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Design Architectures for Operating Theatres Machines

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ABSTRACT

This work presents a multidisciplinary framework for modeling and managing operating theatre (OT) systems through a multi-agent system (MAS) integrated into an Interactive Decision Support System (IDSS). Recognizing OTs as critical bottlenecks in hospital workflows, the authors address the challenge of frequent schedule disruptions particularly from emergency cases by proposing a real-time, adaptive rescheduling architecture. The system features supervisor agents for global coordination and service agents representing operational units (e.g., operating rooms, surgical teams). These cognitive agents negotiate, prioritize, and allocate resources dynamically using algorithms for resource allocation, unavailability handling, and information retrieval. Decision making is enhanced by the ELECTRE III multi-criteria outranking method, which resolves conflicts based on clinical urgency and resource availability. Implemented in JADE, the platform uses FIPA standards to ensure robust, interoperable agent communication. Beyond software coordination, the paper also outlines key principles for OT equipment design including ergonomics, sterility, modularity, safety, and interoperability and emphasizes human centered design, regulatory compliance (e.g., ISO 13485, IEC 60601), and sustainability. Emerging trends such as AI, IoT, and digital twins are noted as enablers of smart, resilient operating theatres. The approach aims to optimize resource utilization, reduce delays, and improve res ponsiveness in high pressure surgical environments, filling a gap left by prior domain specific MAS application that overlook emergency surgical coordination.

Keywords: Multi-Agent Systems (MAS), Operating Theatre Management, Real-Time Scheduling Emergency Surgical Cases, Interactive Decision Support System (IDSS), Resource Allocation, Human Centered Design

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1. Introduction

Operating theatres (OTs) represent a critical bottleneck in most hospital systems. Surgical patient flows from diverse clinical departments converge at the OT, making its efficient management essential to overall hospital performance. To coordinate this complex workflow, an operational surgical program is typically established. This program specifies the list of patients scheduled for surgery, their sequence of passage through each operating room, and where applicable their routing to postoperative recovery units such as the Post-Anaesthesia Care Unit (PACU), also referred to as SSPI (Salle de Surveillance Post Interventionnelle).

However, adherence to this planned schedule is frequently disrupted by real-world contingencies most notably unscheduled emergency cases. These disruptions are inherent to operating theatre dynamics and require rapid, informed decision making to maintain system stability and patient safety.

This paper presents a robust and adaptive approach to enhance the resilience and performance of the surgical program. By integrating Multi-Agent Systems (MAS) into an Interactive Decision Support System (IDSS), our framework enables real-time monitoring, dynamic rescheduling, and proactive hazard management within the operating theatre environment. Central to this architecture are two key agent types: a supervisor agent, responsible for global coordination and policy enforcement, and multiple service agents, which represent individual operational units (e.g., surgical teams, rooms, or support services) and manage local execution.

The design and modeling of operating theatre systems and their associated technologies require a multidisciplinary approach. This integration spans biomedical engineering, human factors engineering, industrial design, clinical workflow analysis, and regulatory compliance. The following sections outline how agent-based modeling aligns with these domains to support more responsive, efficient, and human centered operating theatre operations.

2. Design Stages for Operating Theatre (OT) Machines

2.1 Understanding Clinical Needs

2.1.1 Stakeholder Engagement

The design of operating theatre machines must begin with a comprehensive understanding of clinical requirements, achieved through systematic engagement with all relevant stakeholders. These include surgeons, anesthesiologists, perioperative nurses, biomedical engineers, infection control officers, and hospital administrators. Each group contributes distinct perspectives related to clinical performance, patient safety, maintenance feasibility, and cost-effectiveness. Multidisciplinary workshops and structured interviews are widely recommended to capture both explicit and latent needs that influence device usability and adoption [1,2].

2.1.2 Workflow Analysis

Detailed workflow mapping of surgical procedures is essential to identify inefficiencies, safety hazards, and ergonomic stress points. Techniques such as process flow diagrams, time motion studies, and failure mode and effects analysis (FMEA) are commonly employed to assess intraoperative interactions between clinicians, patients, and equipment. Understanding these workflows helps ensure that new machines integrate seamlessly into existing surgical environments without disrupting critical processes [3].

2.1.3 Use Case Definition

Use cases translate clinical workflows into concrete design requirements. Scenarios may include minimally invasive laparoscopic procedures, open cardiac surgery, orthopedic trauma cases, or emergency interventions. Defining both routine and extreme use cases ensures that devices perform reliably under varying clinical conditions and patient profiles [4].

2.2 Key Types of Operating Theatre Machines

Modern operating theatres rely on a complex ecosystem of interconnected medical devices, including:

• Anesthesia Machines – Deliver controlled mixtures of gases and anesthetic agents while monitoring ventilation parameters.

• Electrosurgical Units (ESUs) – Enable tissue cutting and coagulation using high-frequency electrical currents.

• Operating Tables – Provide patient positioning with high load capacity, stability, and radiolucency.

• Surgical Lighting Systems – Offer shadow-free illumination with adjustable intensity and color temperature.

• Patient Monitoring Systems – Continuously track vital signs such as ECG, blood pressure, SpO, , and end-tidal CO, .

• Surgical Robotic Systems (e.g., *da Vinci*) – Enhance precision, dexterity, and minimally invasive capabilities.

• Sterilization and Waste Management Units – Support infection control and safe disposal of biohazardous materials.

• Imaging Systems – Including C-arms, fluoroscopy, and intraoperative MRI/CT for real-time visualization [5–7].

2.3 Design Principles

2.31 Ergonomics

Ergonomic design is critical to reduce surgeon fatigue, musculoskeletal strain, and human error. Equipment must support intuitive positioning, height adjustability, and ambidextrous use to accommodate clinicians of varying body dimensions. Poor ergonomic design has been directly linked to increased procedural errors and occupational injuries [8].

2.3.2 Sterility and Cleanability

Operating theatre equipment must comply with strict infection-control requirements. This necessitates smooth, non-porous surfaces, sealed joints, and materials resistant to aggressive disinfectants. Design features should minimize crevices and exposed fasteners where microbial contamination can accumulate [9].

2.3.3 Modularity and Scalability

Modular architectures allow devices to be adapted across surgical specialties and upgraded over time. Interchangeable components reduce downtime, extend product lifespan, and improve return on investment for healthcare facilities [10].

2.3.4 Safety and Risk Mitigation

Safety is ensured through redundant fail-safes, alarms, electrical isolation, grounding, and compliance with electromagnetic compatibility standards. Risk management processes aligned with ISO 14971 are integral throughout the design lifecycle [11].

2.3.5 System Integration

Interoperability with hospital information systems is increasingly important. Devices should support standardized communication protocols such as HL7 and DICOM to enable seamless data exchange with electronic medical records (EMR) and picture archiving and communication systems (PACS) [12].

2.4 Modeling and Simulation Approaches

2.4.1 Conceptual Modeling

Early stage ideation employs sketches, storyboards, and personas to explore functional concepts and user interactions. These low fidelity tools encourage rapid iteration and stakeholder feedback before committing to detailed designs [13].

2.4.2 Digital Prototyping

• Computer-Aided Design (CAD): Tools such as SolidWorks and Autodesk Inventor support precise mechanical modeling and tolerance analysis.

• Finite Element Analysis (FEA): Used to validate structural integrity, load-bearing capacity, and fatigue life of components such as operating tables.

• Computational Fluid Dynamics (CFD): Applied to thermal management and airflow optimization in sterile environments, including laminar airflow systems [14].

2.4.3 Human in the Loop Simulation

Virtual reality (VR) and augmented reality (AR) simulations enable clinicians to interact with digital prototypes, allowing early identification of usability issues and ergonomic constraints [15].

2.4.4 Digital Twins

Digital twins real time virtual replicas of physical devices are increasingly used for predictive maintenance, performance optimization, and lifecycle management within smart hospitals [16].

2.5 Regulatory and Standards Compliance

Compliance with international regulatory frameworks is mandatory for operating theatre machines:

• ISO 13485: Quality management systems for medical device manufacturers.

• IEC/ISO 60601 Series: Electrical safety and essential performance standards.

• IEC 62304: Software lifecycle processes for medical device software.

• FDA (U.S.) / CE Marking (EU): Risk-based classification, clinical evaluation, and post-market surveillance requirements [17–19].

Early incorporation of regulatory considerations reduces redesign costs and accelerates time to market.

2.6 Human Factors and Usability Engineering

Human factors engineering aims to minimise use related errors through the systematic application of user-centred design principles. The IEC 62366-1 standard requires formative evaluations during early development and summative usability validation before regulatory submission. Evidence shows that usability driven design significantly improves patient safety and clinical efficiency [20].

2.7 Sustainability and Lifecycle Considerations

Sustainable design practices are gaining prominence in healthcare technology. These include design for disassembly, repairability, recyclability of materials, and reduced reliance on single use components. Lifecycle cost analysis should account for maintenance, consumables, energy consumption, training, and end of life disposal to determine the total cost of ownership (TCO) [21, 22].

2.8 Emerging Trends in Operating Theatre Technology

- Artificial Intelligence (AI): Real-time surgical decision support, predictive maintenance, and workflow optimization.

- Internet of Things (IoT): Connected devices enabling remote monitoring and asset management.

- Miniaturization and Portability: Compact systems for ambulatory surgery centers and field hospitals.

- Green Operating Theatres: Energy-efficient lighting, smart HVAC systems, and reduced environmental footprint [23–25].

3. Related Works

Multi-agent systems (MAS) have emerged as a powerful technological paradigm for the design and control of complex systems. In recent years, they have found successful application in healthcare particularly in addressing challenges in operating theatre management, where autonomous agents must interact, communicate, and reconcile differing perspectives and competing interests [26].

The research literature documents a variety of agent-based applications in healthcare. Among the earliest contributions, Huang et al. [27] developed a MAS for distributed medical care, tackling issues such as decentralized data and control, information uncertainty, and dynamic environmental conditions. Their coordination model relies on commitments and conventions between distinct agent types: managing agents oversee task execution, while contractor agents carry out specific tasks.

Haeng-Kon Kim [28] introduced a proactive, multi-agent based ubiquitous healthcare (u-healthcare) system capable of autonomously recognizing and responding to domain specific problems. This architecture supports rapid and efficient mobile healthcare services through intelligent, context aware agents.

Mutingi and Mbohwa [29] proposed a home-care MAS architecture designed to support decision-making in multi-objective, dynamic environments. Their system integrates genetic algorithms with web services, enabling coordinated, adaptive decision support through efficient inter-agent communication.

Decker and Li [30] modeled a MAS for hospital patient scheduling involving complex medical procedures. Adopting a function centered perspective, they represented nursing wards as autonomous agents and employed a Generalized Partial Global Planning (GPGP) approach a constraint based coordination mechanism to prevent resource conflicts. In their framework, patients are treated as a distinct resource governed by a dedicated management protocol.

Additional applications of MAS in healthcare have been explored by Nealon and Moreno [31], who examined use cases such as inter hospital coordination for organ transplants, patient scheduling, and elderly care. Similarly, Riano [32] leveraged information technology and multi-agent systems to enhance the delivery of palliative care.

While these studies demonstrate the versatility of MAS in healthcare, they remain largely domain specific often tailored to particular patient populations or care settings. Consequently, they do not adequately address the unique challenges associated with managing emergency patients in operating theatres, as outlined in Section 1. The potential effectiveness of MAS in this critical and dynamic context remains underexplored. In the following sections, we introduce and elaborate on the application of agent-based technology and decision support systems theory to this pressing operational challenge.

4. Tools & Software Commonly Used

- CAD: SolidWorks, Siemens NX, PTC Creo

- Simulation: ANSYS (FEA/CFD), COMSOL Multiphysics

- PLM: Windchill, Teamcenter

- Usability Testing: Tobii Pro (eye tracking), VR platforms (Unity/Unreal Engine

4.1 The system approach for modelling the operating theatres

The block's operation is determined by a preliminary operating program that specifies the patients to be operated on during the day, the critical resources assigned to each operation, and the order in which operations are performed. However, this operating program may not be adhered to due to the diverse hazards that can occur. These uncertainties include prediction errors in surgical time, unforeseen complications, and the arrival of urgent cases to be performed during the day before a specified time.

For this reason, a real-time control tool appeared appropriate for the operating theatres. In addition, real-time management complements the proposed decision making approach by enabling timely intervention when a hazard occurs. Particular attention has been paid to the consideration of urgency in the surgical program. We proposed a real-time strategy based on multi agent systems [33] and a decision support system, guided by the principles of supervision and mathematical modelling, to support the piloting of operating theatres in the event of such a hazard.

The agents employed in our approach are cognitive agents, each with distinct functions. It is a genuine multidisciplinary co-operative team that participates in the design and implementation of decisions by combining its efforts and continually adapting to the evolution of the operating theatre system. Service agents and supervisors are distinguished.

The model of the proposed agents is adapted to the context and specificities of operating theatres. In particular, it enables research, selection, negotiation, coordination, and cooperation to be carried out to realize real-time control of operating theatres.

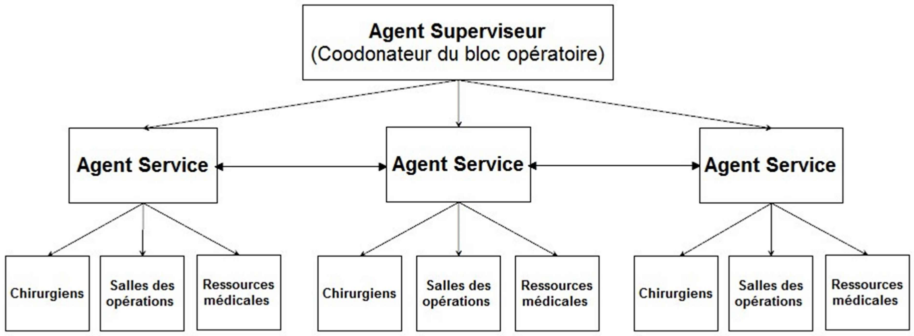

Figure 1. The design of the operating theaters (Multi-agent structure)

Figure 1 describes the steps of the design and modelling, and the unavailability of resources (resource breakdowns, nonexistence, or busy status) following the arrival of an urgent order.

4.2 Resource Allocation Algorithm

The coordinating agent applies the resource allocation algorithm upon receiving resource allocation requests from the service agent.

Répéter
Réception des demandes d'allocation de ressource Ri par les agents services
RequestList[]=liste des ressources demandés ;
AgentRest[]=liste des agents demandeurs ;
Identificateur de l'état de la ressource Ri ;
If (Ri.Etat = n'existe pas)
Envoi le rejet d'initialisation à l'AgentRest[]

Else
If(Ri.Etat= occpées)
Identification de la durée de libération de la ressource
D=durée de la libération de la ressource
Demande de rappel de demande de ressource après temps =D

Else
If Ri.Etat==libre
//selon la priorité d'AgentRest
Identification des priorités des opérations d'AgentRest
AgentRest[]=PrioritéMax(AgentRest)
If (AgentRest[]= contient un seul demande)
Allocation faite pour AgentRest[]

Algorithm 1. The Resource Allocation Algorithm

4.3 Resource Unavailability Algorithm

During emergencies, resources are at constant risk of breakdown or unavailability, whereas the performance of surgical operations is imperative. The service agent uses algorithm 2 to identify resources similar to those that do not exist or are unavailable.

L'agent service reçoit la demande de l'urgente
Mise à jour de la base de données de l'agent service
Ressources « R» pour réalisation de l'urgente ne sont pas disponibles (n'existe pas)
Recherche des ressources identiques à R
Demande de l'aide l'agent coordinateur ;

Traitement de l'aide l'agent coordinateur ;
If (proposition de ressource)
Envoi la confirmation de l'affectation de l'urgente à l'agent superviseur

Else
Affectation impossible
Ajout des informations du manque de ressources à la BD de l'agent coordinateur
Fin

Algorithm 2. Resource Unavailability Algorithm

4.4 Information retrieval algorithm (request for help)

The agent uses Algorithm 3 to search for information about resources

Réception de demande d'aide de la part de l'agent service
Liste_ressource[]=recherche liste de ressources identiques Libres
If (Liste_ressource[].size==1)
Envoi proposition Liste_ressource[]d'allocation
Réception la confirmation

Else
If (liste_ressource[] !=0)
R=choisir entre Liste_Ressource[]
Envoie de R à agent service

Else
//Recherche des ressources identiques sous le contrôle des autres agents
Liste_ressourcesIdentique []
If (liste_ressourcesIdentiques[] !=0)
Envoie de ressourcesIdentique [] à chirurgien

Else
Envoie pas d'aide ;
Fin

Algorithm 3. Information retrieval algorithm (request for help)

5. Experimentation of the System

To evaluate the proposed multi-agent framework, we conducted a simulation in which a supervisor agent negotiated with four service agents. The goal was to collaboratively reschedule urgent surgical operations in real time while respecting resource constraints and operational priorities. The interaction sequence unfolds as follows:

1. The supervisor agent requests Service Agent 2 (AC2) to insert an urgent surgical case into the current schedule.

2. If the required resourcessuch as an available operating theatre or a surgeon managed by Service Agent 1 (AC1) are unavailable or inoperative, the analysis and reaction module detects this disruption and triggers the appropriate behavioral response.

3. Should the initial insertion fail, AC2 forwards the request back to the supervisor, activating the supervisor's Type 1 behavior (i.e., escalation and replanning).

4. The supervisor then broadcasts the request to the remaining service agents and processes their responses to identify a feasible solution.

5. Once a viable option is found, the supervisor communicates the decision to both the selected service agent and the requesting agent (AC2).

6. The selected agent accepts the supervisor's directive, concluding the initial decision-making phase.
At this point, a potential conflict may arise between service agents due to competing priorities or resource claims. To resolve this:

7. A negotiation phase is initiated, with AC2 acting as the initiator and the other involved service agent serving as the participant.

8. The initiating agent uses its proposition generation module to formulate an initial scheduling proposal, which is sent to the participant.

9. The participant evaluates the proposal using its preference and priority matrix, which ranks operations based on clinical urgency, resource availability, and other contextual factors.

10. Proposal assessment or the generation of a counterproposal is supported by the ELECTRE III outranking algorithm, which enables robust multi-criteria decision-making under uncertainty.

Implementation Framework

The proposed system was implemented using JADE (Java Agent Development Framework), a widely adopted platform for building multi-agent systems. JADE was selected for several key advantages:

- Compliance with FIPA (Foundation for Intelligent Physical Agents) communication standards,

- Built-in support for interoperability and portability,

- A distributed, programmable architecture that simplifies agent coordination,

- Overall simplicity in modeling agent behaviors and interactions [16, 17].

These features made JADE particularly well-suited for modeling the dynamic, real-time decision-making environment of an operating theatre.

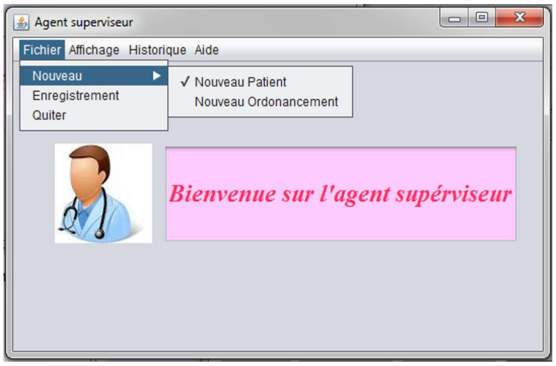

Figure 1. Supervisor Agent

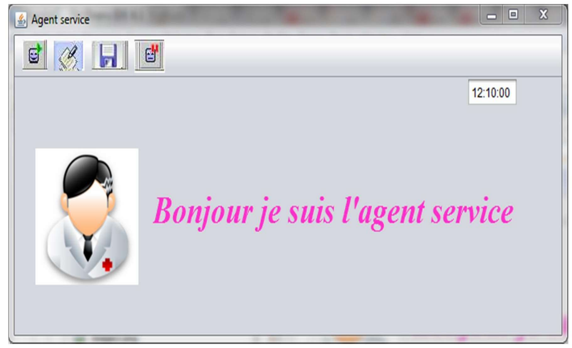

Figure 2. Service Agent

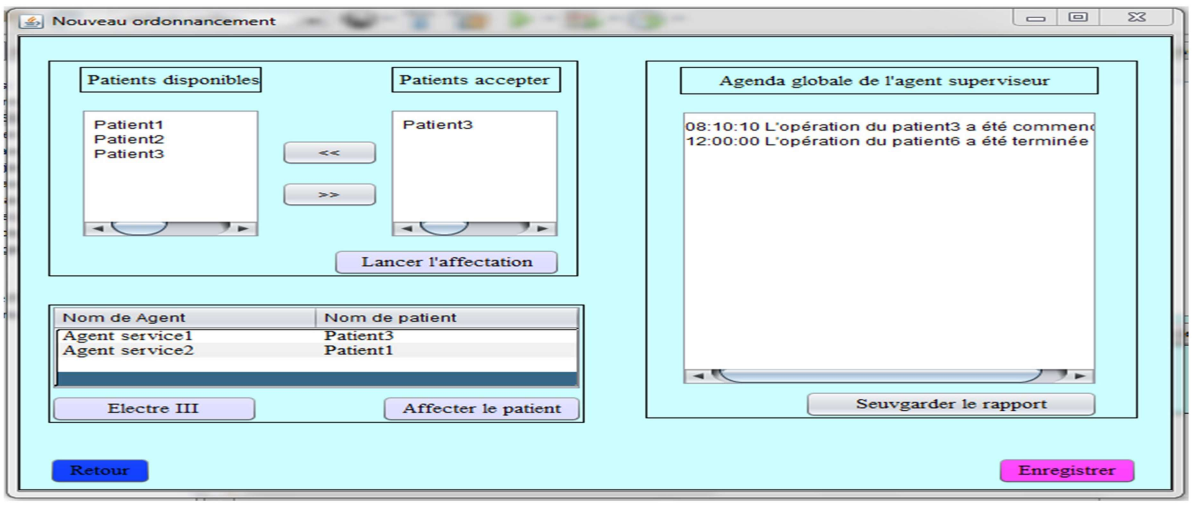

Figure 4. Description of new ordering request

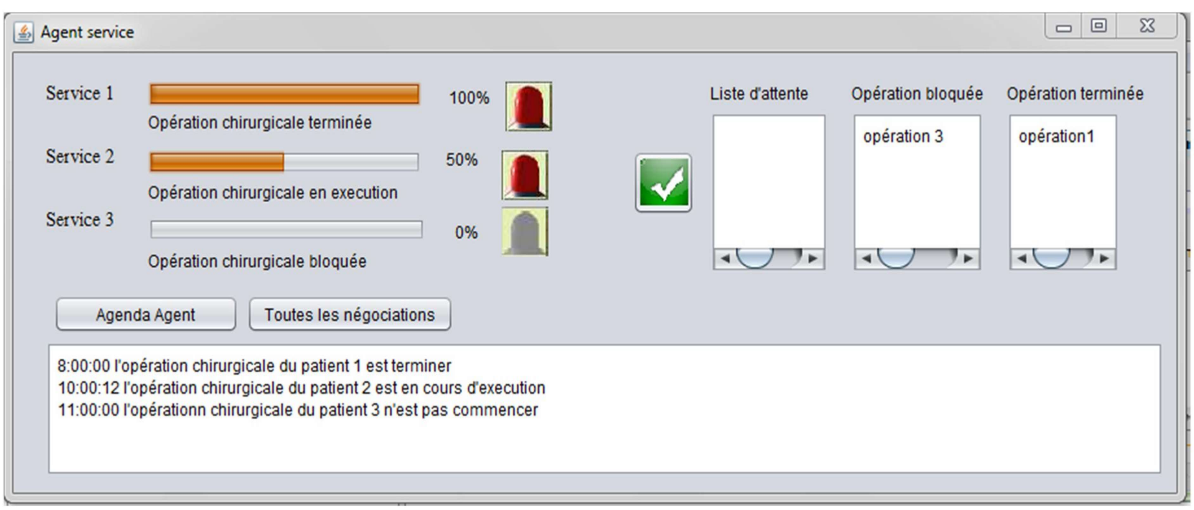

Figure 5. Negotiation Scenario

6. Conclusion

The overarching objective of this work is to optimise the use of operating theatre resources while adhering to clinical, logistical, and temporal constraints. To this end, we developed a global scheduling plan that is collaboratively maintained and adjusted by service agents under the supervision of a central coordinator.

The system explicitly addresses two critical challenges:

- The disruptive impact of urgent surgical cases, and

- The risk of resource shortages that can cascade into broader scheduling failures.

By leveraging JADE's robust communication infrastructure, our multi-agent application demonstrates how autonomous agents can negotiate, adapt, and coordinate in real time, thereby ensuring both operational resilience and clinical responsiveness in high-stakes environments.

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