A Next Generation Architecture for Internet of Things in the Automotive Supply Chain for Electric Vehicles

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Abstract

This paper presents a next-generation architecture that focuses on the advancement of edge computing and Internet of Things (IoT) technologies in the context of the automotive supply value chain for electric vehicles (EVs). First, we outline the general architecture design, the specific layers and their goals. Based on the principles of the proposed architecture, we also give a use case for improving the traceability, monitoring and efficiency of EV battery transportation using innovative approaches in federated data spaces, AI-powered inference and orchestration of a multi-objective computational continuum. The automotive supply chain use case is presented with potential Key Performance Indicators (KPIs) while emphasizing the potential impact on operational efficiency, cost reduction and sustainability. By addressing the current limitations in distributed intelligence, data governance, and cross-domain interoperability, we emphasize the importance of real-time data processing, dynamic field governance, and energy-efficient machine learning in the context of the electric vehicle supply chain. At the end of the paper, a discussion and comparative analysis highlights the advances over existing technologies and frameworks and identifies future directions to further improve innovations and applications in this area.

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Decentralized AI, Distributed Computing, IoT Orchestration, Cloud Orchestration, Edge Data Processing

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1 Introduction

In the ever-evolving landscape of edge computing, artificial intelligence (AI) and the Internet of Things (IoT), breakthrough initiatives are essential to revolutionize the application of these technologies in real-world environments [11]. As the digital world becomes more complex, dynamic and connected, the demand for innovative edge solutions is increasing. Recent breakthrough efforts [7] have served as beacons pointing the way to a future where the seamless integration of cutting-edge technologies not only increases efficiency, but also transforms the structure of our technological ecosystem. Across the various sectors of the European ecosystem, there are several key issues related to the lack of seamless interoperability between different edge sources, the need for improved security operations in hyper-distributive environments and the challenge of fostering strategic industrial collaboration for future-proof computing and processing. Critical factors related to these issues include the need for advanced orchestration mechanisms, robust security protocols, and the establishment of open platforms to promote collaboration and standardization.

This paper focuses on addressing the increasing complexity and challenges associated with the deployment of distributed intelligence and edge technologies in the automotive supply chain for Electric Vehicles (EVs). The global edge computing market was valued at $22.85 billion in 2021 and is expected to reach $190.1 billion by 2028, growing at a staggering CAGR of 36.8% [8]. Given the complex and ever-evolving challenges of integrating distributed intelligence and edge technologies, this paper takes a strategic, multi-layered approach. This strategy includes improving interoperability and collaborative computing, building a secure data ecosystem, deploying advanced AI tools and efficiently orchestrating data, infrastructure and services. This also includes the use of swarm intelligence, the strengthening of security measures and the implementation of hyper-distributed pilots at the application level.

The overarching goal of this paper is to advance emerging smart IoT and edge platforms that leverage customized IoT and distributed intelligence to meet the diverse needs of industries clustered in 2 main categories, namely, Energy & Climate Efficiency and Supply Chain & Industrial Optimization. The aim is to harmonize technological innovations with the requirements of real-world applications from different sectors (e.g. Energy & Climate Efficiency, Supply Chain & Industrial Optimization) and applications. The development of such a comprehensive solution, which combines the orchestration of data, infrastructure, and services with secure infrastructure lifecycle management, will help establish a mature and customized ecosystem for the adoption and standardization of IoT and next-generation interoperable and secure edge computing environments for an advanced and interconnected future. This will empower users to leverage insights, conduct AI experiments, and optimize orchestration automation with unprecedented precision and efficiency. The main contributions of the paper can be summarized as follows:

- We introduce a next generation architecture for distributed Artificial Intelligence (AI)/Machine Learning (ML) computation in edge environments. The framework uses cross-domain federated data objects and advanced orchestration with data spaces, energy-efficient multi-tiered data processing and leveraging meta-operating systems and cognitive cloud technologies for real-time analytics and decision-making enhancing interoperability and security in data exchange.
- We propose a use case scenario on automotive supply chain chain for electric vehicles where our framework can enable sharing reusable portions of distributed AI models, distributing computational tasks among nodes, and detecting concept drift to maintain model reliability. These innovations reduce computational and energy costs significantly while enhancing AI model interpretability and trustworthiness, addressing current limitations in resource efficiency and explainability.
- We introduce a dynamic, secure, decentralized computing continuum that includes Internet of Things (IoT) devices and services. This continuum enables seamless application operation across multiple administrative domains with transparent orchestration strategies, optimizing for multiple objectives such as cost, performance, sustainability, and security. This approach surpasses the static and limited integration capabilities of current cloud-to-cloud and edge computing solutions.

The rest of the paper is organized as follows: Section 2 provides the related work. Section 3 describes the general architecture of the proposed next generation distributed AI/ML computation framework for edge environments. Section 4 gives an use case description on automotive supply chain for electric vehicles. Section 5 provides discussions and comparative analysis on advances with proposed framework in comparison to existing landscape. Finally, Section 6 provides the conclusions of the paper.

2 Related Work

Nowadays there are relevant advancements in distributed intelligence, edge technologies, and cross domain data governance with respect to domain-level federated data spaces. The current state of the art includes the latest approaches to interoperability frameworks, refined domain modelling techniques, and the establishment of secure connections with EU Data Spaces. Advanced data modelling techniques [12] and domain-specific data governance strategies guarantee effective representation and management within specific domains. Integration of edge computing capabilities enables real-time processing and analytics at the edge, contributing to enhanced efficiency. Robust security infrastructure, including encryption and access controls, safeguards data integrity and confidentiality. The connection with EU Data Spaces aligns with EU standards and regulations, emphasizing compliance with data protection directives [13]. Integration of machine learning and analytics facilitates insightful decision-making, while sophisticated orchestration mechanisms optimize data flows across clusters, clouds, and edge devices. Cross-domain standardization efforts promote common interfaces, architectures, and design principles, fostering interoperability and collaboration across diverse sectors.

In spite of the pervasiveness of AI/ML models as essential components of decision-making processes, we are still far from the realization of sustainable intelligence in the present computing systems. This becomes a significant hurdle in an edge continuum including nodes with different capabilities in terms of energy and computational resources, and ability to collect data. To overcome this issue, there is a growing need for disruptive methods that cater for resource-efficient, tuneable AI/ML. Some of the existing solutions [4] leverage model compression to reduce the models' size (hence, their computational footprint), as well as distributed training and inference paradigms to make an ML operational pipeline suitable for the available resources. However, a general approach to ML model design that can serve different types of tasks and scenarios is still missing, as well as a solution that jointly addresses all aspects involved in an ML operational pipeline, including communication, computational,and data collection related costs. Additionally, explainability is pivotal for creating trustworthy AI/ML models, hence secure decision processes. Current Explainable Artificial Intelligence (XAI) techniques [3] fall short of generality, or of providing easy-to-understand (hence practical) explanations or insights on the physical meaning of the contextual domain of model execution.

Although several projects investigated Cloud-to-Cloud interoperability and cooperation [1], existing solutions are static (federation lasts for long periods), bring all resources to the pool (do not allow a fine-grained control of federated resources) [2], and have limited coverage over edge devices. On the other side, current industrial platforms such as Amazon Greengrass or Azure IoT Edge create a bridgehead at the edge, without building a platform continuum nor guaranteeing interoperability. Furthermore, workload and storage placement, also in case of edge platforms, are well investigated only for single administrative domains; however, solutions become less clear when multiple administrative domains are involved and in the presence of huge node heterogeneity (IoT, edge devices, cloud servers). Finally, scalability still represents an open point, as well as the capability to transparently deploy an application in any location of the continuum, a novel concept [5] that has been recently introduced in the Liqo.io opensource project. In recent years cloud/edge computing platforms have been deployed and used to support cross-domain use cases in a variety of industrial sectors and value chains, including for example manufacturing, logistics, supply chain management13, and the circular economy. However, these platforms offer access to industrial capabilities in support of the dynamic combination and orchestration of services in service-oriented (i.e., microservices-based) workflows.

In most cases, the latter are developed in ways that serve optimization objectives [9] [6] such as sustainability, performance/latency, security/privacy/data protection, resilience, and cost. Nevertheless, they are not typically engineered and developed to support multiple optimization objectives by selecting the services that fulfil application requirements such as CO2 or cost constraints. The optimization of multiple objectives requires novel approaches that go beyond conventional techniques (e.g., linear programming) [10] and can handle and resolve conflicting requirements and their trade-offs.

3 General Architecture Design

The proposed architecture substantially contributes to the advancement of IoT/Edge technologies and ensures efficiency, adaptability, and sustainability in the evolving landscape of data-driven industrial environments. We utilise and integrate cutting-edge technological advances in various domains, including Data Spaces, Cognitive Intelligence, Digital Twins, and IoT/Edge/Cloud orchestration. The goal is to develop a comprehensive and state-of-the-art framework tailored to real-world edge paradigms. The resulting architecture is expected to be a game changer in scenarios, use cases and verticals that require distributed execution and precise control of their environments. This holistic approach aims to push the boundaries of technological possibilities and provide innovative solutions that significantly impact the landscape of edge computing. The proposed architecture includes three layers:

(i) Governance and Domain Federated Data Spaces: This layer ensures seamless interconnection with IoT/Edge pilots' infrastructure, monitor IoT/Edge assets, conduct data modelling, sensitivity analysis, and align extracted information using standardized, dynamic and adaptable data models (based on standards like W3C, NGSI-LD, RDF, FIWARE Smart Data Models, JSON-LD, OWL). Furthermore, this layer provides a collection of federated data objects, significantly reducing query times for IoT/Edge originated data. aiming on delivering high-quality data to upstream analytical services and components, thereby contributing to the establishment of a multi-objective Data Space. **(ii) Decentralized Cognitive Intelligence**: This layer encapsulates the intelligent components within the Computing Continuum, offering a comprehensive toolkit for exploratory analytics, data quality enhancement, and effective decision making. This toolkit encompasses a library of reusable, cross-domain, and decentralized ML models. The objective is to ensure transparency, trustworthiness, and causal reasoning before deploying these models into production. Additionally, the platform facilitates cloud-native-enabled distributed execution of AI/ML operational pipelines, enhancing scalability and efficiency in the deployment process. **(iii) Intent-Based Edge Cloud Orchestration and Management**: This layer dynamically allocates resources across IoT/Edge/Cloud infrastructure, supporting the storage and processing of intricate IoT/Edge workflows and provides the ability to self-configure and adapt to runtime changes. Furthermore, it incorporates a robust framework for vulnerability assessment, to ensure early detection of security breaches, with prompt mitigation actions. The layer is also entrusted with runtime actuation and policy enforcement, playing a critical role in maintaining the integrity of the underlying IoT/Edge/Cloud infrastructure. At the application layer, multi-objective optimization establishes a multi-sided ecosystem for Digital Twins, allowing end-users of industrial pilots to interact with results from Decentralized Cognitive Intelligence (ML/DL/FL) artifacts and high-level insights.

4 Automotive Supply Value Chain for Electric Vehicles

This scenario focuses on tracking battery shipments to monitor critical conditions in real time and maintain integrity in a crucial part of a battery's lifecycle as shown in Fig. 2. In a global market, long transportation routes are often unavoidable, as various production and assembly steps are outsourced or bought in. An important example is the Stellantis Supply Chain (SC) for the electric batteries used in one of models, the Fiat 500e. In this use case, the automotive industry player CRF, as the end user of the automotive manufacturing sector, is willing to test and validate the capabilities of the proposed platform under operating conditions in a real use case. The automotive industry wants to evaluate data, processes and assets related to inbound logistics for the delivery of their vehicles' traction batteries. The production plant is located in Turin, Italy; currently the batteries are supplied by a supplier based in Göd, Hungary. Hence, the batteries in this use case scenario are manufactured and tested in Hungary. After travelling through three countries in Europe and being tracked, they are delivered, retested and assembled at the Stellantis plant in Mirafiori, Italy. The purpose of this assessment is to identify potential risks, vulnerabilities and threats associated with the assets of our processes in order to take the right protective measures and prevent the potential spread of risks throughout our automotive logistics network.

Monitoring transport routes is essential to proactively detect potential quality deterioration, minimize disruptions, reduce shrinkage, improve supply chain reliability and enable supply chain certification. Monitoring relies on sensors attached to each battery pack container that provide real-time data to ensure accurate and efficient tracking. They transmit information such as GPS position, temperature and acceleration up to 6 times per hour with high localization accuracy. However, mastering the complexity of monitoring transportation routes is no easy task. The interplay of sensor life,

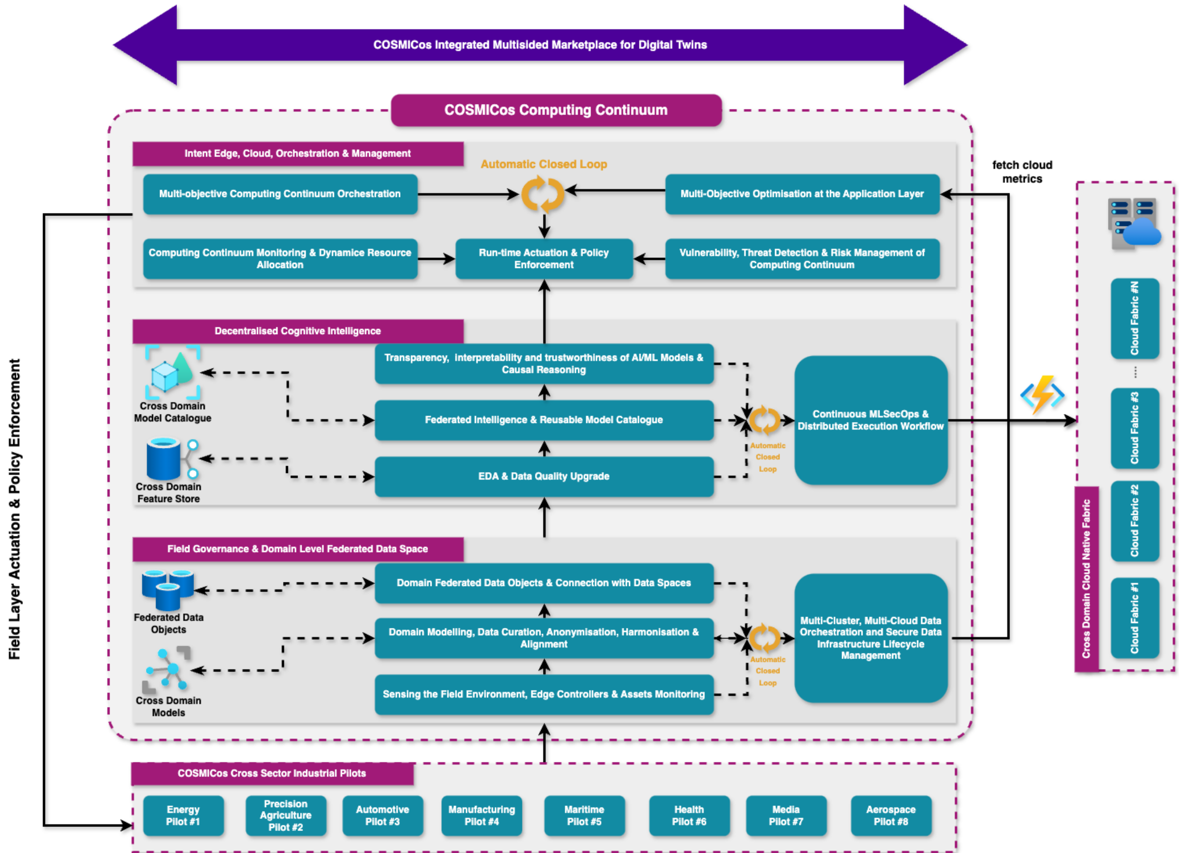

Figure 1: Next generation architecture for distributed AI/ML computation in edge environments

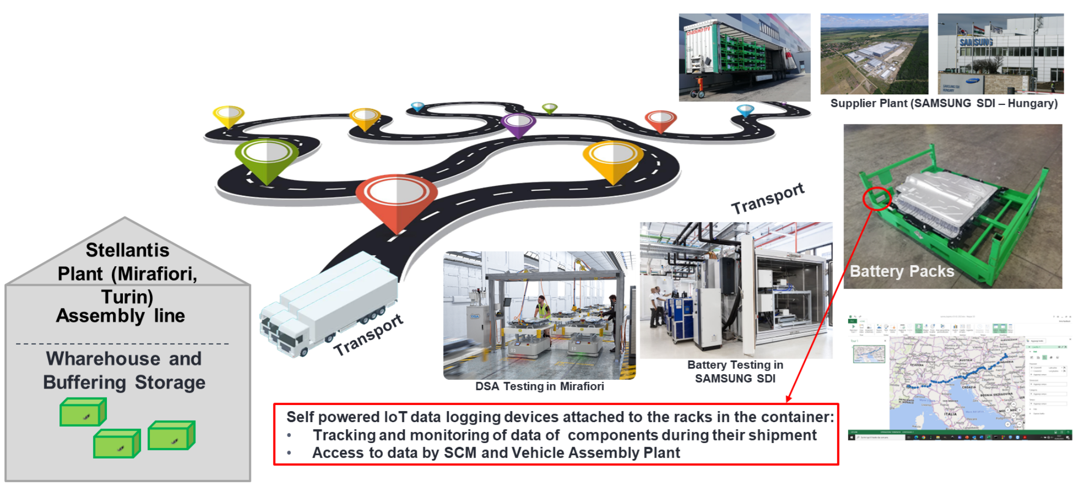

Figure 2: Supply chain IoT use case

lack of battery charging or replacement, required network coverage and operating conditions presents a number of challenges. On the other hand, with multiple battery packs (currently up to 50) on the same truck at the same time, each monitored by an independent sensor, one can imagine huge optimization opportunities, such as coordinated collection and transmission of data from a single, dynamically chosen "gateway", the ability to turn off some sensors with huge improvements in terms of battery life, the ability to increase the frequency of monitoring without impacting the overall cost of the system, and much more.

4.1 Main objectives and KPIs

The primary objective is to show high reliability, continuity, and accuracy in tracking EV batteries along the entire supply route. By ensuring the traceability and monitoring of EV batteries with high reliability and efficiency, economic benefits can also achieved by addressing issues such as the "lost" battery containers, reducing annual losses. Digital certification can be used to certify delivery quality, security, and absence of tampering. The scenario also explores a federated IoT configuration to validate swarm intelligence behaviors for IoT loggers, automating data collection and minimizing mobile communication costs. Specialized data processing approaches can also be used to orchestrate IoT components of the EV battery SC. Data interoperability and governance, efficient positioning of battery racks, federated learning for positioning, continuous monitoring of battery status, computing continuum orchestration, and a simulator/digital twin design for service simulation and validation are some enablers as shown in Fig. 2.

In general, from Key Performance Indicator (KPI) perspective, this use case aims to achieve an accuracy rate of 95% or more for the real-time position data of battery containers. The effectiveness of swarm AI aims to reduce communication costs and battery consumption by 20%. The accuracy of the data packets for position, temperature and acceleration should be above 98%. This use case also aims to reduce the response time to anomalies or deviations by at least 30%, increase the number of tracked containers by 50% without significant performance degradation and maintain a system uptime of over 99% for continuous monitoring and tracking. The target for economic impact is a cost reduction of 10% due to lower losses of battery containers, and the target for simulation accuracy is a deviation of less than 5% between simulated and actual data during testing.

4.2 Proposed Approach, Potential Activities and Impact

The proposed framework in this paper ensures seamless interoperability and governance over data flow and quality, monitoring the battery status of container sensors in real time, improving the accuracy of positioning data, orchestrating local training for effective edge positioning, pushing training artifacts to the management server for global model creation, and orchestrating computations based on battery/device status to increase sensor lifetime. Dedicated Industrial Internet of Things (IIoT) devices installed on battery containers enable communication of data packets, including position, temperature and acceleration. The data is collected via IIoT devices, ingested by a dedicated edge infrastructure and visualized in real time on an online platform. This setup enables proactive problem detection during delivery. The use case ensures high data quality, optimizes the processing logic of the application and uses self-organizing distributed computing. Data fusion and validation techniques are used for global tracking, using different localization methods to ensure accuracy even when GPS is insufficient. Novel services to detect and combine process improvements and AI methods for real-time data validation and monitoring can also be used for enhanced intelligence from the system. Finally, the integration with the proposed platform can bring multiple benefits to this scenario, such as enabling real-time interaction of SC operators with assets via innovative IoT solutions, providing IoT infrastructure targeting Sustainable Development Goal (SDG)-related objectives, and equipping IoT devices with swarm intelligence for dynamic re-purposing and sustainability. This new generation of IoT devices can respond to sustainability requirements by enabling intelligence and adaptability on the edge.

5 Discussion and Comparative Analysis

The proposed framework has the potential to significantly advances the current landscape of edge computing and IoT technologies by introducing innovative solutions across multiple domains. It introduces cross-domain federated data objects and orchestrates connections with multiple data spaces, enhancing interoperability and data exchange efficiency. By customizing meta-operating systems and cognitive cloud technologies, this next generation architecture and framework enables real-time edge processing and analytics, which can greatly improve energy efficiency and adherence to open standards. The framework also brings dynamic monitoring and control mechanisms to field governance, next-generation domain modelling techniques, and machine learning for optimized data curation. These innovations harmonize data models across domains and enable efficient multi-cluster, multi-cloud data orchestration, ensuring robust governance and security.

In addition, the framework innovates in the field of AI-assisted inference and decentralized intelligence by sharing reusable ML model portions and distributing computational tasks across different nodes, reducing energy and computational costs while improving model reliability and interpretability. The framework also creates a dynamic, secure, decentralized computing continuum that includes IoT devices and services and enables seamless operation of applications across multiple administrative domains. Multi-objective orchestration strategies optimize for factors such as energy, performance and cost. The new framework of this work develops digital twins and AI-based reasoning tools to optimize service workflows with respect to various goals such as cost, sustainability and security. These comprehensive innovations remove existing limitations and significantly improve the efficiency, robustness and sustainability of edge computing environments. By leveraging these advances, the architecture not only meets the requirements of modern industrial applications, but also contributes to a wider acceptance and integration of cutting-edge technologies in various sectors, such as the supply chain, which is provided as an application example. The proposed framework makes a step beyond the existing landscape by introducing multiple advancements in the following areas in comparison to traditional approaches in data landscape: **(i) Data Spaces** - Conventional data landscapes typically consist of siloed systems for data storage and processing that hinder seamless interoperability and real-time data exchange. These conventional systems are often based on centralized data management, which leads to inefficiencies in handling different data sources and formats. We introduce cross domain data objects and orchestration to synchronize the multiple data spaces by introducing multi-tiered data processing with a focus on energy efficiency and adherence to open standards. **(ii) Field Governance and Domain Modelling** - Traditional field governance often relies on static data models that cannot easily adapt to changing data structures or incorporate real-time updates. This rigidity leads to challenges in maintaining data quality and security, especially as data volumes grow. Our approach uses ensemble mechanisms for the development of data structures, ML operations for optimised data cleansing and anonymization, and policy enforcement points to secure data exchange. **(iii) AI-assisted Inference and Decentralized Intelligence** - Traditional AI/ML implementations often involve centralized data processing, which can lead to bottlenecks and inefficiencies, especially with large amounts of data. These systems also tend to require a lot of computing power and energy, which limits their scalability. The proposed architecture consists of a full-fledged AI/ML suite that leverages the capabilities of the underlying infrastructure and introduces the cooperative distribution of computational burden to multiple nodes to significantly reduce energy and computational costs. **(iv) Multi-objective Computing Continuum Orchestration** - Traditional computing infrastructures often operate within a fixed, centralized framework that does not adapt well to changing workloads or environmental conditions. These static systems can be energy intensive and are usually optimized for individual goals, such as performance or cost, without considering broader impacts such as sustainability. Ultimate goal of the proposed architecture is the creation of a dynamic and secure decentralized computing continuum, using orchestration strategies aiming to reduce the infrastructure's consumed energy, emissions and other external factors. **(v) Multi-objective Optimization of the Application Layer** - Conventional application optimization often focuses on isolated goals, such as performance or costs, without considering the complex interplay of various factors. This can lead to suboptimal results and higher operating costs. The proposed architecture automates the service workflows and develops digital twins that make decisions based on AI-based reasoning tools to shape optimization strategies for application behaviour based in cost, performance, sustainability and security.

6 Conclusions and Future Work

To summarize, this paper has shown that potential advances in edge computing and IoT technologies are possible, especially within the automotive supply value chain for electric vehicles with a next-generation architecture. By introducing cross-domain federated data objects, dynamic field governance, and innovative AI-powered inference techniques, the proposed new design can improve data interoperability, real-time processing and resource efficiency. The creation of a dynamic, decentralized computing continuum that integrates IoT devices and services can enable seamless application operations across multiple administrative domains. In addition, the consideration of multi-objective orchestration strategies and the development of digital twins and AI-based reasoning tools can optimize service workflows for various objectives, including cost, performance, sustainability and security. Together, these contributions can overcome current limitations and set a new benchmark for the efficiency, robustness and sustainability of edge computing environments. Future work can focus on further improving the scalability and adaptability of the next generation framework. Some potential innovation aspects are the refinement of multi-level data processing techniques to handle larger data volumes and more complex application scenarios. Another focus could be on expanding the harmonization and alignment of data models in even more diverse domains, to ensure broader applicability and interoperability. Finally, efforts to improve the security and compliance aspects of the framework are also of interest, adapting to evolving regulations and standards to ensure the integrity and confidentiality of data in increasingly complex and distributed computing environments.

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