Enabling Network and Service Programmability in 6G Mobile Communication Systems

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Abstract

Network programmability is crucial for addressing the multiplicity and heterogeneity of Network Services, the diversity of the underlying infrastructure of Sixth Generation (6G) communication systems, and the requirements for maximum efficiency. The programmability of a service platform enables algorithmic network management by leveraging contemporary software virtualization technologies. Moreover, network programmability will abstract the essential network/service and resource configuration, as well as the production and administration of policy lifecycles, as the number of local breakouts (both public and private) is anticipated to grow exponentially. Network programmability is the central point of interest for Hexa-X, the European 6G flagship project, which aims to facilitate the dynamic adaptation to changing network situations and requirements for the most efficient use of available resources. To explore such a critical enabler of futuristic mobile networks, this article addresses the role of network and service programmability and its impact on various aspects of 6G within the context of Hexa-X. In order to accomplish this, the article begins by discussing Hexa-X's proposed service Management and Orchestration (M&O) framework for 6G. Based on this framework, it identifies and explores in greater detail the programmability of four primary processes in 6G: expressing application and service requirements; service description models and profiling; monitoring and diagnostics; and reasoning. Beyond the scope of the Hexa-X, this article aims to serve as a foundation for future research into network and service programmability in 6G.

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***Abstract*—Network programmability is crucial for addressing the multiplicity and heterogeneity of Network Services, the diversity of the underlying infrastructure of Sixth-Generation (6G) communication systems, and the requirements for maximum efficiency. The programmability of a service platform enables algorithmic network management by leveraging contemporary software virtualization technologies. Moreover, network programmability will abstract the essential network/service and resource configuration, as well as the production and administration of policy lifecycles, as the number of local breakouts (both public and private) is anticipated to grow exponentially. Network programmability is the central point of interest for Hexa-X, the European 6G flagship project, which aims to facilitate the dynamic adaptation to changing network situations and requirements for the most efficient use of available resources. To explore such a critical enabler of futuristic mobile networks, this article addresses the role of network and service programmability and its impact on various aspects of 6G within the context of Hexa-X. In order to accomplish this, the article begins by discussing Hexa-X's proposed service Management and Orchestration (M&O) framework for 6G. Based on this framework, it identifies and explores in greater detail the programmability of four primary processes in 6G: expressing application and service requirements; service description models and profiling; monitoring and diagnostics; and reasoning. Beyond the scope of the Hexa-X, this article aims to serve as a foundation for future research into network and service programmability in 6G.**

***Index Terms*—6G, Intent-based Processes, Monitoring and Diagnostic, Network Profiling, Network Programmability, Programmable Processes, Reasoning, Service Description, Service Management and Orchestration, Service Programmability**

I. Introductory Remarks

In parallel with the global deployment of Fifth-Generation (5G) communication systems, the research and development of Sixth-Generation (6G) communication systems have garnered significant interest from both industry and academia. 6G networks are anticipated to be equipped with a broader range of radio frequencies, a faster data and voice transmission rate, an improved spectrum efficiency, a greater user density capability, an extremely shorter latency, a vast coverage area, and a more automated and intelligent capability aimed at meeting the diverse set of functional, operational, and performance requirements of communication services of the next decade [1], [2]. To accomplish these goals, in addition to regulatory and technological trends that are essential for the design and deployment of 6G networks, major societal and economic trends must be analyzed one by one to help guide research and design for human-centered 6G communication networks in the 2030s [3].

Hexa-X, an European flagship project dedicated to developing a vision and technological enablers for Beyond 5G (B5G) and 6G, is committed to researching and developing wireless technologies and architectural solutions for B5G and 6G. The Hexa-X vision calls for an x-enabler fabric of connected intelligence, networks of networks, sustainability, global service coverage, extreme experience, and trustworthiness [2], [3]. The ambition of the Hexa-X project includes developing key technology enablers in the areas of: (a) fundamentally new radio access technologies at high frequencies and high-resolution localization and sensing; (b) connected intelligence through Artificial Intelligence (AI)-driven air interface and governance for future networks; and (c) 6G architectural enablers for network disaggregation and dynamic dependability [2], [4].

Network and service programmability in 6G is a key technological trend being researched by the Working Package 6 (WP6) of Hexa-X [5]. The grand objective of programmability is to use a set of intelligent tools to configure, deploy, manage, and troubleshoot a node (domain or layer) in a 6G network aimed at improving the performance and security of application delivery. This set of intelligent tools employs Application Programming Interfaces (APIs) and intelligent software to collect data for training the AI/Machine Learning (ML) algorithm [6], [7]. The API serves as an interface or controller during data collection or the entire service delivery process. The intelligent software is designed for a variety of purposes and can be executed locally or remotely. In either case, intelligent software is aimed at intelligently and automatically executing the required functionality or reacting to external events. Due to the fact that programmability offers numerous benefits, such as improved time and cost savings, enhanced customization, decreased human-made errors, and increased innovations, the Hexa-X WP6 has been motivated to explore its various aspects and effects on the Management and Orchestration (M&O) of 6G networks [5].

In this regard, Hexa-X WP6 has proposed an architectural framework for the M&O of 6G networks and services, on top of which programmability has been explored. The Hexa-X M&O Framework highlights that 6G networks are expected to be an extremely complex and heterogeneous environment, requiring intelligent solutions from the core network to the extreme-edge domain and the implementation of *device-edge-cloud continuum* management mechanisms [5]. In order to accomplish these goals, the entire 6G ecosystem must be transferred into a programmable environment and the intelligent tools and software must execute the processes autonomously. This will undoubtedly simplify the M&O of 6G networks.

On the basis of these benefits, in this paper we make the following contributions: *(a)* we provide an architectural framework for intelligent M&O of 6G networks oriented towards facilitating programmable processes; *(b)* we describe a set of programmable building blocks to specify Network Services (NSs), their requirements, and how they can be automatically profiled and monitored; and *(c)* we provide guidelines on how the novel software building blocks can be integrated and deployed as part of a DevOps workflow.

The rest of the article is structured as follows. In Section II, we discuss the Hexa-X M&O Framework for 6G networks. In Section III, we present the programmable processes for expressing NS applications and requirements. In Section IV, intent-based processes pertaining to the profiling and description models of 6G NSs are highlighted. Section V sheds light on programmable monitoring and diagnostic processes in the 6G network. In Section VI, programmable network enablers for reasoning are elaborated upon. Section VII addresses software integration-related processes in the 6G network. Finally, Section VIII provides concluding remarks.

II. Service Management and Orchestration Framework for 6G Mobile Communication Systems

In contrast to previous generations and even though 5G is said to have a great gap in management needs and complexity, 6G Service Management will cope with a humongous set of heterogeneous services and infrastructure complexity. One of the objectives of the Hexa-X M&O Framework is to be able to reduce the overall M&O complexity despite this expected increase in the intricacy of the infrastructure, network, and services. To address the aforementioned requirements as well as the ones considered in [5], the following novel capabilities have been defined as requirements for 6G M&O systems:

1) **Device-Edge-Cloud Continuum unified M&O:** The extreme-edge domain will provide resources for the deployment of 6G services through the M&O system. Extreme-edge end-devices will be characterized by being largely numerous, widely heterogeneous, and limited by a set of specific constraints such as computation capacity, power capability, and network volatility.
2) **Unified M&O across a multi-domain and multi-stakeholder ecosystem:** In this kind of ecosystem, each stakeholder would own and administer different domains using their own technologies, platforms, and interfaces. Thereupon, it is of paramount importance to define converging interfaces, resource-exposure mechanisms, and access control procedures in order to allow the M&O to cope with this scenario.
3) **Increasing levels of automation:** It is a critical enabler at several operational levels (such as service planning, provisioning, and optimization) for addressing the enormous complexity of future 6G networks and services. Beginning from a continuous monitoring perspective, the M&O Framework should be able to automatically identify and predict errors, failures, or misconfigurations and trigger the appropriate dynamic reactions.
4) **AI/ML and data-driven techniques adoption:** The M&O Framework should support AI/ML collaborative platforms that allow the use of AI/ML [8] and the sharing of scalable data and trained models across the Device-Edge-Cloud continuum in multi-domain and multi-stakeholder scenarios.
5) **Intent-based service planning and definition:** Future 6G M&O systems should be able to support service definitions and specifications based on natural language or intents. This approach will allow “non-technical” service verticals to define their own services without the requirement of learning specific service-definition languages (see Section III for more information).
6) **Cloud-native principles adoption in a telco-grade environment:** This innovative capability includes three aspects: *(i)* microservice-based Network Functions (NFs); *(ii)* Service Mesh implementation; and *(iii)* implementing Continuous Integration (CI) and Continuous Delivery (CD) pipelines with a high level of automation. The latter aspect will be highly innovative and challenging due to the requirement of pairing development and operational teams in a scope where service development is executed by multiple vendors.

It is worth noting that the 5G network architecture [7] was used as a baseline for the design of the Hexa-X Framework and that it inherits some key aspects from it. The 5G architecture is composed of three domains: the Service Domain for Verticals, the Network Domain, and the Infrastructure Domain. Each domain contributes to addressing business-related concerns, NFs capability requirements, and infrastructure complexity, respectively. Furthermore, it contemplates network automation by integrating two main Control Loops (CLs): *(i) Vertical CL*, within the Service Domain, steers the behavior of the network; and *(ii) Operator CL*, within the Network Domain, with specific functions related to network and management data analytics. The Hexa-X M&O Architectural Design is implemented by means of three different architectural views that, jointly, aim at providing a coherent and comprehensive description of the complete M&O Framework [5]:

- **Structural View:** Presents the main building blocks of the system and the interfaces that enable the communication between them. Section II-A is focused on describing the main points of this View.
- **Functional View:** Describes system behavior and functionalities. The rest of the sections of this paper focus on this View, specifically on those functionalities that are associated with programmable processes.

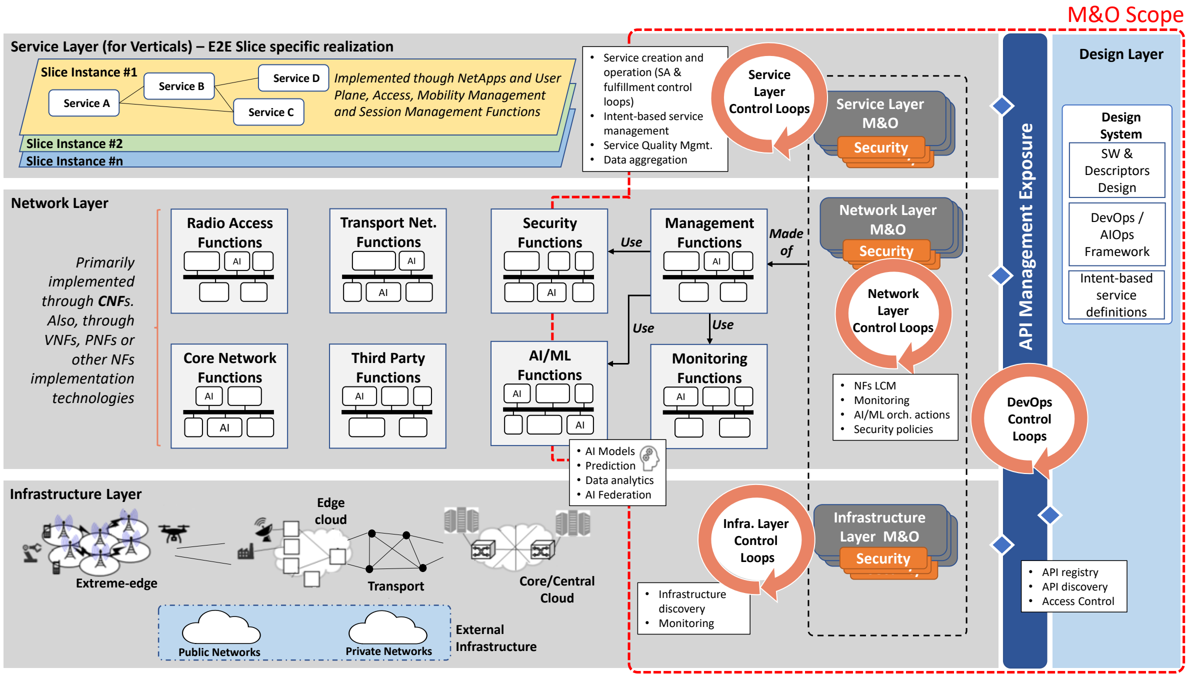

Fig. 1. The Structural View of the Hexa-X M&O Framework proposed for the 6G mobile communication systems [5].

- **Deployment View:** Considers and analyzes how the components from the *Structural View* may be deployed, contemplating infrastructure resources and topological aspects. This View is beyond the scope of the paper. The interested readers may refer to D6.2 of the Hexa-X [5].

A. *Hexa-X M&O Framework Structural View*

The Hexa-X M&O Framework Structural View represents, in general terms, Network Slices (NSls) and NSs at the Service Layer as being comprised of NFs from the Network Layer and running on Network Elements at the Infrastructure Layer. All NSls, NSs, and NFs are designed and provided by the Design Layer and communicate using the cross-layer API Management Exposure. Compared with the 5G Architecture [7], Figure 1 integrates a set of innovations and adopts the Service-Based Model Architecture (SBMA) introduced in [9], [10]. First, a new layer known as the *Design Layer* has been added as one of the innovations introduced by Hexa-X to address the previously mentioned challenges of telco-grade environments; the adoption of DevOps practices based on cloud-native principles; and the enhancement of overall service and network programmability. Another novel feature is the cross-layer functional block known as API Management Exposure, which enables and regulates communication among the different M&O resources within and across administrative domains, enabling the so-called capability exposure of network elements in different layers [11]. Both innovations are beyond the scope of this paper, but are greatly detailed in [5].

Furthermore, two additional CLs have been included: *(i) DevOps CL*, which reflects the CI/CD iterations between the Mobile Network Operator (MNO) scope (grey color) and the *Design Layer*; and *(ii) Infrastructure CL*, which automates the infrastructure discovery processes, associated monitoring, and facilitates network programmability. To represent the significance of the extreme-edge domain and the highly heterogeneous resources that will co-exist in 6G networks, Hyperscalers, Non-Public Networkss (NPNs), and extreme-edge resources have been added to the *Infrastructure Layer*. As shown in Figure 1, the Hexa-X M&O Framework represents Generic Functions at the Network Layer rather than specific functions, e.g., Communication Service Management Function (CSMF), Network Function Virtualization Orchestrator (NFVO), etc., to avoid any alignment with a specific existing standard and to be able to integrate potential functions that may be defined for the 6G stack. It is important to remark that Functions within the Network Layer are associated with different functional groups and are primarily implemented using Containerized Network Functions (CNFs) but with backwards compatibility with previous virtualization techniques.

There is a clear separation between the *M&O Scope* (shown with dashed red line) and Managed Objects (MOs). MOs represent resources such as NSls, NSs, or NFs that can be managed by *Managing Resources* within the *M&O Scope*. M&O resources represent, according to the SBMA model, a collection of management services owned by a concrete MNO, each featuring a specific M&O capability over the given MOs. These M&O resources can be mapped to vendor "boxed" solutions as they would be consumable or producible by management functions. Hexa-X distinguishes between two Management Functions Groups: *(i) Primary Management Functions*, depicted in Figure 1 as "Management Functions," offer fulfilment, assurance, and artifact management capabilities, which are considered as the Basic Management capabilities; and *(ii) Complementary Management Functions* may be used by *Primary Management Functions* in order to widen their available resources, i.e., Monitoring Functions, AI/ML Functions, and Security. Both Security Functions and AI/ML Functions are split by the M&O Scope dashed red line because certain parts of their functions would be designed to give direct support to the *Primary Management Functions*, whereas other parts could aid MOs functionalities. In general terms, Security Functions protect the confidentiality and integrity of operations and data and ensure the continuity of the provided services; AI/ML Functions provide the mechanisms to build out the knowledge and intelligence for controlling, managing, and optimizing the deployed services and help to decide which actions are to be performed at all the architectural layers; and Monitoring Functions provide information regarding the operational processes in the form of trace files, Key Performance Indicators (KPI) values, etc.

III. Intent-based Processes for Expressing Application and Service Requirements

The concept of *"intent"* [12], [13], [14] allows one to declare service and network connectivity requirements, constraints, and global objectives in an abstract and technology-independent manner, relying on the intelligence and programmability of autonomous networks to translate such intent definition into concrete configuration actions and enforce them on the infrastructure. The internal network operations are completely hidden and automated, requiring no manual intervention. The behavior and performance expected by the network are expressed in a language easy to interpret for humans and manageable for vertical users without deep expertise in mobile networks, slicing modelling or infrastructure resource configuration, i.e., natural language. In this context, a network intent can be described with different levels of granularity, starting from high-level business or service-oriented considerations and moving towards more detailed expectations at the network and resource infrastructure layer. The corresponding degrees of abstraction delegate an increasing number of concrete decisions on the network configuration to the M&O logic, which needs to include dedicated functions for intent translation and enforcement.

In 6G, intent will define network connectivity characteristics beyond capacity and Quality of Service (QoS). For example, intent may identify security requirements that are internally translated into the deployment and configuration of additional NFs for security services. Similarly, an intent describing a streaming service in a geographic region can be automatically translated into the definition of an enhanced Mobile Broadband (eMBB) NSI featuring the instantiation of dedicated User Plane Functions (UPFs) and caches placed to serve the target users. At runtime, the M&O system will continuously monitor the relevant metrics for service assurance and, exploiting the CL control capabilities, will automatically adjust the network operational state to match the requested intent requirements.

AI/ML techniques can further enhance the management of network intents, from the initial interpretation, validation, and translation stages to intent monitoring and updating at runtime. The AI/ML functions enrich the M&O system with a "self-learning" process that improves the translation logic and allows it to automatically identify changes in the provisioning-time-declared intent, triggering network reconfiguration actions. Moreover, while current approaches for intent interpretation are based on static rules, the adoption of AI/ML techniques can lead to a process in which the intent translation rules are learnt and improved dynamically on the basis of a continuous evaluation of the intent matching with the service and network metrics collected at runtime.

Figure 2 shows an architecture for the management of service intents using AI/ML techniques in intent interpretation, intent evaluation, and intent translation. The intent management is handled by new functions operating at the Service Layer represented in Figure 1 (purple boxes) and at the *Design Layer* (pink boxes), which interact with M&O functions at the Network Layer (black boxes) to provision the NSIs or NSs corresponding to the intent and monitor the service and infrastructure KPIs to continuously verify the intent match with the current network conditions.

The intent-based interfaces of the M&O system allow users to describe their intents using natural language or an intent definition in a formal information model. In the former case, AI/ML techniques can efficiently support the intent interpretation and its transformation in the formal model adopted by the system [15]. In the latter case, tools and wizards can guide the user in compiling the intent description, which can be modeled through common and generalized blackprints or templates. Relevant information models are available from standards [12], [13], [16], [17].

The intent declared by the user is then verified by the *Intent Validator* block, which validates the format and the content of the intent and returns feedback and suggestions in case of errors. Based on the errors detected by the validator and the related fixes provided by the user, the AI/ML engines at the *Intent Interpretation* function can learn how to correctly interpret the user inputs in a progressive manner.

The following step involves the *Intent Translator*, which uses some translation rules and operator policies to decode the service intent and identify the type of network configuration required to meet the intent requirements. The output of the translation phase consists of the technical specification of the NSIs or NSs to be provisioned and configured in the infrastructure. The lifecycle management of these elements is then delegated to the corresponding M&O Management Functions, e.g., a NSI Management Function or a NFVO, which instantiate the virtual functions and configure the network resources on the infrastructure, activating their monitoring.

During runtime, the service intent declared initially may change (for example, due to increasing service demands) variations in the users' distribution or the application configuration, etc. In order to reduce manual intervention, an *Intent Evaluation* function assisted by AI/ML can be introduced to automatically detect a modification in the service intents through the analysis of the related service KPIs and trigger an autonomous reconfiguration of the affected NSIs/NSs. In

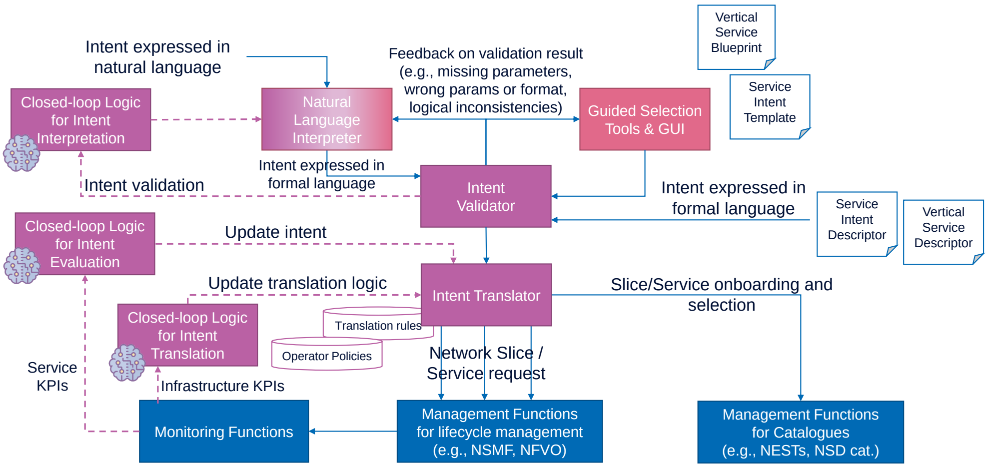

Fig. 2. AI-based management of service intents [5].

parallel, AI/ML can be adopted to improve the performance of the intent translation logic. In this case, the joint analysis of service and infrastructure KPIs can detect a mismatch between the usage of the allocated resources and the service demands of the declared intent. This would have an immediate impact on the infrastructure metrics, e.g., reflecting a condition of traffic congestion, followed by a degradation of service KPIs. The system will react automatically by updating the rules that translate service intents into network configuration directives and triggering a modification of the provisioned NSIs/NSs.

IV. Enhanced Service Description Models and Profiling

In 6G networks, it is expected that additional information can specify characteristics, dependencies, or resource constraints for the services, e.g., targeted placement of application elements towards the extreme-edge domain. Traditional network KPIs can be complemented with service-level metrics, potentially linked to automated actions to be triggered in the case of alerts raised when the measured metrics and KPIs are out of predefined ranges. These actions can be updates of the service-level requirements or explicit corrective actions for the various layers of the architecture. The service descriptor can also declare explicit service-level AI/ML components and their related requirements, i.e., the type of input data to be ingested, the models to be applied, etc. The definition of the AI components of the service can drive the holistic management of resources, virtual functions, and monitoring sources specifically dedicated to the distributed AI/ML processing in support of data-driven service management.

From a network perspective, increased programmability is required, both for the 6G network and service elements. Existing models for describing these elements are focused on the description of components and deployments, but completely disregard performance. Therefore, these models need to be extended to accommodate all the various new requirements that 6G is bringing. One such extension is the information pertaining to profiling the NSs/NSIs. The increased programmability in the use of available resources leads to mechanisms that allow for different operational conditions for a NS/NSI during its operation. Profiling NSs/NSIs provide a description of the expected performance within the known operational conditions and also provide a way to determine the expected impact of changes in the current operational conditions. Modifying these conditions, such as changing resource allocation or changing the placement of components, can have from none to significant impact on the observed performance.

In the Hexa-X architecture, the Profiling process, leveraging the monitoring functionalities and diagnostic processes as part of the service assurance systems, generate static profiles that estimate the expected performance of an NS/NSI given the current set of known conditions. This process can be triggered statically under predefined conditions or dynamically based on the significance of the changes in the operational conditions, such as traffic load and interference. This information can be inserted into the description of said NSs/NSIs, e.g., by following the format of Service Profiles or Slice Profiles proposed in the 3GPP Network Resource Model (NRM). Additionally, utilizing the increased programmability provided by the M&O systems, and supported by the CLs tasks with fulfilling the requested operations, the NSs/NSIs can become more elastic, considering resource reallocation, element placement, energy consumption, etc. During the profiling process, potential changes to deployment of an NS/NSI, like dynamic reallocation of resources or element placement [18], can be tested and used to enrich these elastic profiles. This enables a more precise estimation of expected performance based on resource utilization trends. Even more so, it provides additional options to assist in the service quality assurance and performance diagnosis by increasing the options of the various fulfilment CLs to meet the service quality requirements.

V. Monitoring and Diagnostic Processes

The extension of the SBMA and the incorporation of AI/ML across all architectural layers make apparent the importance of having an overview of all the moving parts and monitoring their operations across the various layers. While this concept is already a common practice across all architectures and is typically implemented through monitoring mechanisms, the capability to detect anomalous behavior and its source is still missing. This enables other mechanisms to determine the optimal countermeasures and execute corrective actions that may alleviate any performance degradation caused by the anomalous behavior. In the Hexa-X M&O architecture, diagnostic processes are an integral part of the M&O functions and one of the cornerstones of the assurance systems. These systems provide the link between the provided requirements and the assurance that they are met by the offered services. Existing implementations of such mechanisms, while effective, are limited in scope since they focus mainly, if not exclusively, on the Network or Infrastructure Layers. In order to handle the diverse needs of 6G services and networks and provide a completely automated and programmable operation, a more holistic approach is needed, able to bridge the gaps between service, network, and infrastructure layers.

Typically, a diagnostic process includes three stages: Data Ingestion, Analysis, and Corrective Action [5]. The first stage leverages implemented monitoring functions to retrieve current state and live information about the examined deployment. This information is used to obtain a near real-time snapshot of the system based on the capabilities and supported granularity of the monitoring system. After spatiotemporal correlation, the information is fed to the next stage. During the Analysis stage, the acquired cross-layer pictures of the system are examined sequentially to detect anomalies and individually identify the root cause of said detected anomalies. Commonly used analysis techniques – also employed by the Hexa-X diagnostic process, e.g., statistical analysis, historical trends, and training of AI/ML models for detection and prediction of anomalies – are utilized to extract meaningful insights from generated raw data. In parallel to the performance analysis, the profiling process is responsible for generating a dynamic profile that takes service components, allocated resources, operational conditions, etc. into account. Using this mechanism, detection and, whenever possible, prediction of performance issues or bottlenecks could be validated. The Corrective Action Stage is triggered on the detection of an anomaly, based on the difference between observed and desired performance, and after examining the findings utilizing algorithms for Root Cause Analysis, a number of corrective action suggestions can be generated to help minimize the delta between these two states. These suggestions can include scaling service components, scaling NSIs, redeploying elements, etc. A previous validation of these suggestions is also required to satisfy any existing infrastructure, vendor, security, and other constraints.

To maximize the impact of this mechanism, the aforementioned operations need to run in parallel with components and services as part of a CL. Thereupon, the diagnostic process is interfaced with the respective components responsible for collecting information from all layers as well as enforcing the M&O actions. A critical requirement of this mechanism is the need for verifiable relations between the components and the elements that stem from various NS/NSl descriptions. This information allows for cross-domain correlation and matching of events and observed performance, which, in turn, unlocks the path for other innovative mechanisms and functionalities, i.e., automated per-domain performance optimization, optimized resource allocation, and response to unexpected conditions.

VI. Programmable Network Enablers for Reasoning

The programmability of 6G networks can be exploited by the network intelligence to dynamically trigger several automated actions following zero-touch and data-driven patterns. In particular, reasoning techniques combined with extensive network knowledge representations are getting attention in the area of AI/ML to build semantic learning strategies applicable to 6G networks M&O [19]. Still, in this direction, ML and reasoning, together with data and knowledge management, are key enablers for cognitive networks that are expected to play a crucial role in End-to-end (E2E) 6G architectures [6].

The creation of a representative knowledge base for 6G networks is one of the challenges to enabling efficient reasoning. In the case of reasoning applied to M&O strategies, this knowledge base should capture a wide variety of parameters that may impact the performance and requirements at the service, network, and infrastructure layers, since they should be jointly considered when taking decisions about network, NSl, or NS re-optimization. In this context, network programmability offers the capability to generate and expose a variety of monitoring data to build an extensive base of knowledge as required to feed the reasoning entities.

The AI/ML agents, where the reasoning engines run, are provisioned and re-configured dynamically. The need of monitoring data to feed such agents may vary in time, e.g., in terms of type of metrics to be monitored, frequency of metrics generation and collection, options for filtering, granularity and level of details and aggregation of the monitoring data. Thereupon, programmable interfaces at the Infrastructure, Network, and Service layers should be provided to enable, on one hand, the provisioning of new probes in different segments of the infrastructure and the configuration of heterogeneous monitoring data sources, and on the other hand, the efficient retrieval of the collected data in a distributed, scalable, and secure manner. The former must be orchestrated through the Management Functions at the various layers in the architecture, in strict coordination with the Monitoring Functions (see Figure 1). The latter constitutes the enablers for the AI/ML Management Functions to feed their reasoning logic. In the reasoning procedures, the following categories of parameters and monitoring data can frequently be mixed together.

A. Parameters Related to Service Demands and Requirements

These parameters can be declared in an explicit manner with different levels of detail. For example, following a service-oriented perspective, the customer can define "intents" to describe the expectations of the network, as explained in Section III. An alternative could be the adoption of the Network Slice

Type (NEST) [6], which provides an intermediate level of definition for the requested NSl, declaring its network requirements and filling the Generic Network Slice Template (GST) parameters (e.g., data rates, latency, jitter, packet loss, etc.). A further level of request, more oriented to the technicians and administrators of the network, can include the fine-grained directives for the network configuration, i.e., the number, type, and dimension of the virtual NFs to be deployed, their specific configuration, etc. [18]. However, the service demands are not always declared explicitly since they may not be known in detail a-priori or they may change during the service runtime. For this reason, suitable monitoring mechanisms should be adopted as explained in Section V.

B. Network capabilities, Including Resource Availability and Related Constraints

In 6G networks, these types of parameters are dynamic and variable with context. For this reason, in some cases, they cannot be modelled as static and well-defined inputs for the reasoning process but must be acquired on-demand or even continuously monitored and updated. For example, due to the multi-domain nature of the infrastructure, some scenarios involve multiple stakeholders cooperating together, where each of them applies their own policies and may offer resources with different Service Level Agreements (SLAs) and costs [20]. Moreover, the presence of extreme-edge resources requires mechanisms for dynamic discovery and, where needed, dynamic negotiation of SLAs. These nodes also have a number of characteristics, e.g., power capacity or computing resources, that should be carefully considered by the reasoning logic when taking decisions about composing the final E2E service.

C. External Factors not Directly Related to the Network Itself but Impacting its Performance or the Service Demands

This includes a variety of information that may be collected through very different data sources. For example, information about traffic congestion in a city may help the reasoning identify and predict potential mobility patterns for mobile users. In the case of integration with Non-Terrestrial Networks, weather conditions may impact the selection of the satellite gateways placed in different geographical areas. In Standalone NPNs deployed in smart factories, the information coming from the production lines may help to identify the profile of the traffic generated by Internet of Things sensors and devices [21]. These examples highlight the fundamental role of a scalable, secure, multi-domain, and distributed monitoring and data management system, able to collect, aggregate, filter, and elaborate data coming from very different sources to efficiently feed the intelligent decisions of the 6G network.

VII. Software Integration Processes

The way NSs are built and consumed needs to be architected differently. The system becomes a big integration fabric of different pieces of software coming from different vendors/stakeholders. This integration problem between the development and the operations part is known as DevOps, but it should be revisited considering the multi-domain, multi-stakeholder dimension of the relationship between providers/vendors/developers and MNOs. The DevOps processes in the Hexa-X M&O architectural design would be implemented through the specific Design Layer included in the M&O architecture (see Figure 1). They cover:

- **Continuous Integration (CI):** Main DevOps process, referring to the automation of the initial development stages. Different software providers or developers can simultaneously work on a common repository. Each of them delivers a piece of the NS, such as core function, radio access function, etc.
- **Continuous Testing (CT):** Multiple automated test batteries are executed on the provided code to ensure it meets specifications. This step stays similar to what we have in DevOps workflow. Each composite of the NS should be tested and validated.
- **Continuous Delivery (CD):** Logical step following CI, it ensures that the changes validated in the common repository are transferred to a centralized artifacts repository, in the operational environment, to be verified in a production environment by combining all the pieces of the NS.
- **Continuous Deployment (Cd):** Typically, artifacts generated during the CD stage are stored in a repository until they are manually deployed in a production environment. However, this could be automated without (or with minor) human intervention. This enables direct delivery of new features to end-users.
- **Continuous Monitoring (CM):** Monitoring processes are oriented to using production data to guide development/vendors and operational teams. It enables autonomous responses to certain metrics or alerts, and the auto-scaling of NSs according to certain QoS/Quality of Experience (QoE) metrics. Of course, each vendor/developer retrieve only the data related to the behavior of its component or piece of software.

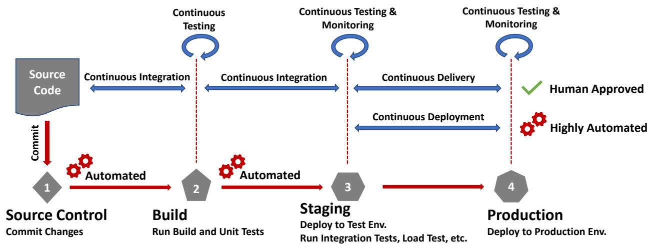

Fig. 3. Continuous DevOps Processes [5].

Figure 3 depicts these five concepts (CI/CT/CD/Cd/CM). Although other processes could be considered, these five are the main processes related to DevOps practices. They showcase how the DevOps approach breaks down the barrier between development and the operational scopes: although CI is still on the development side, CD and, especially, Cd, CT and CM, are clearly beyond the developer's scope, entering clearly into the operations area. Implementing this in a telco-grade environment is highly challenging since development and operational scopes are usually isolated; MNO and software providers are typically different companies, with different interests and corporate cultures. Implementing this concept in such an environment will probably require addressing not only technical challenges but also cultural and procedural changes in the involved companies, as mentioned in Section II-A.

VIII. Concluding Remarks

This paper examined the significance of upgrading or introducing the whole extent of service and network programmability towards 6G. The precise objective of the study was to investigate the impact of programmability on the M&O aspects of 6G networks. To that end, this article has provided in-depth information on several aspects of network and service programmability proposed by Hexa-X, the European 6G flagship project. Firstly, a detailed vision of Hexa-X regarding the main novelties proposed by its 6G Service M&O Framework has been presented. Secondly, an intent-based process that enables the expression of the requirements of 6G services and applications has been described, relying on intelligence and programmability to translate these requirements into configuration actions and enforce them on the underlying infrastructure. Thirdly, the use of programmability in the profiling of NSs and the description of NSl models has been addressed, with the goal of autonomously determining the expected impact of operational condition changes and modifying these changes throughout the lifetime of the NSls. Fourthly, automated and programmable monitoring and diagnostic processes that enable all layers of the M&O Framework in order to detect and determine the source of performance-impacting anomalous behavior, as well as the importance of improving existing monitoring mechanisms, have been discussed. Fifthly, reasoning techniques and parameters applicable to the 6G Service M&O Framework have been highlighted. Lastly, in order to integrate different pieces of software coming from different sources, five DevOps processes have been proposed to break down the barrier between the development and operational scope of 6G communication networks.

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