online]. Available: https://docs.gns3.com/docs/using-gns3/design/architecture/ [Cited on page 6.]

[3] Proxmox Server Solutions GmbH, *Proxmox VE Administration Guide*, 2025, accessed: March 21, 2025. [Online]. Available: https://pve.proxmox.com/pve-docs/pve-admin-guide.html [Cited on page 9.]

[4] P. J. Eby, *PEP 333 – Python Web Server Gateway Interface v1.0*, Online, 2003, accessed: March 21, 2025. [Online]. Available: https://peps.python.org/pep-0333/ [Cited on page 12.]

[5] P. Projects, "Flask documentation," Online, 2025, accessed: March 21, 2025. [Online]. Available: https://flask.palletsprojects.com/en/stable/ [Cited on page 13.]

[6] K. Reitz and R. Contributors, "Requests: Http for humans," Online, 2025, accessed: March 18, 2025. [Online]. Available: https://requests.readthedocs.io/en/latest/ [Cited on page 14.]

[7] T. Christie and E. Contributors, "Httpx: A next generation http client for python," Online, 2025, accessed: April 04, 2025. [Online]. Available: https://www.python-httpx.org/ [Cited on page 18.]

[8] D. Barroso, "Nornir: The python automation framework," Online, 2025, accessed: March 21, 2025. [Online]. Available: https://nornir.readthedocs.io/en/latest/ [Cited on page 19.]

[9] J. Leal and F. Silva, "Mooshak: a web-based multi-site programming contest system," *SOFTWARE-PRACTICE & EXPERIENCE*, vol. 33, no. 6, pp. 567–581, MAY 2003. [Cited on pages 21 and 22.]

nornir_lib documentation

This library is responsible for connecting to GNS3 devices in a given topology, inputting commands, retrieving output, and analyzing results to evaluate success or failure.

It consists of the following components:

- `modules/` – Described in detail in the Subsection 6. Contains predefined command modules.
- `utils/` – Provides helper functions that interface with GNS3 or facilitate command execution.

Additionally, it uses several configuration files located in the `app/` folder:

- `config.yaml` Contains paths to the `host_file`, `group_file`, and `defaults_file`, as well as the configuration of the Nornir `runner`.
- `host_file` Describes the VMs or containers hosting GNS3 servers. At minimum, the IP address, group (typically `linux`), username, and password (in plain text) must be specified.
- `group_file` Defines default settings for groups. **Note:** `fast_cli` must remain `false` to ensure tests run reliably.
- `defaults_file` Currently unused.

Modules

The project comes with built-in test modules. To use a module:

1. Instantiate the module class by passing the configured Nornir object for the desired machine/project.
2. Call the `command()` method with the required arguments, which may vary by module.

Implementing a New Module

To create a custom module:

- Subclass the `CommandModule` class located in `modules/module.py`.
- Implement the following methods:
  - `_command_router`
  - `_command_switch`
  - `_command_vpcs`
  - `_command_linux`
  - `interpret_cisco_response`
  - `interpret_linux_response`
  - `interpret_vpcs_response`
- For command methods, use `PingModule` as a skeleton and modify the command string accordingly.
- For interpretation methods, implement logic that evaluates command output and determines whether it meets expected results.

proxmox_api endpoints

This library is responsible for interacting with the Proxmox VE API, automating management tasks such as starting, stopping, and templating virtual machines and containers.

Unless otherwise specified, all methods return a boolean value. In the event of network errors:

- Functions expecting a boolean will return `False`.
- Functions expecting other types will return `None`.

All other exceptions are propagated and should be caught by the caller.

Module: `proxmox_vm_actions`

```
_get_status(proxmox_host, session, vm_id)
    Queries the state of a VM. For internal use. Returns the raw response.

acheck_free_id(proxmox_host, session, id)
    Checks if given VM/CT ID is unused. Does not reserve it.

create(proxmox_host, session, template_id, clone_id, hostnames)
    Clones the specified template VM with the given hostname.

check_vm_status(proxmox_host, session, vm_id)
    Checks if the VM is running and the QEMU guest-agent is active.

check_vm_is_template(proxmox_host, session, vm_id)
    Checks if a VM is in template format.

start(proxmox_host, session, vm_id)
    Starts the specified VM.

stop(proxmox_host, session, vm_id)
    Stops the specified VM.
```

```
template(proxmox_host, session, vm_id)
    Transforms the VM into a template.

destroy(proxmox_host, session, vm_id)
    Destroys the specified VM.
```

The `session` parameter must be created using the `connection` module in `utils/`, and must contain valid credentials for the Proxmox cluster.

Module: `proxmox_vm_firewall`

```
create_proxmox_vm_isolation_rules(proxmox_host, first_vm_id, last_vm_id, allowed_vm_ip, s
    Enables firewall and blocks communication between student VMs.
    Only allows communication with the allowed VM (typically the teacher VM).

delete_proxmox_vm_isolation_rules(proxmox_host, first_vm_id, last_vm_id, allowed_vm_ip, s
    Removes previously set firewall rules, re-enabling inter-VM communication.
```

Module: `utils`

Various utility functions to support Proxmox interaction:

- `connection.proxmox_connect`: Authenticates and returns an HTTP session with a valid authentication cookie. See the ProxmoxVE authentication documentation for details.
- `proxmox_base_uri_generator`: Generates the base URI for API calls to Proxmox.
- `proxmox_vm_ip_fetcher`: Retrieves the current IP address or hostname of a VM or container given its ID.