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Fuzzy Performance Coordination in Service-Level Multi-Agent Hospital Systems under Uncertainty

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Research Article

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Abstract

Hospital performance assessment is increasingly challenged by the complex interaction between clinical resource availability, support logistics, and operational uncertainty. While fuzzy logic and multi-agent systems have been widely adopted to model hospital resources and decision processes, existing approaches largely remain fragmented, focusing on isolated subsystems or static performance indicators. Such models fail to capture interdependencies, degradation propagation, and coordination effects that critically influence service-level performance.

This paper introduces a service-oriented Performance Coordination Agent (PCA) embedded within a fuzzy multi-agent hospital framework. Unlike traditional performance evaluation modules, the proposed PCA operates as an active supervisory layer instantiated at the healthcare service level. It coordinates local resource states produced by distributed Resource Agents with global logistic sustainability signals provided by a Logistic Support Agent. Through a Mamdani-type fuzzy inference mechanism, the PCA explicitly models non-linear interactions and degradation coupling between subsystems to generate a service-specific Global Performance Index.

The proposed architecture preserves service heterogeneity while enabling coherent system-wide performance interpretation. Simulation-based experiments conducted under multiple degradation scenarios demonstrate that combined resource and logistic disturbances lead to disproportionate performance loss, which cannot be captured by additive or independent assessment models. These results highlight the necessity of coordinated fuzzy decision mechanisms for resilient hospital performance management.

The proposed approach advances intelligent hospital modeling by bridging resource assessment and logistic sustainability through a distributed coordination layer, offering a robust and interpretable decision-support tool for healthcare managers operating under uncertainty.

1. Introduction

Healthcare systems are increasingly confronted with operational complexity driven by fluctuating patient demand, limited clinical resources, and growing dependence on auxiliary support services. Hospital performance can no longer be adequately assessed through isolated indicators such as bed occupancy or staffing ratios. In practice, service-level performance emerges from the interaction between clinical resources, support logistics, and coordination mechanisms operating under uncertainty.

Fuzzy logic and multi-agent systems have been widely adopted to address uncertainty and decentralization in healthcare modeling. Fuzzy inference systems enable the integration of heterogeneous and imprecise indicators, while multi-agent architectures naturally support distributed decision-making across hospital services. Despite these advantages, most existing approaches remain focused on either local resource assessment or high-level performance evaluation, often overlooking the

dynamic interdependencies that link resource degradation, logistic sustainability, and service-level outcomes.

Recent research has highlighted the critical role of hospital support logistics—including sterilization, laundry, information systems, transport, and waste management—in maintaining operational continuity. However, these components are frequently represented as static constraints or aggregated indices, without explicit coordination with service-specific resource states. As a result, degradation effects propagate implicitly, and non-linear amplification phenomena remain insufficiently captured.

Previous works have proposed fuzzy resource-oriented agents to model the availability and stress of clinical and support resources, as well as logistic-oriented agents to assess the sustainability of auxiliary services. While these agents provide valuable localized insights, they do not by themselves ensure coherent service-level performance interpretation. In particular, the absence of an explicit coordination mechanism limits the ability of such systems to integrate heterogeneous signals and anticipate compounded degradation scenarios.

To address this limitation, this paper introduces a service-oriented Performance Coordination Agent (PCA) within a fuzzy multi-agent hospital framework. Unlike conventional performance evaluation modules, the proposed PCA operates as an active supervisory layer instantiated at the level of each healthcare service. It coordinates local resource states produced by distributed Resource Agents with global logistic sustainability signals provided by a Logistic Support Agent. Through a Mamdani-type fuzzy inference mechanism, the PCA explicitly models interaction effects and degradation coupling between subsystems.

The proposed architecture preserves service heterogeneity while enabling coherent and interpretable performance assessment under uncertainty. By producing a service-specific Global Performance Index, the PCA provides decision-makers with a structured representation of operational resilience and risk. Simulation-based experiments demonstrate that combined resource and logistic disturbances lead to disproportionate performance degradation, which cannot be captured by independent or additive assessment models.

The remainder of this paper is organized as follows. Section 2 reviews related works on fuzzy multi-agent hospital modeling and performance assessment. Section 3 presents the proposed architecture and the formal definition of the Performance Coordination Agent. Section 4 describes the fuzzy inference mechanism and performance indicators. Section 5 discusses simulation scenarios and results. Finally, Section 6 concludes the paper and outlines future research directions. This work focuses on methodological modeling rather than predictive or optimization-based deployment.

2. Related Works

2.1 Fuzzy Logic for Decision-Making under Uncertainty

Fuzzy logic has been widely adopted for modeling complex systems characterized by uncertainty, imprecision, and gradual transitions [1, 2]. Its ability to encode expert knowledge and handle linguistic reasoning makes it particularly suitable for decision-making in environments where crisp thresholds are inadequate [1, 3]. Numerous studies have demonstrated the effectiveness of fuzzy inference systems in capturing non-linear behaviors and degradation mechanisms in real-world systems [2, 3].

Recent fuzzy-based decision models have shown strong potential in industrial and organizational contexts, particularly for prioritization, performance assessment, and action selection under uncertainty. Decision-support models using fuzzy logic have been successfully applied to quality improvement, maintenance strategy selection, and action relevance estimation, highlighting the interpretability and robustness of fuzzy approaches [4–6].

2.2 Fuzzy Multi-Agent and Distributed Decision Models

The integration of fuzzy logic within distributed and agent-based architectures has emerged as an effective paradigm for coordinating complex systems. By combining local fuzzy reasoning with decentralized structures, such approaches enable scalable decision-making while preserving system heterogeneity [3, 6].

Several contributions by Lakhouil and Soulhi have demonstrated the relevance of fuzzy logic for risk assessment and resilience evaluation in complex supply chain environments. In particular, fuzzy extensions of classical methods such as FMEA have been proposed to better capture uncertainty, linguistic reasoning, and prioritization under disrupted conditions [7, 8]. These works highlight the importance of coordination, visibility, and resilience metrics when dealing with interconnected subsystems.

2.3 Fuzzy Models for Performance, Maintenance, and Improvement

Fuzzy logic has also been extensively applied to performance-driven decision-making, particularly in maintenance and improvement planning. Mortada and Soulhi proposed fuzzy decision-support models to determine defect criticality, maintenance strategies, and action relevance by integrating multiple performance indicators rather than relying on single aggregated metrics [4, 5]. Their results show that fuzzy reasoning significantly outperforms classical prioritization tools when multiple interacting criteria are involved.

More recent works extend these ideas toward action selection and improvement planning, confirming that fuzzy models provide reliable and interpretable support for managers facing complex trade-offs between effectiveness, feasibility, cost, and implementation delay [6].

2.4 Positioning of the Present Work

While the aforementioned studies demonstrate the effectiveness of fuzzy logic for decision-making, risk assessment, and performance evaluation, most existing approaches remain either centralized or limited

to isolated decision problems [3, 7]. Explicit coordination mechanisms that integrate resource states, logistic sustainability, and service-level performance within a unified fuzzy multi-agent framework remain underexplored in the healthcare domain [8].

This paper builds upon these foundations by introducing a service-oriented Performance Coordination Agent, extending fuzzy decision-making toward coordinated, service-level performance assessment under uncertainty. These studies motivate the need for an explicit coordination mechanism at the service level, which remains insufficiently addressed.

3. Proposed Architecture and Performance Coordination Agent

3.1 Overview of the Proposed Fuzzy Multi-Agent Architecture

The proposed framework adopts a **distributed fuzzy multi-agent architecture** designed to assess and coordinate hospital performance at the **healthcare service level**. Unlike centralized performance evaluation models, the architecture decomposes the hospital system into autonomous yet interacting agents, each responsible for a specific operational dimension.

The architecture is structured around three complementary layers:

1. **Resource Agents (RA)**, responsible for modeling the availability, workload, and degradation of clinical and support resources at the service level.
2. **Logistic Support Agent (LSA)**, responsible for evaluating the sustainability of auxiliary and cross-cutting hospital logistics.
3. **Performance Coordination Agent (PCA)**, introduced in this work as a supervisory fuzzy agent dedicated to service-level performance coordination.

This layered structure enables both **local autonomy** and **global coherence**, allowing heterogeneous services to be evaluated independently while remaining influenced by shared logistic conditions. The proposed architecture, highlighting the mutualization of the Logistic Support Agent and the independent instantiation of Resource and Performance Coordination Agents at the service level, is illustrated in Fig. 1.

3.2 Resource Agents and Logistic Sustainability Assessment

Each healthcare service is associated with one aggregated Resource Agent, which may internally integrate multiple resource dimensions modeling critical operational resources such as beds, medical staff, equipment, sterilization capacity, or waste management facilities. Resource Agents operate independently and produce fuzzy indicators reflecting:

- resource availability,
- operational stress,
- degradation or backlog levels.

In parallel, a Logistic Support Agent evaluates the sustainability of auxiliary hospital services, including information systems, laundry, transport, maintenance, and waste collection. Based on fuzzy inference, the LSA produces a Logistic Sustainability Index (LSI) that reflects the global condition of support logistics shared across services.

The outputs of both Resource Agents and the Logistic Support Agent constitute the input signals for the Performance Coordination Agent.

3.3 Performance Coordination Agent (PCA): Role and Scope

The Performance Coordination Agent (PCA) is the core contribution of this work. It is instantiated independently for each healthcare service, ensuring service-specific performance assessment while preserving the distributed nature of the architecture.

Unlike conventional performance evaluation modules, the PCA does not merely aggregate indicators. Instead, it operates as an active supervisory layer, explicitly modeling the interaction between:

- local resource states provided by Resource Agents, and
- global logistic conditions provided by the LSA.

Through this coordination mechanism, the PCA captures non-linear dependencies, degradation propagation, and amplification effects that cannot be represented by independent or additive models. The PCA does not directly modify resource states or logistic processes. Its role is limited to performance assessment and coordination, ensuring a clear separation between evaluation and operational control.

3.4 Fuzzy Inference Mechanism of the PCA

The PCA relies on a Mamdani-type fuzzy inference system, chosen for its interpretability and suitability for expert-driven modeling. The inference process follows four main stages:

1. **Fuzzification**, where numerical resource and logistic indicators are transformed into linguistic variables using predefined membership functions.
2. **Rule evaluation**, where expert-defined fuzzy rules model coordination and interaction effects between resource availability and logistic sustainability.
3. **Aggregation**, combining the activated rules into a unified fuzzy output.
4. **Defuzzification**, producing a crisp performance value using the centroid method.

The input variables of the PCA typically include resource stress levels, degradation indicators, and the Logistic Sustainability Index. The output is a service-specific Global Performance Index (GPI), representing the coordinated operational performance of the service under uncertainty. Fuzzy rules were defined based on expert knowledge and validated through iterative simulation scenarios, focusing on consistency and interpretability rather than data-driven optimization.

3.5 Service-Level Performance Coordination

By instantiating a PCA for each healthcare service, the proposed architecture preserves service heterogeneity and supports localized decision-making. Each PCA produces a performance assessment that reflects both internal service conditions and external logistic constraints.

This design avoids the limitations of centralized performance aggregation, which often masks local vulnerabilities and delays intervention. Instead, it enables hospital managers to identify critical services, prioritize corrective actions, and anticipate cascading failures resulting from combined resource and logistic degradation.

3.6 Advantages of the Proposed Architecture

The proposed architecture offers several key advantages:

- Distributed scalability, allowing new services or resources to be integrated without redesigning the system.
- Explicit coordination, capturing interaction effects between clinical resources and logistics.
- Interpretability, ensured by the use of fuzzy logic and linguistic rules.
- Resilience-oriented assessment, enabling anticipation of non-linear performance degradation.

These characteristics position the proposed framework as a robust and extensible solution for intelligent hospital performance coordination under uncertainty.

4. Robust Service-Level Fuzzy Coordination Model

4.1 Rationale and Positioning of the Coordination Model

The Performance Coordination Agent (PCA) is designed as a robust fuzzy coordination mechanism to support service-level performance assessment in hospital systems operating under uncertainty. Rather than focusing on prediction or optimization, the proposed model emphasizes structural robustness, interpretability, and adaptability, which are essential properties in real healthcare environments.

Hospital performance is viewed as an emergent outcome resulting from the interaction between resource availability, degradation processes, and logistic sustainability. By relying on fuzzy logic and multi-agent principles, the PCA provides a formal yet flexible coordination framework capable of handling incomplete information, expert knowledge, and gradual operational degradation.

4.2 Definition of the Coordination Input Space

For each healthcare service s, the Performance Coordination Agent (PCA) operates on a coordinated set of input variables derived from the Resource Agent and the Logistic Support Agent, defined as:

$X_s = \{ RSL_s, RDL_s, LSI \}$

where:

- RSL_s denotes the Resource Stress Level, capturing workload intensity, congestion, and utilization pressure;
- RDL_s denotes the Resource Degradation Level, reflecting progressive loss of efficiency or availability;
- LSI denotes the Logistic Sustainability Index, representing the global condition of auxiliary hospital services.

It is important to emphasize that the Resource Stress Level (RSL_s) and the Resource Degradation Level (RDL_s) are not additional outputs computed by a separate model. Instead, they are two complementary interpretations of the Resource Agent output (RA_{out}), exploited by the Performance Coordination Agent.

As defined in our previous work, $RA_{out} \in [0,1]$ results from a weighted fuzzy aggregation of both instantaneous operational indicators (e.g., occupancy, workload) and cumulative indicators (e.g., delays, backlogs, persistent unavailability). Therefore, RA_{out} implicitly embeds both stress-related and degradation-related information, although these components remain fused in a single capacity assessment.

Within the proposed coordination framework, RSL_s is interpreted as the instantaneous projection of RA_{out}, reflecting short-term congestion and workload pressure. A simple and robust formulation can be expressed, for instance, as:

$$RSL_s(t) = 1 - RA_{out}(t)$$

This monotonic relation ensures that high values of RA_{out} correspond to low stress levels, whereas low-capacity states indicate high stress.

In contrast, RDL_s captures the cumulative and persistent effects of degradation. It reflects the duration over which RA_{out} remains low and can be interpreted through a temporal aggregation, for instance using a moving average over a horizon T:

$$RDL_s(t) = 1 - (1/T) \int_{t-T}^{t} RA_{out}(\tau)\, d\tau$$

The time horizon T is not fixed and can be adjusted according to the temporal granularity of the application. This interpretation introduces a memory effect without modifying the underlying Resource Agent model, enabling a clear distinction between short-term stress and long-term degradation within the coordination process.

All variables are normalized to the unit interval to ensure robust comparability across services and time periods, enabling consistent performance assessment.

4.3 Robust Fuzzy Representation and Membership Design

Each input variable is represented using a **limited and overlapping set of linguistic terms**, such as *Low*, *Moderate*, and *High*. Triangular or trapezoidal membership functions are employed to ensure smooth transitions and tolerance to measurement uncertainty.

This representation avoids brittle threshold effects and enhances robustness by ensuring that small variations in operational indicators do not lead to abrupt or unrealistic changes in performance states. Such behavior is particularly relevant in hospital environments, where operational data are often noisy, delayed, or partially unavailable.

4.4 Coordination-Oriented Fuzzy Rule Base

The core of the PCA lies in its coordination-oriented fuzzy rule base, which explicitly models interaction effects between resource conditions and logistic sustainability. Rules are formulated to capture non-additive behavior and degradation coupling, as illustrated by the following structure:

IF RSL_s is High AND RDL_s is Medium AND LSI is Low THEN GPI_s is Critical

This rule design enables the PCA to represent:

- **amplification effects**, where moderate degradations jointly produce severe performance loss;
- **buffering effects**, where strong logistic sustainability mitigates local resource stress;
- **latent vulnerability**, where performance remains acceptable until combined stressors reach critical levels.

Rules are defined based on expert knowledge and refined through iterative scenario analysis, prioritizing robustness and interpretability. The rule base is intentionally kept compact to preserve interpretability and robustness.

4.5 Fuzzy Inference and Robust Aggregation

A Mamdani-type fuzzy inference mechanism is adopted for its transparency and suitability for expert-driven coordination modeling. Rule activation is computed using the minimum operator, ensuring conservative reasoning under uncertainty, while aggregation is performed using the maximum operator to preserve dominant degradation effects.

Defuzzification is carried out using the centroid method, producing a **Global Performance Index** GPI_s for each service. The resulting index is stable with respect to small input perturbations and reflects the coordinated impact of all considered factors.

4.6 Service-Level Independence and Architectural Robustness

Each PCA operates independently at the service level:

PCA_s ⊥ PCA_s' ∀ s ≠ s'

No direct information exchange occurs between service-level coordination agents. Cross-service influence is exclusively mediated through the shared Logistic Support Agent, ensuring architectural coherence and preventing artificial propagation of performance degradation.

This structure mirrors real hospital operations, where services are operationally autonomous but constrained by common logistic infrastructures.

4.7 Robustness Properties

The proposed coordination model exhibits several robustness properties:

- Structural robustness: the model remains valid when services or resources are added or removed;
- Behavioral robustness: performance assessment evolves smoothly under gradual degradation;
- Interpretability robustness: coordination outcomes can be explained through linguistic rules;
- Data robustness: the model operates without reliance on large or precise datasets.

These properties make the PCA a generic and extensible coordination layer suitable for hospital performance assessment under uncertainty.

5. Simulation Scenarios and Performance Analysis

5.1 Objectives of the Simulation Study

The purpose of the simulation study is to analyze the behavior of the proposed fuzzy coordination framework under various operational conditions and degradation patterns. Rather than aiming at predictive accuracy or optimization, the simulations are designed to evaluate the internal coherence, robustness, and interpretability of the Performance Coordination Agent (PCA) when coordinating service-level performance under uncertainty.

Specifically, the simulations aim to:

- assess the sensitivity of the Global Performance Index (GPI□) to variations in resource stress and degradation,

- analyze the interaction effects between service-level resource conditions and logistic sustainability,
- illustrate non-linear and non-additive behaviors captured by the coordination-oriented fuzzy rule base.

5.2 Simulation Setup and Assumptions

The simulation environment considers a hospital composed of multiple healthcare services, each associated with a dedicated Resource Agent and a corresponding Performance Coordination Agent. A single Logistic Support Agent provides a shared Logistic Sustainability Index (LSI), reflecting the global state of auxiliary services.

All input variables are normalized to the unit interval [0,1]. The simulation does not rely on real patient data and is based on controlled synthetic scenarios, allowing systematic exploration of operational conditions without loss of generality.

Unless otherwise stated, the following assumptions are adopted:

- each service operates independently at the coordination level,
- cross-service influence occurs exclusively through the shared LSI,
- fuzzy membership functions and rule bases remain fixed across scenarios to preserve interpretability and robustness.

5.3 Baseline Scenario: Balanced Operational Conditions

In the baseline scenario, resource stress and degradation levels are maintained at moderate values, while logistic sustainability remains stable. This configuration represents a nominal operating regime where services are neither overloaded nor structurally degraded.

Under these conditions, the PCA produces stable and consistent GPI values across services. Minor fluctuations in input variables lead to smooth variations in performance scores, confirming the absence of abrupt threshold effects. This behavior validates the internal coherence of the fuzzy inference mechanism and demonstrates the model's ability to represent normal hospital operations realistically.

5.4 Isolated Resource Stress and Degradation Scenarios

To evaluate the distinct roles of short-term stress and long-term degradation, isolated scenarios are simulated by independently varying RSL_s and RDL_s. When resource stress increases while degradation remains low, the GPI decreases progressively, reflecting immediate congestion effects without structural collapse. Conversely, when degradation increases under moderate stress, the performance deterioration is slower but more persistent, highlighting the cumulative nature of degradation processes.

These scenarios confirm that the PCA successfully differentiates between transient overloads and persistent resource erosion, a distinction that cannot be captured through single aggregated indicators.

5.5 Combined Stress and Logistic Degradation Scenarios

More complex scenarios are constructed by jointly degrading resource conditions and logistic sustainability. In these configurations, moderate increases in RSL_s and RDL_s, when combined with low LSI values, lead to disproportionate drops in GPI□.

This behavior illustrates non-linear amplification effects explicitly encoded in the fuzzy rule base. Logistic degradation acts as a global constraint that reduces the buffering capacity of services, amplifying local resource vulnerabilities. The results emphasize that hospital performance cannot be accurately represented through additive or independent indicators and must instead be analyzed through coordinated interaction mechanisms.

5.6 Cross-Service Consistency and Coordination Effects

Although PCA instances operate independently at the service level, shared logistic conditions introduce implicit coordination effects. When the LSI deteriorates, all services experience performance degradation, regardless of their local resource states.

Importantly, no artificial propagation of degradation occurs between services, as direct PCA-to-PCA interactions are excluded by design. This confirms that the proposed architecture preserves service autonomy while ensuring global coherence through logistic mediation, consistent with real hospital operational structures.

5.7 Robustness and Interpretability Analysis

Across all simulated scenarios, the coordination framework exhibits several robustness properties. Performance indicators evolve smoothly under gradual input variations, and extreme states emerge only when multiple stressors are simultaneously activated.

Furthermore, the linguistic structure of the fuzzy rule base allows direct interpretation of coordination outcomes. Performance degradation can be traced back to specific combinations of stress, degradation, and logistic sustainability, facilitating expert validation and decision support.

These properties demonstrate that the proposed PCA provides not only quantitative performance indices but also qualitative insight into the underlying coordination mechanisms.

5.8 Discussion and Limitations

The simulation results confirm the ability of the proposed fuzzy coordination model to capture complex interaction effects under uncertainty. However, the study remains illustrative and does not aim to provide predictive validation or optimal decision strategies.

The use of synthetic scenarios allows controlled analysis but does not replace empirical validation. Future work will focus on extending the framework toward decision-oriented and optimization-based mechanisms, as well as integrating additional agents within the hospital multi-agent architecture.

5.9 Summary of Findings

The simulation study highlights the following key findings:

- the PCA produces stable and interpretable performance assessments under nominal conditions,
- short-term stress and long-term degradation exert distinct and complementary effects on service performance,
- logistic sustainability plays a critical coordinating role across services,
- non-linear amplification effects emerge naturally from the fuzzy coordination mechanism.

These results confirm the relevance of the proposed service-level fuzzy coordination framework as a robust foundation for hospital performance assessment under uncertainty.

6. Conclusion

This paper introduced a robust fuzzy multi-agent coordination framework for service-level performance assessment in hospital systems operating under uncertainty. The proposed approach extends existing resource and logistic modeling by incorporating a dedicated Performance Coordination Agent (PCA), designed to explicitly coordinate short-term resource stress, long-term resource degradation, and shared logistic sustainability.

By relying on fuzzy logic and a distributed multi-agent architecture, the framework provides an interpretable and flexible representation of hospital performance as an emergent outcome of interacting operational factors. Unlike centralized or purely aggregated performance models, the proposed PCA enables service-level autonomy while preserving global coherence through a shared Logistic Support Agent.

Simulation scenarios demonstrated the internal coherence and robustness of the coordination mechanism. The results showed that the PCA successfully differentiates between transient overload situations and persistent degradation processes, while capturing non-linear amplification effects arising from combined resource and logistic constraints. These behaviors confirm the relevance of coordination-oriented fuzzy reasoning for modeling complex hospital operations under uncertainty.

The main contribution of this work lies in the introduction of an explicit service-level coordination layer that bridges detailed resource assessment and global performance evaluation. The proposed framework emphasizes robustness, interpretability, and modularity, making it suitable as a foundation for decision-support systems in healthcare environments.

Future work will focus on extending the coordination framework toward decision-oriented and optimization-based mechanisms, as well as integrating additional agents within the hospital multi-agent architecture. Empirical validation using real operational data and the exploration of advanced coordination strategies represent promising directions for further research.

Declarations

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Clinical Trial Registration

Not applicable.

Consent to Publish

Not applicable.

Consent to Participate

Not applicable.

Ethics Approval

Not applicable.

Data Availability Statement

The data used in this study consist of simulated datasets generated within the proposed fuzzy multi-agent framework. The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

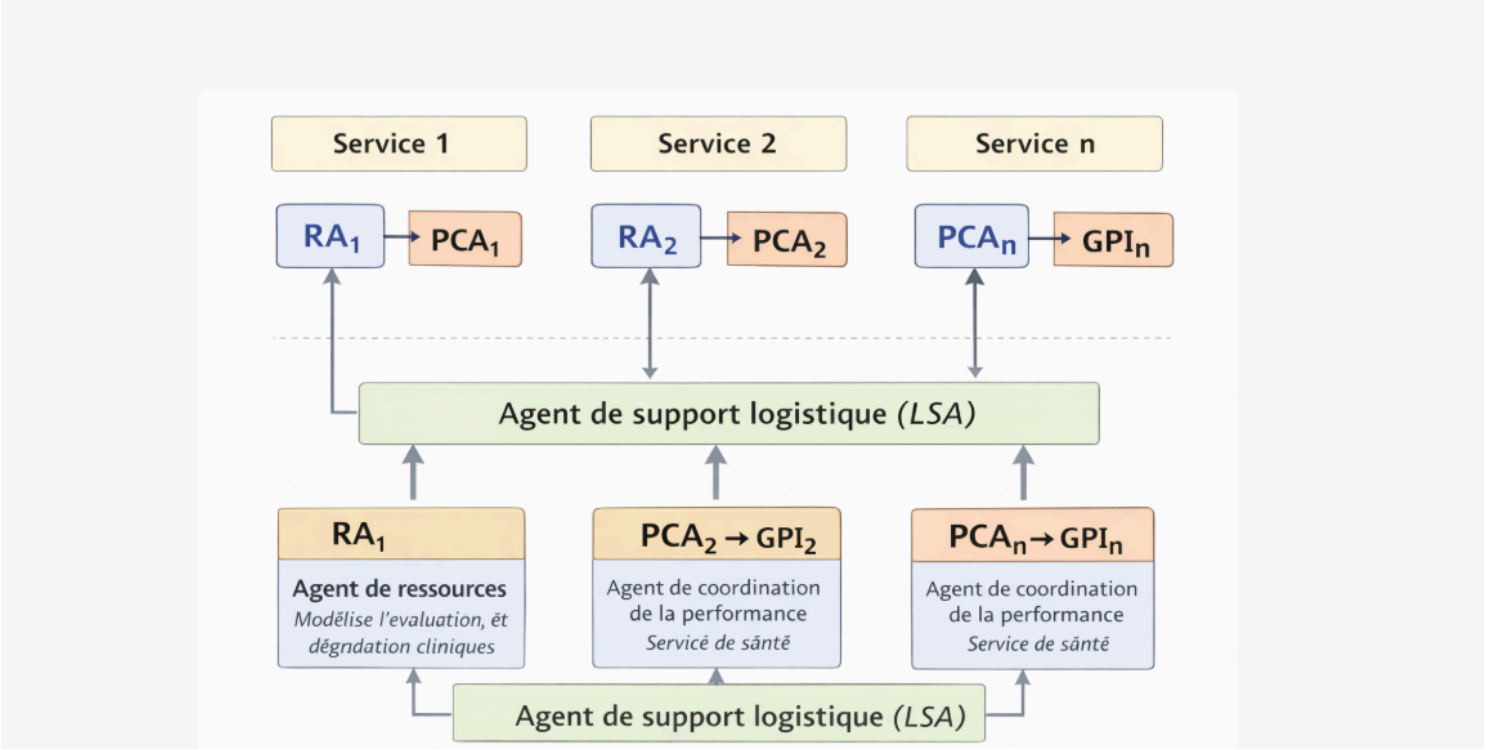


Figure 1

Overview of the proposed fuzzy multi-agent architecture. Each healthcare service is associated with a dedicated Resource Agent (RA□) and a Performance Coordination Agent (PCA□), while a shared Logistic Support Agent (LSA) provides a global logistic sustainability assessment across services.



Figure 2

Functional role of the Performance Coordination Agent (PCA), illustrating the coordination between local resource states and global logistic sustainability to produce a service-level performance index.