Open Source approach in two metaOS projects

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Abstract

Transparency, collaboration, security, and digital sovereignty are the open source values that are also important to many European countries and institutions. Open source software offers practical advantages, cost savings, and opportunities for innovation that contribute to the region's technological advancement and competitiveness, as well as fosters collaboration among developers and encourages innovation. On top of these values, several European projects try to build a sustainable and innovative future. In this paper the authors present two examples of an open source applications of meta-operating system (metaOS). The first NExt generation Meta Operating systems (NEMO) builds the future of the Artificial Intelligence of Things(AIoT)-edge-cloud continuum by introducing an open source, modular and cybersecure metaOS. The second regards the open source solutions provided by the NEPHELE project to assist orchestration of distributed applications across resources in the computing continuum. In this matter, the open source components of the metaOS projects are presented for each functional layer in the architecture, demonstrating the value of open source for the metaOS sustainability in a specific use case.

CCS Concepts

• **Software and its engineering → Open source model**; *Software prototyping*; • **Computing methodologies →** *Distributed computing methodologies.*

Keywords

open source software, virtual object, virtual object stack, meta-orchestration framework, distributed application

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1 Introduction

Open-source meta-operating systems (meta-OS) are becoming a key focus in Europe as industries move toward more interconnected and intelligent computing environments. Unlike traditional operating systems, a meta-OS works across multiple layers, enabling seamless integration of microservices, AI-driven applications, and cloud-edge deployments. By embracing open-source principles, Europe aims to create flexible, secure, and interoperable solutions that reduce reliance on proprietary technologies. These efforts are not just about innovation, they're also about digital sovereignty, ensuring that European businesses and researchers have control over the technologies shaping their future. To support this vision, the European Union is actively funding and promoting open-source meta-OS initiatives that prioritize security, scalability, and ease of deployment.

In fact, community-driven open source is proven to be the best way to co-innovate on high-quality, scalable, and sustainable technologies that allow organizations to build better products faster, accelerate revenues, and create value. Collaborating with competitors on non-differentiating technologies frees scarce resources to focus on delivering value-added and differentiating features faster [1, 2]. An Open Source community is the keystone for the sustainability of any project. If you are not able to attract and convince people that your code is worth spending time and resources on testing it, providing feedback, providing patches, and contributing in general, then all the intrinsic value of open source is lost. In other words, without Maturity, Quality, Cost of Acquisition and Control, the sustainability of our code is nearly impossible. And vice-versa, Sustainability is a great indicator demonstrating the Maturity, the Quality and the Control of the code.

With this in mind, in this paper two European projects present their open source core development.

NEMO [1] is leading the charge by developing decentralized, AI-driven platforms that automate resource management and streamline complex computing environments. By fostering a strong open-source community, these initiatives not only enhance transparency and security but also create sustainable ecosystems where businesses, developers, and researchers can collaborate. As Europe pushes forward with its digital strategy, open-source meta-OS technologies are set to play a crucial role in shaping the next generation of AIoT and edge-cloud computing.

NEPHELE [2] has adopted an open-source strategy for the development of the main artifacts of the project, focusing on the orchestration aspects for distributed applications over resources in the computing continuum. Among others, these artifacts include an open-source stack for the virtualization of IoT devices, a development enviroment for distributed applications, and a meta-orchestration framework for the lifecycle management of distributed applications. The paper is organized as follows: in Section 2, the authors give a brief overview about Open Source importance in Europe. Complementary, Section 3 presents the open source components of the NEMO use case solution describing the architecture and the results?. Section 4 presents two of the main open-source artifacts produced within the NEPHELE project, considering the adoption of a System of Systems (SoS) approach for their development. Finally, Section 5 concludes the paper by summarizing and discussing the work.

[1]https://meta-os.eu/
[2]https://nephele-project.eu/

2 Open Source in EU projects

The open-source model aligns closely with the core values of transparency, collaboration, security, and digital sovereignty that many European nations and institutions hold dear. It offers numerous benefits, including cost savings, practical advantages, and a strong potential for innovation, all of which contribute to Europe's technological growth and global competitiveness.

By embracing open-source software, European countries can lessen their reliance on proprietary vendors, many of which are based outside Europe. This reduces the risk of external influence and helps safeguard digital sovereignty, giving European institutions more control over the technologies they adopt.

Open-source software also promotes collaboration among developers and fosters innovation. Since anyone can contribute to and refine the code, open-source projects tap into the collective expertise of a global community. European countries are increasingly recognizing the potential of open-source ecosystems to drive both innovation and economic development.

There are also political motivations behind Europe's support for open-source solutions. A key concern for Europe is data privacy and protection. Open-source software enhances transparency, offering full visibility into the code, which makes it easier for European institutions to ensure compliance with regulations like the General Data Protection Regulation (GDPR). By opting for open-source software, Europe can better mitigate the risks of data breaches and unauthorized access.

Supporting open source also aligns with European ideals of openness, fairness, and transparency. By adopting open-source software, European countries not only demonstrate their commitment to democratic values but also position themselves as leaders in technology governance, creating high-quality software that can be widely adopted both within Europe and globally.

Moreover, because open-source software nurtures innovation and entrepreneurship, European governments recognize its ability to drive technological progress, stimulate economic growth, and generate job opportunities in the tech sector.

In conclusion, Europe's embrace of open-source software reflects a strategic effort to protect its values, promote its interests, and shape the future of technology in line with its broader objectives.

2.1 Open Source in MetaOS EU projects

One of the major roles of the Eclipse Foundation, is to break down the idea that RIA (Research & Innovation Action) projects must develop in silos. It is important to encourage project consortia to collaborate as much as possible, starting with the definition of a common core architecture on which most of them can build. Eclipse call this goal "Breaking down project silos". Then, in order to give a reference and a vision to this goal, an investigation on the six european metaos projects has been conducted. The resulting Open Source Stack (OSS) as reference for the continuum has been consolidated, approved and presented in this paper [3] and shown in Figure 1.

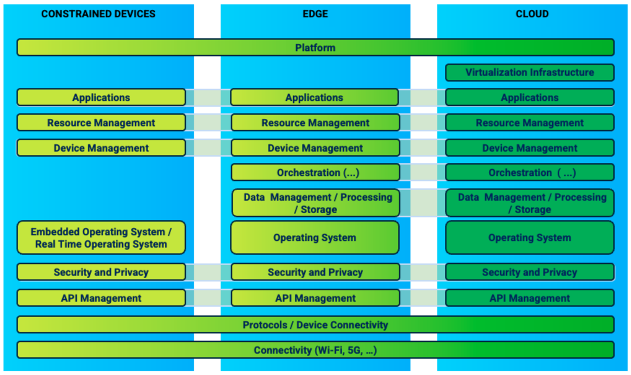

Figure 1: Open Source Stack

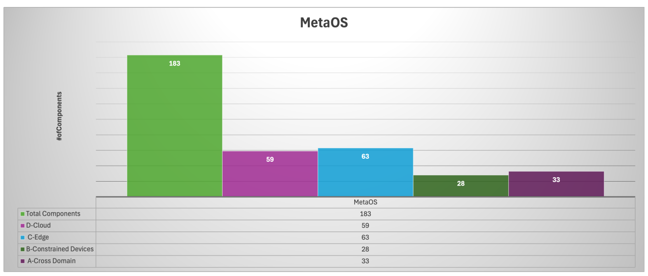

Figure 2: MetaOS open source components in the OSS

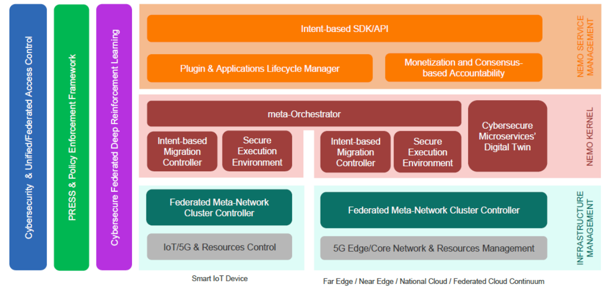

Figure 3: NEMO open source components

This OSS is a results of an investigation where the information related to the open source component in six MetaOS projects has been collected and analyzed [3]. Figure shows the number of this investigation: a total of 183 open source components divided in four layers. The four layers reflect four main domains: one related to a cross domain, A- Cross Domains, and three associated to the Open Source Stack, B-Constrained Devices, C-Edge, D-Cloud.

As the figure highlights, the MetaOS projects are considering mainly components in the "Edge" and "Cloud" vertical domains. This is an expected result given that we work with the cluster of projects dedicated to the cloud to edge continuum. In this paper two of these six meteOS projects are presenting their open source approach on some real use cases....

3 NEMO

As data volume and scaling demands continue to grow rapidly the need for combining the AI technologies with the IoT domain for an efficient resourse managing is of paramount importance. The AIoT edge requires fast, adaptive solutions across development, deployment, and operations. While zero-code tools and ontology-assisted NLPs are advancing, NEMO recognizes that accelerating AIoT adoption demands more than intelligent, intent-driven development—it also requires seamless, automated deployment and orchestration. NEMO envisions intent-based (zero-code) microservices programming tools combined with a platform that allows effortless and seamless building, deploying, executing and managing applications in diverse environments in the edge-cloud continuum (ZeroOps) deployments. While existing solutions like Docker, Kubernetes, Minikube and OpenShift offer orchestration capabilities, the dynamic nature of the AIoT edge demands for opportunistic migration to become the standard way that services are being deployed. NEMO's goal is to simplify deployment by minimizing administrative effort, enabling near-instant installation on virtually any AIoT device. The project seeks to unify various tools, mechanisms, and essential plugins into a meta-operating system, delivered as an automated or semi-automated software package that ensures interoperability, security, and compliance with privacy policies. With its innovative approach, the European-funded NEMO initiative aims to transform the AIoT-edge-cloud continuum by introducing an open-source, modular, and cyber-secure meta-operating system. By integrating AI-as-a-Service into network self-organization and microservices orchestration, NEMO strives to enhance visibility, attract early adopters, and cultivate a sustainable community of users and developers committed to its long-term success [4].

3.1 Open Source Components

An overview of the NEMO open source component can be found here [5]. In this paper the architectural patterns used within the NEMO use cases will be presented. NEMO meta-architecture was designed considering the principles of modularity, interoperability, robustness and scalability, Figure 3 shows all the core components of the NEMO. NEMO since its inception was planned to provide an infrastructure and the components developed to the community embracing an open-source philosophy. It is foreseen that NEMO meta-architecture may act as a leading paradigm for the development of future meta-OS projects. Within the NEMO framework, the NEMO meta-architecture has been instantiated in the domains of agriculture, energy manufacturing and media.

Following the work carried out by EUCEI, the architectural patterns used within NEMO are inspired as reusable solutions in terms of software design and architectural patterns. The NEMO components are categorized into three distinctive layers. The first layer, starting bottom way up in Figure 3, is the Infrasture Management layer. In this layer the related components are responsible for establishing network connections between the several clusters in the edge-cloud continuum. This critical layer provides secure communication and interfaces for 3rd party components to integrate and communicate with the NEMO platform and exchange information on the domain of resources and migration processes. The NEMO kernel layer is the most important layer of the NEMO platform.

In this layer dwells the orchestration process that is responsible for the decision making of the migration of workloads across the edge-cloud continuum. The meta-orchestrator uses as an input the policies and rules from the upper layer, along with the information regarding the available resources across the multiple clusters and based on the application's requirements selects the most appropriate infrastructure for its execution. The migration controller is responsible for performing all the necessary steps for deploying and executing the workloads based on the meta-orchestrator's decision on the hosting cluster. The last layer is the NEMO Service Management layer. In this layer the mechanisms related to business oriented information is collected, such as policies and user-restrictions. This information is passed to the meta-orchestrator for decision making. In addition, this layer houses the REST API that 3rd party services can use to integrate and use the NEMO platform. In the following section the verticals used to validate NEMO's innovation are described to provide an example of the extensive possibilities NEMO offers.

3.2 Use Case Application

NEMO is designed to be used in numerous and versatile applications expanding from sensing/actuating use cases to heavy multi-media applications. NEMO is validated in 5 most prominent application domains such as Farming, Energy, Mobility/City, Industry 5.0 and Media/XR and 8 use cases in 5+1 Living Labs [3], utilizing more than 30 heterogenous IoT devices and real 5G infrastructure. Moreover, with several projects joining NEMO through the Open Call process, it is envisioned that the areas of applicability will be much more. In this paper, the uses cases investigated by the pilots participating in NEMO will be presented as well as the key features of NEMO that will improve their processes. The Smart Farming domain focuses on two innovative use cases to improve olive grove management. First, Aerial Precision Bio-Spraying is using UAVs to protect olive trees from fruit flies by conducting targeted bio-spraying, guided by real-time microclimate data from IoT sensors and video analysis from drones equipped with visual and multispectral cameras. Machine learning models determine where spraying is needed, with the training process enhanced for better performance and energy efficiency using Federated Deep Reinforcement Learning across IoT, edge, and cloud resources. The second approach, Terrestrial Weed Management, utilizes Autonomous Guided Land Vehicles (AGLVs) to control weeds organically. These robots, equipped with cameras and sensors, are using machine learning to detect obstacles and mow weeds autonomously within olive groves. The models are running either on AGLVs, edge devices, or even external servers to ensure energy efficiency and optimal service quality. NEMO is being tested in the Smart Energy & Smart Mobility Living Lab through two main use cases. In Smart Grid Flexibility, the focus is on monitoring and analyzing the quality of electricity voltage at MV/LV levels using advanced sensors like smart meters and power quality analyzers. AI will assist with predictive maintenance, power flow forecasts optimizations and improvements in the grid protection. In the Smart Mobility/City, NEMO is providing driver-friendly solutions for smart city mobility, including EV charging based on the demand of renewable energy solutions. It is using a variety of data sources, such as traffic cameras and weather data, to train AI models that predict traffic flows and parking availability. In the Smart Industry 4.0 domain, NEMO is being validated through two use cases. The first, a fully automated indoor logistics/supply chain, is focusing on automating the transport of materials in ADAS manufacturing, replacing the manual handling of components with an integrated system of 3D cameras, barcode scanners, and collaborative robots (cobots and AGVs) to autonomously pick and transfer materials from Auto Store to production lines. The second application, Human-Centered Indoor Factory Environment Safety, is enhancing the AGV safety by combining real-time localization data from cognitive sensors like cameras, radar, and lidar. Supported by a high-speed, low-latency private network, AI is tracking human positions and creates a "safety shell" around workers, while federated deep reinforcement learning (CF-DRL) will allow AGVs to avoid collisions autonomously.

In the Smart City & Smart media domains, NEMO is being tested in three use cases in which ML and IoT technologies are used for enhanced UX. Athens Race Media Coverage – Spectators and professional cameras capture race footage, which is processed using AI both on devices and at the network edge. Key moments, such as top runners' progress or notable events, are automatically highlighted and shared on social media. Spectators can enhance their contributions and engage with others during incidents. VR Experience of Phidias' Workshop – Visitors at the FHW Cultural Center can immerse themselves in an interactive VR reconstruction of the ancient sculptor Phidias' workshop. Using AR/VR headsets and wearable devices, the system adapts the experience based on users' emotional and physical responses, leveraging AI across IoT, edge, and cloud networks. Enhanced Audiovisual Experience in the Tholos Dome VR Theatre – A smart system improves the VR theatre experience by integrating IoT devices and AI-driven gesture recognition. It analyzes the presenter's movements, triggering real-time effects and interactions in the virtual world, enhancing the audience's engagement.

4 NEPHELE

In the NEPHELE project, three of the main outcomes that are produced regard an open-source software stack that supports the virtualization of IoT devices, a development environment for distributed applications, and an open-source meta-orchestration framework for the lifecycle management of distributed applications over multi-cluster resources in the computing continuum.

NEPHELE has adopted an open source software development strategy from the very beginning of the project activities. The objective is to tackle challenges in the IoT, edge, and cloud computing part of the continuum and to develop open source software modules that can be adopted and extended in the future, considering their application in different vertical industries. Under this perspective, a set of generic functionalities are offered for IoT virtualization, IoT convergence with edge and cloud computing technologies, and orchestration of distributed applications over multi-cluster infrastructure. Such functionalities can be adopted and extended in the future, leading to customized versions of the offered software tools to meet performance, security, privacy, and energy efficiency requirements from different vertical industries.

[3] https://www.youtube.com/@henemoproject

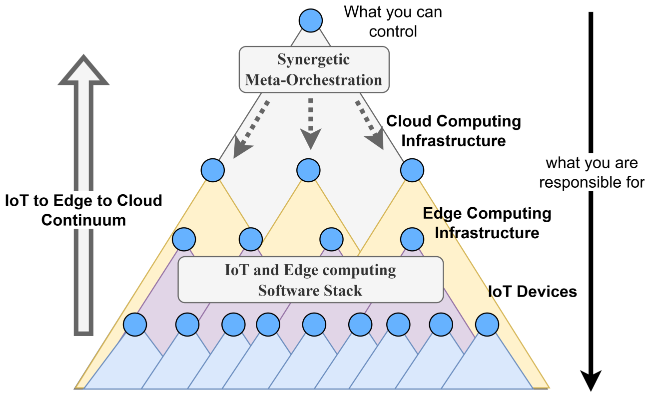

Figure 4: System of Systems approach in NEPHELE.

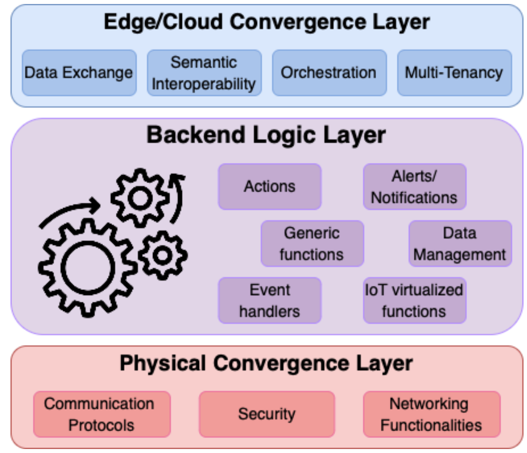

Figure 5: VOStack Layers [6].

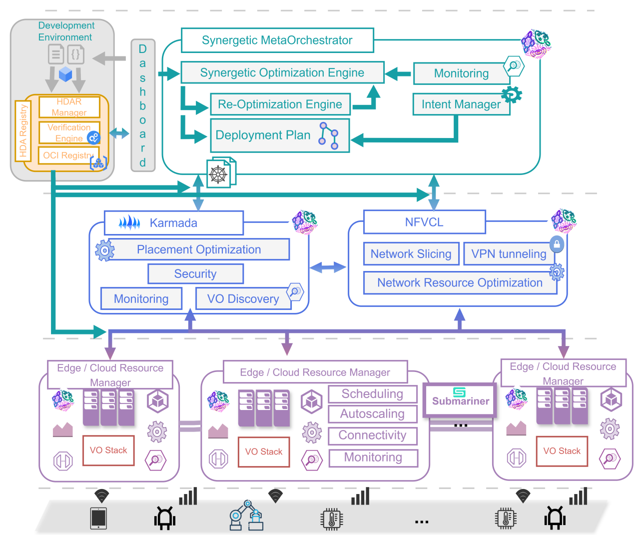

Figure 6: NEPHELE Development Environment, SMO architecture and interaction with VOStack.

Toward this direction, a system of systems (SoS) approach is adopted, as depicted in Figure 4. In the SoS approach, the node at the top of the pyramid has the responsibility for the deployment of a distributed application over resources that span the computing continuum. However, the control of the provision of the application is distributed across multiple nodes in different levels of the hierarchy. Collaboration among nodes is expected to achieve a common goal, considering both local and global optimization objectives. Following the SoS approach, a synergy is established among the main software outcomes of the NEPHELE project.

The NEPHELE SoS approach is also depicted in the development of the main open-source artifacts. At the top level, the NEPHELE Synergetic Meta-Orchestrator (SMO) is responsible for the lifecycle management of distributed applications. The NEPHELE SMO manages resources across the continuum, allocating control to different entities for compute and network resource management (e.g., one entity per cluster). Moving down to the IoT part of the infrastructure, interoperability is supported with the Virtual Object Stack (VOStack) that is an open-source software stack that supports virtualization of the IoT infrastructure. An open-source development environment is also made available, enabling application developers to develop and onboard distributed applications to the SMO. Following, we provide details for these open-source components.

The open-source software stack is called the Virtual Object Stack (VOStack) and builds upon the concept of the Virtual Object (VO). A VO is considered as the virtual counterpart of an IoT device. It provides abstractions for managing any type of IoT device while augmenting the supported functionalities through the development of custom functions. The concept of a composite virtual object (cVO) is also introduced to manage information coming from multiple VOs or to extend the functionalities offered by a VO. The VOStack supports interaction with both physical IoT devices and edge/cloud computing orchestration platforms. It has three main architectural layers, namely the physical convergence layer, the edge/cloud convergence layer, and the back-end logic layer [6]. A high-level view of the VOStack layers is provided in Figure 5. Open-source implementations of the VOStack are made available, well-aligned with the specifications of the W3C Web of Things (WoT) working group, as well as the Open Mobile Alliance LwM2M.

The NEPHELE Synergetic Meta-Orchestration (SMO) platform supports the orchestration of distributed applications over multi-cluster environments [7]. A high-level intent is translated into deployment and operational policies that manage the lifecycle of distributed applications while taking advantage of AI/ML techniques to increase automation and distributed intelligence. The management of both network and compute resources is supported by the NEPHELE SMO. Openness and modularity are supported by offering a set of orchestration modules that are activated on demand to manage orchestration actions (e.g., scaling, migration).

The NEPHELE Development Environment is built as a combination of several systems. It includes the Highly Distributed Applications (HDA) Registry and Verification Engine which offer a novel way of harmonizing the storage, distribution and verification pipelines for the artifacts from the telco, cloud-native and custom NEPHELE ecosystems, and the development sandbox that provides specialized utilities and an intuitive dashboard to develop and customize HDA graphs which natively connect to the lifecycle management of those applications over multi-cluster compute and network infrastructure.

5 Conclusion

In conclusion, open-source software and MetaOS represent two key advancements in the ever evolving landscape of technology. Open-source software fosters collaboration, transparency, and innovation, empowering developers and users to create and improve tools collectively. MetaOS, as a conceptual framework, further builds on this by creating a flexible and adaptive ecosystem that integrates various open-source components to provide a seamless, user-centric experience. By leveraging the power of open-source development and the adaptability of MetaOS, we can move towards a future where technology is more accessible, customizable, and capable of addressing diverse needs. Together, they represent a vision of a more open, interconnected, and dynamic digital world, where innovation thrives and users are at the center of technological advancement.

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