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AN EFFICIENT PROGRAMMING SYSTEM FOR OPERATING THEATERS BASED ON DISTRIBUTED ARTIFICIAL INTELLIGENCE

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ABSTRACT

The operating theater is an essential element of any hospital structure. It is distinguished by the heterogeneity of its components, some of which have antagonistic characteristics, and receives emergency, planned or ambulatory surgery on a permanent and unpredictable basis. The management of an operating theater involves multiple human and material elements to ensure better quality of medical services for the benefit of patients. In this study, we propose a planning tool that uses a multi-agent planner based on distributed artificial intelligence to ensure efficient and reactive surgical planning that satisfies the various demands of surgical teams despite the constraints encountered, contributing to maximizing operating room occupancy and thus improving operating theater performance and patient satisfaction. We describe the multi-agent system in relation to surgical planning, before presenting its application on a real case of a surgical department. The structure of the tool is detailed, along with its interaction mechanism and decision logic for each step of the planning procedure. The aim of our study is to create a dynamic and weekly operating theater program, taking into account the various incidents that can alter the normal sequence of surgical procedures, and responding to the increased needs of surgical teams and patients.

Keywords: *Multi Agent Planner, Distributed Artificial Intelligence, Planning, Scheduling, Operating Theater.*

1. INTRODUCTION

The world we live in is rapidly moving to modernize the techniques that will determine the future. Today's technology is at the peak of its constant evolutionary phase, and innovative solutions with a global vision are widely accepted [1]. New approaches are available to generate studies with a good level of evidence based on the construction and exploitation of massive and detailed databases, integrating a large number of parameters to be analyzed [2]. Health establishments are undergoing a major evolution based on increased productivity and optimization of available resources (human and material), reflected in improved quality of care. Good management of healthcare facilities is the result of optimizing their processes and improving their overall performance, which implies rapid local reactivity in the event of disruptions [3]. Responsiveness is one of the key performance characteristics of the medical domain. The operating theater is one of the most expensive and complex elements of a hospital [4], accounting for up to 40% of resource costs [5]. Operating theater management is a meticulous process, involving multiple factors that need to be well balanced [6]. Surgical procedures are performed according to an operating schedule during a predefined time interval. The elaboration of an operative schedule is a complicated and very critical step, much discussed in the literature. The multi-agent system (MAS) is one of the solutions that can be used to optimize surgical planning in order to achieve the set objectives [7]. Few works have dealt with this subject in Morocco, and few authors have proposed the multi-agent system (MAS) or the multi-agent planner (MAP) as a solution to the problem of surgical scheduling. The contribution of our work is to improve the quality of surgical scheduling after elucidating its current classical design, in order to maximize operating room occupancy and consequently satisfy both surgeons and patients. The aim of our work is to generate an intelligent surgical scheduling system based on a distributed artificial intelligence (DAI) approach that is reactive and flexible, to benefit the good workflow of hospital operating theaters.

2. PROBLEMATIC

The main objective of the operating theater process is to respect the planning and scheduling of surgical interventions, while at the same time dealing with the various challenges that can affect this procedure.

the key question here is: how can we optimize the operating theater process while taking into account the uncertainties related to surgical activity?

In our context, the operating theater manager manually prepares an operating schedule, which must normally be adhered to, despite frequent disruptions requiring the already established program to be updated. This has a negative impact on the operating theater process, surgical team productivity and, consequently, long patient waiting lists, not forgetting the administrative complications that operating theater managers have to deal with. Several approaches to operating theater management have been described, but there is a discordance between theoretical models and the multiple realities encountered in the process. Various simplifying approaches have emerged to make the model mathematically affordable. However, incomplete approaches with unrealistic hypothesis have lead to inefficient management [3].

3. MOTIVATION

Our motivation is based on the added value that an intelligent surgical planning tool can provide in our Moroccan context, particularly in certain public hospitals, which provide care for a large number of patients, despite human and sometimes material resource constraints, which will further optimize the management of Moroccan operating theaters. For this purpose, we carried out a study in the B4 orthopedic surgery department of the Hassan II University Hospital in Fez, Morocco.

4. RELATED WORK

After a review of the literature, we found that the issue of planning and scheduling in operating theaters has attracted the interest of various authors in the scientific community. [8] aim to maximise the use of operating theatres and minimise overtime costs in operating theatres and recovery rooms using a hybrid genetic algorithm. [9] propose a model that takes into account the availability of beds in the recovery room and of transporters, using a Lagrangian relaxation heuristic. [10] propose a new algorithm with the objective of maximising the use of the operating theater and minimising the number of cancellations of elective cases. [11] compare different methods: integer linear programming (ILP), the three classic heuristics for Bin-Packing (First Fit Decreasing, Next Fit decreasing, Best Fit) and the coupling of the first variant (FFD) with stochastic descent, having the objectives of minimising the number of unallocated interventions, minimising the number of room-days used and minimising the minimum room occupancy time. [12] have proposed a new hybrid genetic algorithm for solving a multi-objective optimisation model that aims to balance the use of operating theaters, maximise the number of planned surgical operations and minimise the under-use of operating theaters and the cost of overtime. [13] try to minimise access time for patients with a high clinical priority. To achieve this, the authors compare 83 heuristics. [14] involves the development of an intelligent multi-agent system (MAS) for controlling and managing the process in a surgical operating theater.

5. MAS AND MAP CONCEPT FOR SURGICAL PLANNING

5.1. MAS and MAP: definitions

Multi-agent systems are an emerging way of designing computer systems for controlling complex processes. The field of applications covered by MAS is expanding rapidly, and they are used in an increasingly diverse range of applications [14].
[15] define a multi-agent system (MAS) as a distributed system, composed of a set of agents interacting with each other according to modes of cooperation, competition or coexistence.
Operating theaters are complex dynamic systems. Multi-agent systems (MAS) offer an effective and appropriate means of effectively modelling, controlling and managing their processes [14]. The effectiveness of MAS in this context stems from the fact that operating theaters are intrinsically

distributed throughout the block, with each room having its own resources and its own proactive planning. In addition, surgical teams have limited social capacities as well as human and material resources [14].
MAS has been proposed as an appropriate modeling approach for domains such as e-commerce, multi-robot systems, security applications, industrial manufacturing, etc. The planning technique with the Multi-Agent Planner (MAP) makes its appearance. This new methodology continues the integration of planning capabilities into intelligent agents. Thus, a group of agents can develop a plan of action to achieve a set of common goals [16]. MAP stands out as a simple and powerful distributed artificial intelligence (DAI) planning method for multi-agent system (MAS) managed applications where multiple entities or intelligent agents plan by communicating with each other and combining their knowledge, information, and capabilities [17].

5.2. Platforms for MAS development

Multi-agent development environments are essential to the success of multi-agent technology. These platforms allow developers to design and implement their applications without having to spend time setting up the basic functionalities for creating and interacting between agents. In addition, they generally eliminate the need to become familiar with the various theoretical concepts of multi-agent systems [18].
Like development tools for systems based on the object paradigm, development tools for systems based on the agent paradigm have emerged, in particular generic platforms. These include Development and Implementation of Multi-Agent Systems (DIMA), Java Agent DEvelopment Framework (JADE) and MultiAgent Development Kit (MADKIT). There are also other platforms used for other applications [15].
We have chosen the JADE platform to implement our distributed architecture.
JADE is a software environment for creating agent systems for managing information resources in the network in accordance with the FIPA (Foundation for Intelligent Physical Agents) specifications. JADE provides middleware for the development and execution of agent-based applications that can operate and interact transparently in both wired and wireless environments. In addition, JADE supports the development of multi-agent systems via the predefined programmable and extensible agent model and a set of management and testing tools. Currently, JADE is one of the most widely used and promising agent development frameworks" [19].

6. ARCHITECTURE SOLUTION

6.1. MAP structure

Multi-agent planning extends traditional automated planning by distributing the planning task more or less between several agents who work together to design a common, high-performance schedule [14]. We proceed on the assumption that all agents are fully cooperative and engaged in the joint development of a distributed plan to reach our common goal. With this in mind, we select a planning strategy from three distinct layers of coordination, defining the necessary degrees of autonomy or cooperation
The first physical layer contains human resources and operating theaters. The other two layers comprise: the distributed artificial intelligence (DAI) layer involving a MAP and the mediator layer providing interfaces between the MAP and the physical layer.

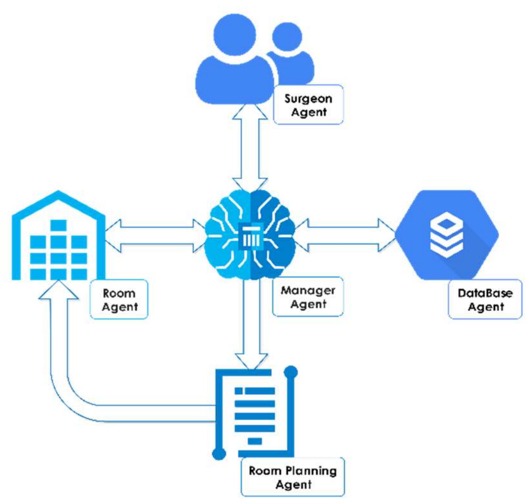

Figure 1: The Structure Of The MAP.

The MAP is composed of five agents, namely (Figure 1): Surgeon -Team- AGENT (Team A, Team B, Team C and Team D), Manager AGENT (Manager), Database AGENT (DataBase), Room AGENT (Main Room, Ambulatory Room and Emergency Room) and Rooms Planning AGENT.

- The Manager Agent is the main agent who collaborates with all the other agents to schedule the operating room according to predefined parameters. After examining all the

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proposals from the operating Room Agents, the Agent Manager allocates the most suitable Room Agent slot possible to the requesting surgeon's team, taking into account the specifics and constraints obtained from DataBase Agent.

- The Surgeon Agent represents a team of surgeons in a specific specialty. This agent asks the Agent Manager to create the weekly schedule for his team or to reschedule it in the event of an incident occurring before, during or after an operation. He gets back his operation schedule with all the necessary details.
- The Room Agent represents a physical surgery room on a given day. Each Room Agent is responsible for creating his individual planning in collaboration with the Manager Agent. Each operating room calculates the virtual cost of each of the residual slots likely to be available at the request of the Manager Agent. It informs the Manager Agent of this result so that he can make the appropriate choice.
- The DataBase Agent is a database containing all the information required for each planned intervention, including date, duration, type, equipment, human resources and intervention constraints. This information can be retrieved in a predefined format.
- The Rooms Planning Agent is an agent that establishes the global planning calendar for all the rooms in the operating theater. It contains all the time slots during which the surgical teams use these rooms over a one-week period. This schedule can be adjusted in the event of an incident.

6.2. Planning constraints

In order to make our objectives achievable, Manager Agent has to respect certain constraints:
-To maximize operating room occupancy, the Manager Agent focuses on: minimizing the waiting time between two procedures performed in the same operating room, reducing the time between the date of consultation and the date of surgery, and minimizing the difference between the number of scheduled surgeries and the operating theater's weekly supply.
-To satisfy the surgical teams, the Manager Agent must meet the following requirements: each surgical team must work one weekend guard shift per month, the team on guard must rest the following day, and if a surgical team is on guard twice a week, it must not be on guard at the weekend.

6.3. Agents' interactions

When Manager Agent receives a reservation request from a Surgeon Agent, it processes it with reference to information supplied by DataBase Agent (Figure 2). Manager Agent then sends a call for proposals to the Room Agent. Each room calculates the virtual cost of each of the time slots likely to meet Manager Agent's request, and sends it to the latter, who analyzes the responses received and decides which one offers the lowest cost and respects the constraints defined in advance. Manager Agent informs Room Agent of its decision and asks the winner to include this reservation, then confirms Surgeon Agent's initial reservation. It then transmits the information to Rooms Planning Agent, enabling this latter to include the reservation in the overall program, which can be modified according to unforeseen circumstances; and which, once completed, will be sent to Room Agent for implementation. Reservation filling iterations end when all incoming scheduling requests have been fulfilled. In the event of an unforeseen incident resulting in a delay or even cancellation of the intervention, DataBase Agent informs Manager Agent so that it can reschedule the interventions (Figure 2).

7. SIMULATION RESULTS

7.1. Scenario: case study

in order to evaluate the performance of our proposed algorithm, we conducted a case study involving the B4 Orthopedic Surgery Department at the CHU Hassan II in Fez, Morocco. This department is comprised of four surgical teams that utilize three distinct operating facilities: the Main Operating Room, the Ambulatory Operating Room, and the Emergency Operating Room.
Each surgical team has the capability to submit a scheduling request via the “Surgeon” AGENT, with the requirement being solely the identification of their respective team.
When the Surgeon agent submits a request, the Manager agent undertakes a process to identify an ideal slot within the Room agent to fulfill this request. The Manager agent’s interface is equipped with a feature that enables records of all exchanges with other agents (Figure 3).

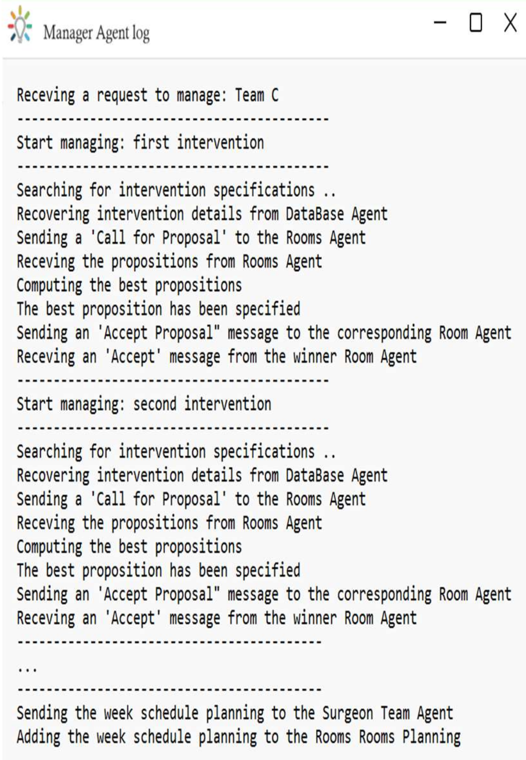

Figure 3: The Log Of The Manager Agent.

The Sniffer agent is designed to monitor a significant portion of interactions, or messages, among the various agents operating on the JADE platform. When a user elects to sniff an agent or a cluster of agents, every message that is either sent to or received from this agent or group is tracked. These tracked messages are then displayed on the Sniffer agent's graphical interface (Figure 4).

7.2. Planning outcomes

Upon the finalization of the schedule, each surgeon is provided with their individual weekly plan. On the day of the procedures, various unforeseen events can occur, such as equipment malfunctions or surgeon unavailability, which may disrupt the surgical operations and necessitate alterations to the schedule. We have accounted for some of these potential disruptions in an effort to maintain the original plan as much as possible, or to make partial changes that do not impact other surgeons' schedules. This process facilitates communication among surgeons, allowing them to declare periods of unavailability. The Multi Agent Planner seeks a substitute for the Surgeon Team available during this period and sends a confirmation message. If the substitute Surgeon Team accepts, the schedule remains unchanged. If the Surgeon Team declines, the MAP attempts to identify the nearest available time slot.

The Surgeon-Agent team is tasked with the creation of the comprehensive weekly agenda, considering various specifics for each procedure such as: the appointment date, duration, nature of the procedure, necessary human and material resources, and any potential constraints (figure 5):

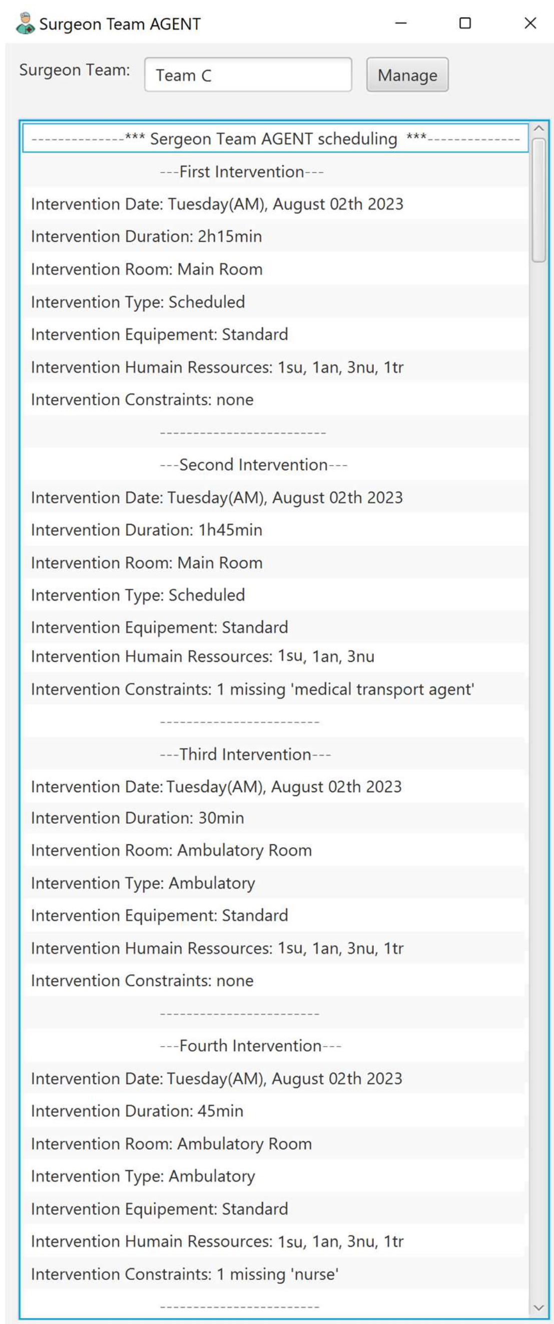

Figure 5: A Practical Illustration Of a Tteam's Daily Scheduling

Please take note of the following abbreviations used in the "Human Resources Intervention" section of the intervention details:
- "su" stands for Surgeon.
- "an" represents Anesthetist.
- "nu" is used for Nurse.
- "tr" denotes Medical Transport Agent.

Following the successful accommodation of all requests from each operating room team, the Rooms Planning AGENT will proceed to integrate the schedules of all operating rooms into the overall plan.
Figure 6 presents the complete weekly schedule for surgical teams operating across all Operating Room units. Cells marked with an “I” denote the identifiers for various procedures allocated to the respective teams (for instance, “I6” corresponds to the sixth procedure). The durations of these interventions are indicated beneath these cells.
It’s evident that the complete schedule adheres to all the stipulations outlined by the Multi Agent Planner, thereby successfully meeting the set goal (Figure 6).

8. DISCUSSION

Traditional planning methods for operating theaters, which use non-real data, often fail to account for the frequent weekly variability influenced by several factors related to medical staff, equipment, operating rooms, and patient care needs. In contrast, the authors [16] examined the characteristics of the Mixed Integer Linear Programming (MILP) procedure for establishing an operating room block schedule. They proposed an alternative approach based on Distributed Artificial Intelligence (DAI) to create an optimal surgical program. Both methods were tested using real data, and the results demonstrated the superiority of the DAI model [20].
The study by [21] centered on a bidding mechanism based on the "Contract Net Protocol" in a multi-agent system for dynamic integrated scheduling of an operating theater. The problem involved an operating theater with multiple surgical rooms that needed to optimally allocate emergency cases that arose during an already in-progress schedule. Agents cooperated and coordinated their actions to find a near-optimal globally effective schedule that maintained the optimization of the initial planning while accounting for disruptions caused by unexpected emergencies in real-time.
Other researchers [22] proposed a new approach using a multi-agent (MA) Decision Making System (DMS) based on a Quadratic Assignment Problem (QAP) and Mixed Integer Linear Programming (MILP) for large Dynamic Operating Theater Layout Problem (DOTLP). The objective was to minimize total travel costs and rearrangement costs by investigating an individual layout for each distinctive time period based on patient demand. The DMS generated efficient solutions in reasonable time and provided the final OT layouts in a graphic interface.
A multi-agent system (MAS) is a distributed system where a group of autonomous entities, known as intelligent agents (whether human or software), pursue their objectives reactively, proactively, and socially [23]. MAS has been proposed as a suitable modeling approach for areas such as electronic commerce [24], multi-robot systems [25], security applications, industrial manufacturing, etc. Multi-Agent Planning (MAP) has emerged as a new methodology that integrates planning capabilities into intelligent agents. As such, a group of agents can develop an action plan that achieves a set of common goals [26]. MAP is used either to produce a distributed schedule or to produce a common schedule for multiple agents [27].
Our research is centered on the development of a weekly, automated, and adaptable schedule for the operating theater. This schedule has certain limitations: it does not cover both the intraoperative and postoperative phases of the operating theater process. However, it focuses on the pre-operative phase, taking into account the potential changes and frequent disruptions that can have an impact on the normal course of surgical procedures. It also considers the utilization of operating theaters and the satisfaction of surgical teams. Our planning approach, which utilizes a Multi-Agent Planning (MAP) based on Distributed Artificial Intelligence (DAI), enhances the efficiency of the operating theater and can potentially improve patient care delivery.

9. CONCLUSION AND FUTURE WORK

Through this research, we suggest the implementation of a Multi-Agent Planning (MAP) system, underpinned by Distributed Artificial Intelligence (DAI). This system enables the development of a robust, weekly surgical schedule in real time, capable of adapting to a variety of potential disruptions. Our proposed approach has been validated through a practical application using real data from the studied surgical department, in collaboration with the operating theater manager. Optimizing surgical planning requires operating theater and hospital managers to consider several performance indicators (both material and human). This is crucial for improving patient care quality and minimizing any weaknesses in the process of the block that have been insufficiently or poorly exploited to date. Our future publications will focus on further developing the operating theater system and enhancing the scheduling of surgical procedures involving both the intraoperative and postoperative phases.

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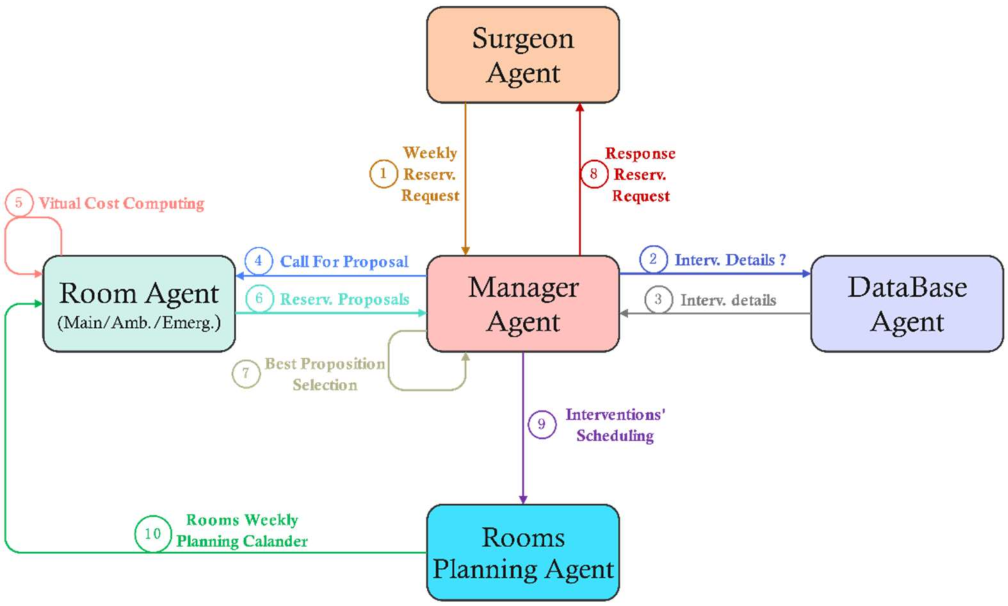

Figure 2: Interactions Between Agents In The MAP.

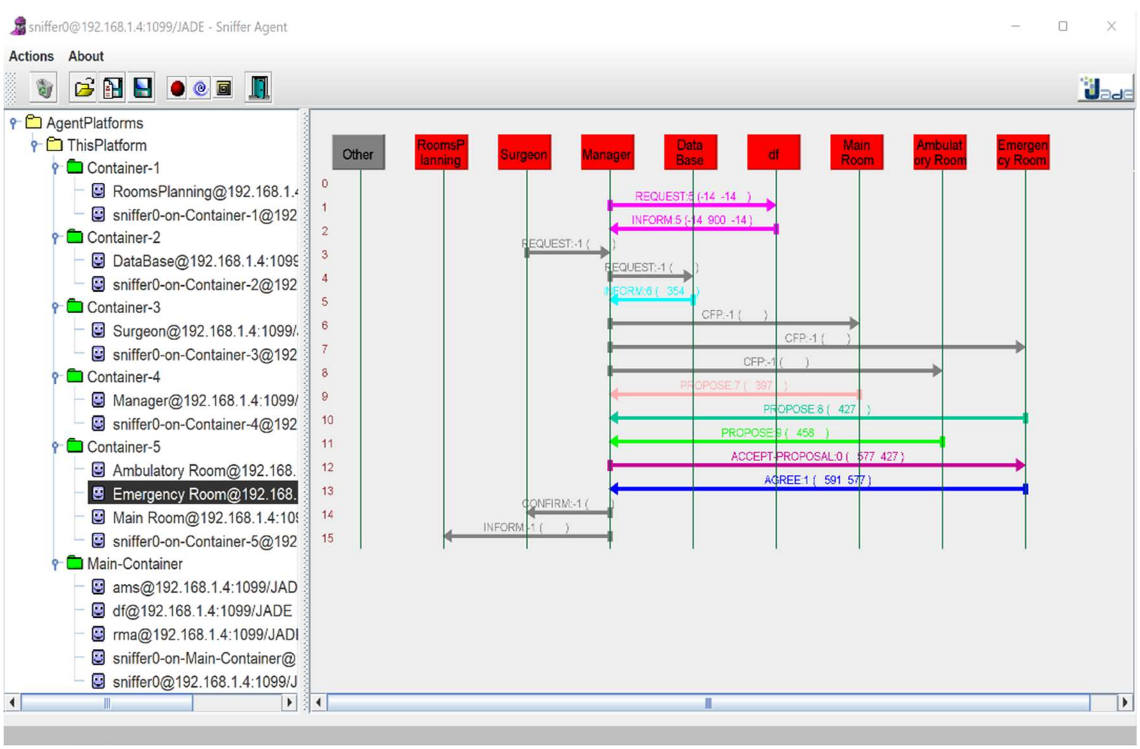

Figure 4: The JADE System's Sniffer Agent.

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MAP Rooms Planning

Room	Inter. details	Monday AM	Monday PM	Tuesday AM	Tuesday PM	Wednesday AM	Wednesday PM	Thursday AM	Thursday PM	Friday AM	Friday PM	Week-End
Main	Team ID	Team C	Team B	Team D	Team C	Team D	Team A	Team A	Team B	Team B	Team C	Not
ROOM	Inter. ID	I5-I6	I1-I2	I10	I13	I22-I19	I17	I25	I23	I29-I30	I28	Available
========	Inter. dur.	2h15'+1h45'	1h+1h05'	3h30'	2h	3h+1h	2h10m	3h45'	2h10'	2h45'+1h10'	1h50'	========
Ambulatory	Team ID	Team B	Team C	Team C	Team D	Team A	Team D	Team B	Team A	Team C	Team B	NoT
ROOM	Inter. ID	I9-I7-I8	I3+I4	I14-I15	I11-I12	I20-I22	I16-I18	I24-I27	I26	I32-I35-I33-I34	I31-I36	Available
========	Inter. dur.	1h15'+1h+1h	30'+45'	2h15'+1h45'	1h+45'	2h10'+2h	45'+50'	2h15'+1h50'	2h	1h+45'+45'+45'	1h+30'	========
Emergency	Team ID	Team A	Team A	Team B	Team B	Team C	Team C	Team D	Team D	Team A	Team A	Team B
ROOM	Inter. ID	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.	Urg. Interv.
========	Inter. dur.	variable	variable	variable	variable	variable	variable	variable	variable	variable	variable	variable

Figure 6: Overall Weekly Operating Schedule.