

An Architecture-Centric Evaluation Model for European Union–Funded IoT and Edge Computing Research Ecosystems

Dr. Noboru Kinoshita

Department of Artificial Intelligence,
Tokushima University, Tokushima, Japan

Dr. Yuna Kitagawa

Graduate School of Science and
Technology, Shinshu University, Nagano, Japan

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ABSTRACT

The rapid expansion of Internet of Things (IoT) and edge computing technologies has significantly transformed distributed digital infrastructures, particularly within research and innovation programs funded by the European Union (EU). However, despite substantial investment in IoT and edge computing ecosystems, there remains a lack of standardized architecture-centric evaluation frameworks capable of systematically assessing interoperability, scalability, intelligence distribution, and infrastructural maturity across heterogeneous EU-funded projects. This paper proposes a comprehensive architecture-centric evaluation model designed to analyze IoT and edge computing research ecosystems through a structured lens that integrates fog-cloud continuum principles, distributed intelligence paradigms, and platform interoperability considerations.

The study synthesizes established theoretical foundations from industrial IoT, fog computing, and edge analytics literature to construct an evaluation framework that captures architectural complexity across multiple layers of computing—device, edge, fog, and cloud. The proposed model integrates key evaluation dimensions such as system scalability, latency optimization, data analytics efficiency, and privacy-aware distributed processing. Drawing on prior research in fog and edge computing architectures (Aazam, Zeadally, & Harras, 2018), distributed intelligence systems, and EU IoT initiatives, the paper critically examines how architectural design choices influence system performance, sustainability, and real-world deployability.

Findings from the conceptual evaluation demonstrate that EU-funded IoT ecosystems exhibit strong innovation potential but remain fragmented in architectural standardization and cross-project interoperability. The study highlights the need for unified architectural benchmarking mechanisms to ensure long-term sustainability and integration of edge-based intelligence systems. The proposed model contributes to bridging the gap between theoretical advancements and practical deployment in large-scale IoT research ecosystems.

Keywords: IoT architecture, edge computing, fog computing, EU-funded projects, distributed intelligence, system evaluation model, industrial IoT, cloud continuum, interoperability, smart systems.

1. INTRODUCTION

1.1 Problem Statement

The evolution of IoT and edge computing technologies has led to the emergence of highly distributed computational ecosystems that extend from sensor-level devices to cloud-based intelligence platforms. Despite the technological maturity of these systems, EU-funded IoT and edge computing projects often operate in fragmented architectural environments, lacking unified evaluation methodologies that can systematically assess their structural efficiency, interoperability, and scalability.

Existing research has largely focused on individual components of IoT systems, such as fog computing architectures, edge analytics, and industrial IoT deployments. However, there is limited emphasis on architecture-centric evaluation models that can holistically assess the full edge–fog–cloud continuum across diverse EU research initiatives. This creates challenges in benchmarking system performance, comparing project outcomes, and ensuring cross-platform compatibility.

1.2 Research Relevance

The importance of architecture-centric evaluation is amplified by the increasing complexity of distributed IoT systems.

Modern IoT infrastructures are no longer isolated deployments but interconnected ecosystems requiring coordinated intelligence distribution across computing layers. According to Aazam, Zeadally, and Harras (2018), fog computing and offloading mechanisms play a critical role in optimizing IoT system performance by reducing latency and improving computational efficiency at the network edge.

Furthermore, EU-funded projects emphasize innovation in smart cities, industrial automation, healthcare IoT, and environmental monitoring. However, the absence of standardized architectural evaluation frameworks limits the ability to assess how effectively these innovations translate into scalable and interoperable systems. This research addresses this gap by proposing a structured evaluation model tailored for EU IoT ecosystems.

1.3 Objectives

The primary objectives of this study are:

1. To analyze architectural characteristics of EU-funded IoT and edge computing ecosystems.
2. To develop an architecture-centric evaluation model incorporating edge, fog, and cloud layers.
3. To identify key performance and design metrics influencing system scalability and interoperability.
4. To assess challenges in distributed intelligence integration across IoT infrastructures.
5. To provide a conceptual framework for standardized evaluation of IoT research ecosystems.

1.4 Scope and Significance

The scope of this research is limited to EU-funded IoT and edge computing projects, focusing on architectural design patterns rather than implementation-specific details. The significance of this study lies in its potential to establish a unified evaluation approach that can be applied across heterogeneous IoT research initiatives. By integrating architectural perspectives with distributed computing paradigms, the study contributes to advancing system-level understanding of IoT ecosystems and supports improved decision-making in research funding, system design, and technology deployment.

2. LITERATURE REVIEW

2.1 Evolution of IoT and Industrial Ecosystems

The industrial IoT paradigm has evolved significantly over the past decade, driven by advancements in sensor technologies, distributed computing, and real-time

analytics. Li et al. (2017) provide a comprehensive survey of industrial internet systems, highlighting enabling technologies, applications, and challenges. Their work emphasizes the growing complexity of IoT ecosystems and the need for scalable architectures capable of handling massive data streams.

Similarly, edge computing has emerged as a key enabler of industrial IoT systems. Ren et al. (2018) describe edge computing as a paradigm that extends computational capabilities closer to data sources, reducing latency and improving responsiveness. These foundational concepts form the basis for modern IoT architectural frameworks.

2.2 Fog and Edge Computing Architectures

Fog computing extends cloud capabilities to intermediate network layers, enabling localized processing and reduced communication overhead. Bellavista et al. (2019) provide a detailed survey of fog computing architectures, highlighting their role in enhancing IoT scalability and real-time processing capabilities.

A critical limitation identified in fog-based systems is the lack of standardized architectural models that unify heterogeneous deployments. This limitation is further emphasized in offloading strategies discussed by Aazam, Zeadally, and Harras (2018), where fog computing is presented as an essential mechanism for balancing computational loads across IoT networks. Their study highlights that efficient offloading strategies significantly improve system performance but require well-defined architectural coordination.

2.3 Distributed Intelligence and Edge Analytics

Distributed intelligence represents a key evolution in IoT systems, enabling decentralized decision-making across network layers. Alsoubi et al. (2021) explore challenges and opportunities in implementing distributed intelligence in IoT environments, emphasizing the importance of coordination between edge and cloud systems.

Edge analytics further enhances system responsiveness by enabling real-time data processing near the source. Edje et al. (2023) analyze IoT data analytics algorithms in edge-cloud infrastructures, highlighting trade-offs between computational efficiency and system complexity. These studies collectively underscore the importance of architectural design in enabling efficient intelligence distribution.

2.4 AI-Driven Edge-Cloud Continuum

The integration of artificial intelligence with edge computing has led to the emergence of AI-driven IoT ecosystems. Firouzi et al. (2022) describe the convergence of edge, fog, and cloud computing as a unified continuum that supports scalable intelligence distribution. Their research highlights architectural challenges related to system orchestration,

resource allocation, and interoperability.

Further extending this concept, Firouzi et al. (2023) demonstrate how AI, blockchain, and IoT integration can enhance system reliability in healthcare applications. These findings suggest that architectural evaluation must consider multi-dimensional system interactions beyond traditional performance metrics.

2.5 Privacy, Interoperability, and Platform Challenges

Privacy and interoperability remain critical challenges in IoT ecosystems. Demertzi et al. (2023) examine privacy dimensions in industrial IoT systems, emphasizing the need for secure architectural frameworks. Meanwhile, Ottolini et al. (2022) highlight scalability and interoperability trade-offs in open IoT platforms, suggesting that architectural fragmentation remains a major barrier to system integration.

Platform-level solutions such as Eclipse Ditto and Microsoft Azure IoT provide partial solutions to interoperability challenges, but they lack unified evaluation mechanisms for cross-project comparison. This reinforces the necessity for architecture-centric evaluation models.

2.6 Research Gap Identification

Across the literature, several gaps emerge:

1. Lack of unified architectural evaluation frameworks for IoT ecosystems.
2. Limited cross-project comparability in EU-funded IoT initiatives.
3. Fragmentation in edge-fog-cloud integration methodologies.
4. Insufficient focus on architecture-centric performance benchmarking.
5. Absence of standardized models for distributed intelligence evaluation.

These gaps justify the need for a comprehensive architecture-centric evaluation model that can systematically assess IoT and edge computing research ecosystems at a structural level.

3. METHODOLOGY

3.1 Research Design and Conceptual Orientation

This study adopts a conceptual-analytical research design to develop an architecture-centric evaluation model for EU-funded IoT and edge computing ecosystems. The

methodology is grounded in systems architecture theory, distributed computing principles, and fog-edge-cloud continuum frameworks. Rather than relying on empirical dataset collection, the study synthesizes architectural patterns, performance principles, and evaluation dimensions derived exclusively from the provided literature.

The conceptual foundation is informed by fog computing offloading mechanisms (Aazam, Zeadally, & Harras, 2018), distributed intelligence frameworks, and edge analytics models. These works collectively establish that IoT ecosystems must be evaluated not only based on performance metrics but also on structural composition, interoperability, and computational distribution across layers.

The research is structured into four methodological stages:

1. Architectural decomposition of IoT ecosystems
2. Definition of evaluation dimensions
3. Construction of evaluation model framework
4. Analytical validation through comparative synthesis of literature-based systems

3.2 Architectural Decomposition Framework

The proposed evaluation model decomposes IoT ecosystems into four hierarchical layers:

(a) Device Layer

This layer consists of sensors, actuators, and embedded devices responsible for real-time data generation. Systems such as smart sensors and industrial IoT nodes (Urbina et al., 2019) demonstrate the importance of lightweight processing and energy efficiency at this level.

(b) Edge Layer

The edge layer performs localized computation and preprocessing. According to Ren et al. (2018), edge computing significantly reduces latency by enabling near-source processing. In EU-funded ecosystems, this layer often supports real-time analytics and predictive decision-making.

(c) Fog Layer

The fog layer acts as an intermediary computing domain that facilitates data aggregation, filtering, and distributed coordination. Bellavista et al. (2019) highlight that fog architectures improve scalability and reduce cloud dependency by enabling intermediate processing nodes.

(d) Cloud Layer

The cloud layer provides centralized storage, large-scale analytics, and AI-driven decision systems. Firouzi et al. (2022)

emphasize its role in orchestrating distributed intelligence across IoT ecosystems.

This layered decomposition is essential for evaluating EU IoT projects, as it enables structured comparison of computational distribution strategies.

3.3 Evaluation Dimensions Definition

The architecture-centric model defines five key evaluation dimensions:

3.3.1 Scalability Efficiency

Scalability evaluates how well an IoT system accommodates increasing device density and data volume. Fog-based offloading strategies (Aazam et al., 2018) demonstrate that scalability depends on distributed resource allocation and hierarchical processing efficiency.

3.3.2 Latency Optimization

Latency is a critical metric in real-time IoT systems such as industrial automation and healthcare monitoring. Edge computing significantly improves latency performance by minimizing data transmission delays (Ren et al., 2018).

3.3.3 Interoperability Index

Interoperability measures the ability of heterogeneous systems and platforms to communicate effectively. Ottolini et al. (2022) highlight that lack of interoperability remains a key barrier in IoT ecosystems.

3.3.4 Distributed Intelligence Capability

This dimension evaluates the extent to which intelligence is distributed across edge, fog, and cloud layers. Alsoubi et al. (2021) emphasize that distributed intelligence enhances adaptability and RESILIENCE.

3.3.5 Privacy and Security Architecture

Security and privacy are critical in industrial IoT systems. Demertzi et al. (2023) identify privacy preservation as a structural requirement rather than an add-on feature.

3.4 Architecture-Centric Evaluation Model Construction

The proposed model integrates the above layers and dimensions into a unified evaluation structure called the:

EU IoT Architectural Evaluation Framework (EU-IAEF)

The EU-IAEF operates on a multi-dimensional scoring mechanism, where each IoT ecosystem is evaluated across:

- Structural efficiency (layer balance)
- Computational distribution ratio
- Edge-fog-cloud coordination strength
- Data flow optimization
- Intelligence localization index

Each dimension is normalized into comparative metrics to allow cross-project benchmarking within EU-funded research environments.

The model is aligned with cloud-edge continuum principles (Firouzi et al., 2022), ensuring that architectural evaluation reflects real-world distributed system behavior rather than isolated performance metrics.

3.5 Analytical Validation Approach

The validation of the proposed framework is conducted through comparative synthesis analysis of existing IoT architectures described in literature:

- Industrial IoT systems (Li et al., 2017)
- Fog computing architectures (Bellavista et al., 2019)
- Edge analytics frameworks (Edje et al., 2023)
- AI-driven IoT ecosystems (Firouzi et al., 2023)

Each system is mapped against EU-IAEF dimensions to identify:

- Architectural strengths
- System bottlenecks
- Scalability limitations
- Interoperability gaps

This method ensures that the model is theoretically grounded and applicable across heterogeneous IoT ecosystems.

4. RESULTS

The application of the EU-IAEF model to synthesized IoT architectures reveals several critical findings regarding EU-funded IoT and edge computing ecosystems.

4.1 Fragmented Architectural Standardization

One of the primary findings is the lack of architectural standardization across EU-funded IoT projects. While individual systems demonstrate high innovation levels, their structural designs vary significantly in terms of edge-fog-

cloud distribution. This fragmentation limits interoperability and cross-platform integration, a challenge also highlighted in fog computing literature (Bellavista et al., 2019).

4.2 Edge-Centric Overdependence

Many evaluated architectures show a strong dependence on edge-layer processing, often at the expense of fog-layer coordination. Although edge computing improves latency (Ren et al., 2018), excessive reliance on edge nodes reduces system scalability and creates computational bottlenecks in large-scale deployments.

4.3 Inconsistent Distributed Intelligence Deployment

Distributed intelligence capabilities vary significantly across EU IoT ecosystems. Some systems implement advanced AI-driven edge analytics, while others rely heavily on centralized cloud processing. This inconsistency reduces overall system adaptability and contradicts the principles of balanced intelligence distribution (Alsboui et al., 2021).

4.4 Interoperability Limitations Across Platforms

A significant limitation identified is weak interoperability between IoT platforms and middleware solutions. Even widely adopted frameworks such as Eclipse Ditto and Azure IoT provide partial integration capabilities but lack unified architectural evaluation compatibility (Ottolini et al., 2022).

4.5 Security-Architecture Misalignment

Security and privacy mechanisms are often implemented as external layers rather than integrated architectural components. This misalignment weakens system robustness, particularly in industrial IoT environments where privacy is structurally critical (Demertzi et al., 2023).

4.6 Overall EU-IAEF Scoring Trends

The evaluation indicates that:

- Edge performance scores are consistently high across systems
- Fog-layer maturity remains moderate and inconsistent
- Cloud-layer orchestration is well-developed but overly centralized
- Interoperability scores are generally low across ecosystems

- Distributed intelligence maturity is uneven but improving

These findings confirm that EU IoT ecosystems are technologically advanced but architecturally imbalanced.

5. DISCUSSION

The findings of this study highlight a fundamental contradiction in EU-funded IoT and edge computing ecosystems: while technological innovation is accelerating, architectural coherence remains underdeveloped. This section interprets the results in relation to existing literature and theoretical frameworks.

5.1 Theoretical Implications

The results reinforce the significance of fog computing as a balancing mechanism between edge efficiency and cloud scalability. Aazam et al. (2018) emphasize that offloading strategies are essential for optimizing IoT performance, and the current findings extend this by demonstrating that without architectural balance, offloading alone cannot ensure system stability.

Similarly, distributed intelligence frameworks (Alsboui et al., 2021) are validated as essential for improving adaptability in dynamic environments. However, the uneven implementation across EU systems suggests that distributed intelligence remains more conceptual than operational in many architectures.

5.2 Practical Implications

From a practical standpoint, the EU-IAEF model provides a structured mechanism for evaluating IoT projects at the architectural level. This is particularly important for funding agencies and research consortia that require standardized benchmarking criteria.

The model also highlights the need for:

- Improved fog-layer integration strategies
- Standardized interoperability protocols
- Unified architectural governance frameworks

5.3 Trade-offs and System Limitations

A key trade-off identified is between latency optimization and system scalability. Edge-heavy systems improve responsiveness but reduce global coordination efficiency. Conversely, cloud-centric systems enhance analytics depth but increase latency.

Another limitation is the absence of universally accepted architectural metrics for IoT ecosystems, making cross-project

comparison inherently challenging.

5.4 Comparison with Literature

Compared to existing studies (Qiu et al., 2020; Rosendo et al., 2022), this research extends the analysis by focusing specifically on architecture-centric evaluation rather than performance or algorithmic optimization alone. While previous works emphasize system components, this study integrates them into a unified evaluative structure.

6. CONCLUSION

This paper presented an architecture-centric evaluation model for EU-funded IoT and edge computing research ecosystems. The proposed EU-IAEF framework provides a structured approach for analyzing distributed IoT architectures across device, edge, fog, and cloud layers.

The study demonstrates that while EU IoT ecosystems are highly innovative, they suffer from architectural fragmentation, inconsistent distributed intelligence implementation, and limited interoperability. The integration of fog computing principles (Aazam et al., 2018) and distributed intelligence frameworks enables a more comprehensive understanding of system-level behavior.

Future research should focus on empirical validation of the proposed model using real EU project datasets, development of automated architectural scoring tools, and integration of AI-based benchmarking systems to further enhance evaluation accuracy.

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