A Multi-Agent System to Schedule Organ Transplant Operations

Antonio Moreno, Aïda Valls, Jaime Bocio

Computer Science and Mathematics Department
University Rovira i Virgili
Carretera de Salou, s/n
Tarragona, 43006
{amoreno,avalls}@etse.urv.es

Abstract

Transplants involve many steps and many people to ensure a good result. We will focus on the management of the team that is going to make the surgical operation to implant an organ to a patient. When a suitable recipient is found, the hospital that is going to perform the transplant must organise all the necessary items to do it: find the medical team and an available operation theatre. This task must be done in the very short period of time while the organ is in good conditions. The quick scheduling of the operation is essential to detect whether it is possible to join all the necessary items or not. In the second case, the general transplant co-ordinator must be immediately informed in order to find another patient in another hospital. We propose to use a multi-agent system to solve this scheduling task in a short period of time.

Key words: Multi-Agent Systems, Transplants, Scheduling, Time constraints.

1. Introduction

Co-ordinating all the processes involved in an organ transplant operation is a very challenging problem. Unlike other human components such as blood or tissues, that may be frozen and kept for days or weeks, there is a very short period of time (just some hours) in which an organ may be used for a transplant. Therefore, we work under important time constraints.

When an organ is available at a certain hospital, at least three issues must be sorted out:

- The most appropriate recipient must be found.
  This problem is quite difficult, since there may be many patients, distributed around the country, waiting for a certain type of organ. It is important to take into account factors such as the distance to the organ's donor (which determines the temporal and economic cost of the transport of the organ), the urgency with which the potential recipient requires the organ, and the adequacy of the available organ with the characteristics of the patients waiting for it.

- The organ must be sent to the hospital of the chosen recipient.
  Once the recipient has been chosen, the organ must be sent to his/her hospital as soon as possible. Finding a good solution to this problem may involve looking up several (spatially distributed) databases with timetables of means of transport, such as trains or planes, and making spatial and temporal reasoning to provide the most efficient route.

- All the necessary elements for performing the operation must be ready when the organ arrives.
  While the organ is being transported to the recipient's hospital, everything must be set up there so that the operation may be performed as

soon as the organ arrives. This is the problem considered in this article.

In the rest of the article the reader should always bear in mind that the following simplifying assumptions have been considered:

- The first two issues (finding a recipient and an optimal way of transporting the organ) have already been sorted out. Thus, it is known which is the type of the organ and its arrival time to the recipient's hospital.
- There may be several operating theatres in the hospital. All of them are assumed to be identical, thus any of them may be used for any kind of transplant operation.
- Each kind of transplant operation requires a certain amount of doctors, nurses and anaesthetists (we have not considered other kinds of medical personnel). The chosen doctors must be specialists in the particular type of organ; nurses and anaesthetists do not have any speciality, and may participate in all transplant operations. Each of these people has access to a personal computer.

The aim of the system is to check if it is possible to have an operation theatre and a surgical team ready before the organ expiration time. The medical team required depends on the type of organ. When an operation can not be done, the system must inform the transplant co-ordinator, who will choose another patient from the waiting list. In this case, the processes of selection and planning of the transport of the organ have to be redone. For this reason, it is crucial to know the availability of the hospital equipment as soon as possible.

Once an operation has been successfully scheduled, it is possible that other parts of the transplant co-ordination process fail (e.g. no way of carrying the organ on time is found, the recipient is not able to go to the hospital). In that case, our system provides the mechanisms to cancel the transplant operation, and notify the personnel about it.

The paper[1] is organised as follows. First of all, it is argued why Multi-Agent Systems (MAS) offer an appropriate framework for attacking this problem. Then, we describe the particular MAS that we have designed and implemented, and we explain in detail the co-ordination process that it supports. We also show how scheduled operations may be later cancelled. The paper finishes with a brief discussion and an outline of some future lines of work.

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[1] A preliminary version of the ideas of this paper can be found in [Moreno et al. 01].

2. The Multi-Agent System

Agents are intelligent autonomous programs that are able to communicate with other agents. If they work together to solve a complex task, we talk about a co-operative multi-agent system (MAS).

After analysing the transplant problem introduced in section 1, we have decided to use a MAS because this methodology is specially indicated for distributed problems. In our case, each member of the hospital team (doctor, nurse, anaesthetist or operation theatre's manager) will have access to a computer, in which a personal agent will provide the services related to his/her agenda. Moreover, MASs facilitate the addition and removal of agents without affecting the rest. The system includes other agents in charge of the formation of the required surgical teams. This division of tasks increases the performance of the system because many jobs are running in parallel, achieving a high speed in the execution of the process (seconds), which is very important in the case of organ transplants due to the rapid degradation of organs. In addition, the ability to co-operate (inherent in a MAS) is necessary to form teams that guarantee a right transplant operation.

The architecture of the MAS that has been designed and implemented is shown in Figure 1. In that figure the agents that take care of the different schedules (medical personnel, operating theatres) are represented by tables. The seven large boxes represent the other agents in the system.
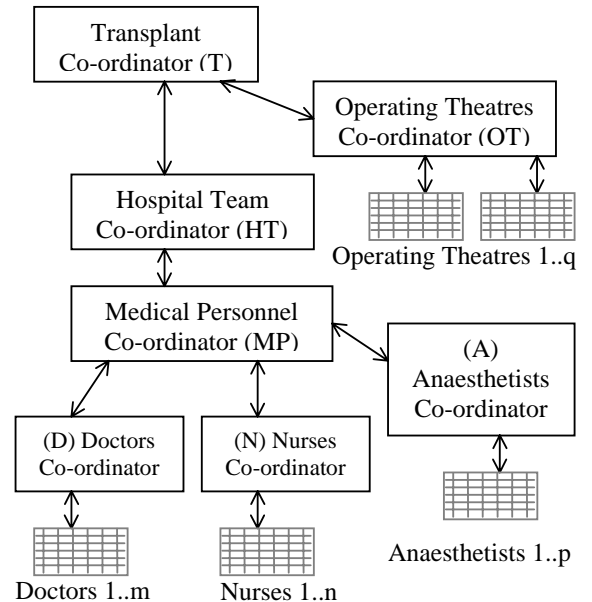

Figure 1. Architecture of the Multi-Agent System

We will now provide a brief description of each of the basic agents of the system. In the next section the co-ordinating process in which they engage will be carefully detailed. The main agents of the system are the following:

- *Transplant co-ordinator* (T)
  This agent presents the interface of the MAS with the environment. When it receives a message with the type of organ and its arrival time, it initiates the co-ordinating process by sending this information to the hospital team co-ordinator (HT). If the process is successfully completed, T will receive from HT a message with the elements selected to perform the operation (initial time, operating theatre, and medical personnel).

- *Hospital team co-ordinator* (HT)
  This is the central agent of the system. It receives from T the basic data necessary for arranging the operation (type of organ and arrival time), and passes it along to the operating theatres co-ordinator (OT) and the medical personnel co-ordinator (MP). When HT receives from these agents the times in which there are free operating theatres and there is enough personnel, it tries to match them to find an appropriate time for the operation. If this matching is successful, OT and MP will receive the confirmation of the selected operating theatre and medical team.

- *Operating theatres co-ordinator* (OT)
  This agent receives from HT the information about the time in which the organ is arriving. It gets in touch with the agents associated to the operating theatres to find out which of them are available in appropriate time intervals. After receiving the different possibilities in which the operation may be performed, it sends them to HT (which tries to match them against the times in which there is enough personnel available). HT will select one of the possibilities, and then OT will inform the selected operating theatre so that it can update its schedule.

- *Medical personnel co-ordinator* (MP)
  This agent receives from HT the information about the type of organ and its arrival time. It sends this information to the agents that co-ordinate the schedules of doctors (D), nurses (N) and anaesthetists (A). It will receive information from those agents about the personnel which may perform the operation, and it will try to form medical teams with the appropriate number of people of each of the three categories. The possible teams that may perform the operation will then be sent to the hospital team co-ordinator.

- *Doctors co-ordinator* (D), *nurses co-ordinator* (N), *anaesthetists co-ordinator* (A)
  Each of these agents is responsible of the communication with the agents that keep the schedule of each person in the hospital. When they receive a request, they collect the data of all available staff members of a certain type, and send this information to the medical personnel co-ordinator.

- *Personal agent*: it manages the schedule of one of the members of the personnel or an operating theatre of the hospital.
  This agent is continuously running on the person's computer, and it has the basic mission of keeping track of the user's schedule. Each day has been divided in 48 slots of 30 minutes. Each of these slots may be in three different states: *free* (the user is not busy at that moment, and could be assigned to an operation, if required), *occupied* (the user has to perform a certain task at that particular time), and *operating* (the user has been assigned an organ transplant operation in that slot). The user may access this schedule at any time, and may modify the days and hours in which he/she is *free* or *occupied*. When an agent notices that his/her associated user has been assigned to a transplant operation, it tells him/her by sending a message or showing an appropriate sign on the computer's screen.
  The MAS also contains agents for maintaining the schedule of each operating theatre. The daily schedule is also divided in 48 slots; each slot may only be *free* (if that operating theatre is available at that time) or *occupied* (if there is an operation scheduled there at that time). These agents are running in the computer of the member of the personnel responsible of co-ordinating the activity of the operating theatres. This person may access the schedules and modify them appropriately, if necessary (see figure 2).

Figure 2. Personal timetable

3. Co-ordinating Process

The agents of the system described in the previous section are involved in a co-ordination process in order to find an operation theatre and a team available at the same time, and for a period long enough to perform the operation.

Let us introduce an example to explain how the co-ordination evolves. We will consider a hospital with 6 doctors, 6 anaesthetists, 6 nurses and 3 operating theatres. Figure 3 shows the initial timetables; the empty slots are *free*, whereas the filled slots denote intervals that are *occupied* or *operating*.

	D1	D2	D3	D4	D5	D6		A1	A2	A3	A4	A5	A6
2:00							2:00						
2:30							2:30						
3:00							3:00						
3:30							3:30						
4:00							4:00						
4:30							4:30						
5:00							5:00						
5:30							5:30						
6:00							6:00						

	N1	N2	N3	N4	N5	N6		O1	O2	O3
2:00							2:00			
2:30							2:30			
3:00							3:00			
3:30							3:30			
4:00							4:00			
4:30							4:30			
5:00							5:00			
5:30							5:30			
6:00							6:00			

Figure 3. Timetables of doctors, anaesthetists, nurses, and operating theatres

The MAS contains 28 agents: the 7 basic co-ordinating agents, 18 agents that control the schedule of each member of the staff, and 3 agents that control the schedule of the operating theatres. Note that the latter 21 agents may be easily running in different computers, while the 7 former agents would probably be running in a single computer (e.g. in the office of the person in charge of organ transplants in the hospital).

When there is an organ available for transplant and it has been assigned to a patient of the hospital, the transplant co-ordinator (T) receives a message with four items: the arrival time of the organ, the final time in which the operation must have been completed, the length of the operation and the type of organ. In the example, this initial message will be (02:00 06:00 01:00 heart). That means that the

system must schedule a heart transplant operation, that this operation will last 1 hour, and that it must be made between 02:00 and 06:00. Thus, the first interval in which the operation may be performed is 02:00-03:00, while the last possible interval is 05:00-06:00. T will send the same message to the hospital team co-ordinator, HT, that will pass it along to the medical personnel co-ordinator (MP) and the operating theatres co-ordinator (OT). In the latter case, as the selected operating theatre does not depend on the type of organ to be transplanted, this information is not sent to OT. MP will send the data to the co-ordinator of doctors (D), nurses (N) and anaesthetists (A). In the two latter cases the type of organ is not needed either (see Figure 4).
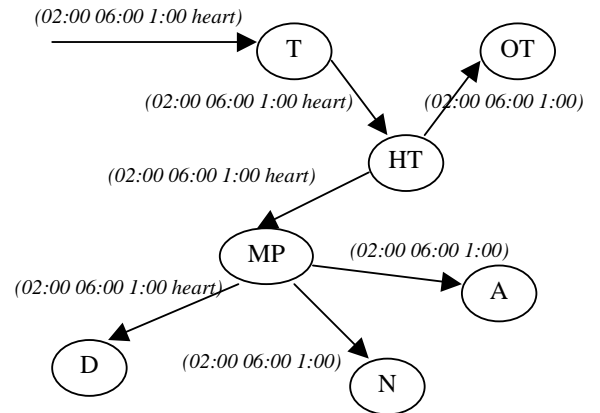

Figure 4. First steps of the co-ordinating process

At this point of the process OT, D, N and A follow the same strategy. Each of them starts a *contract-net protocol* ([Reid et al. 80],[So et al. 98]) in order to find out which operating theatres (doctors / nurses / anaesthetists) could participate in the transplant operation in the required time span. In a contract net protocol, an agent sends a *call for proposals* to a set of agents, asking them whether they are willing to give a certain service. The requested agents may reply with a *propose* (if they want to provide that service, under certain requirements) or with a *refuse* (if they are not interested in making any proposal). The initiator of the protocol evaluates the proposals and may send an *accept-proposal* message to the best offer and *reject-proposal* messages to the rest. In our case, OT will send a *call for proposals* to each of the agents that control the schedule of each operating theatre. Each of them will answer with a *proposal* (specifying the available time intervals) or a *refuse* to make a proposal, if there is not any available free interval of the required length (see figure 5).
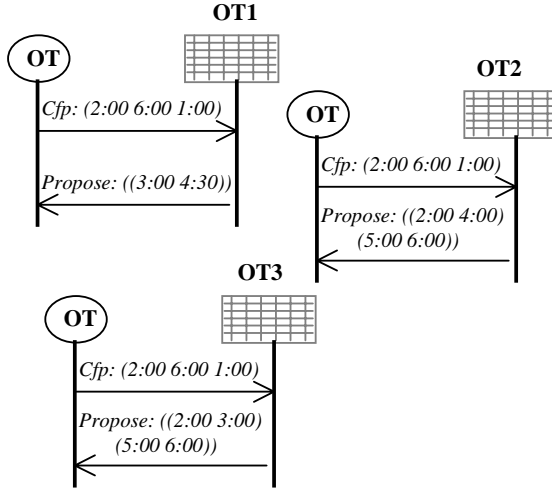
Figure 5. Start of the contract net protocol between OT and the operating theatres

MP knows how many people of each kind of staff is necessary for transplanting each type of organ. In this example it will be assumed that, in the case of heart transplants, it is necessary to have 2 doctors, 3 anaesthetists and 2 nurses. Therefore, MP finds out in which intervals (if any) is possible to join 7 people with the required characteristics. The hospital team co-ordinator receives from MP the intervals in which it is possible to join the medical team, and from OT the intervals in which there is an available operating theatre (see Figure 7).

Figure 7. HT receives time intervals from MP and OT

Following the same strategy, D, N and A receive the availability of each person in the required time interval (i.e. free continuous spaces of at least 1 hour between 02:00 and 06:00). In the example it is assumed that the 6 doctors are heart specialists. Having received all this data, D, N and A send it to the medical personnel co-ordinator (MP). This is shown in Figure 6.
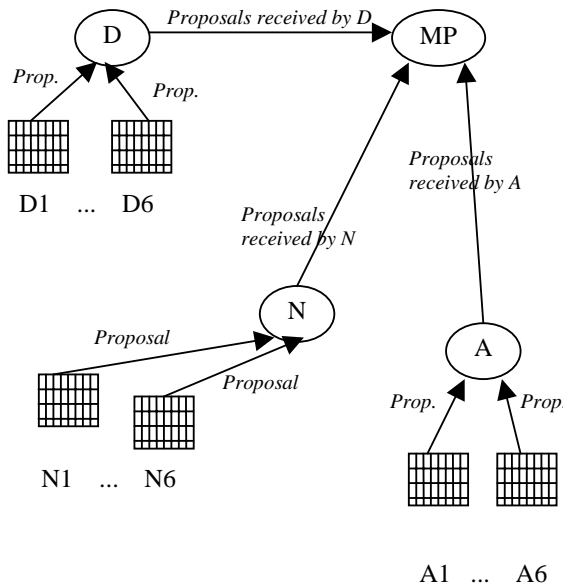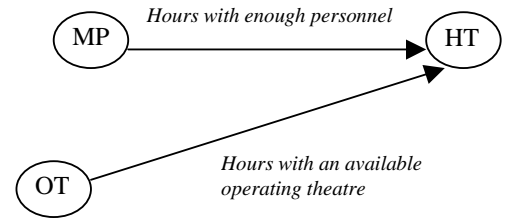
In the example followed in this section, the 1-hour intervals between 02:00 and 06:00 in which there are available operating theatres are ((02:00 03:00) (02:30 03:30) (03:00 04:00) (03:30 04:30) (05:00 06:00)). For instance, it is not possible to perform the operation from 04:00 to 05:00. The 1-hour intervals in which it is possible to join 2 heart doctors, 3 anaesthetists and 2 nurses (which have been computed by MP from the information received from D, A and N) are ((03:30 04:30) (04:00 05:00) (05:00 06:00)). For instance, in the period 03:30-04:30 the operation could be carried by doctors 1 and 5, anaesthetists 2, 4 and 5, and nurses 1 and 4.

HT, after analysing these lists, notices that there are two possible intervals in which there is both an available medical team and a free operating theatre: (03:30 04:30) and (05:00 06:00). In order to decide which is the best possibility, the system follows this criterion: it is interesting that the time intervals in which operating theatres (or staff members) are available are as long as possible, since that will leave the possibility of assigning more operations in the future. To achieve that goal, HT sends the possible intervals to the operating theatres co-ordinator, OT, which forwards them to the agents that control the schedule of each operating theatre. Each of these agents replies to OT with a *score* for each possibility. This score reflects how well the interval "fits" in the empty spaces in the operating
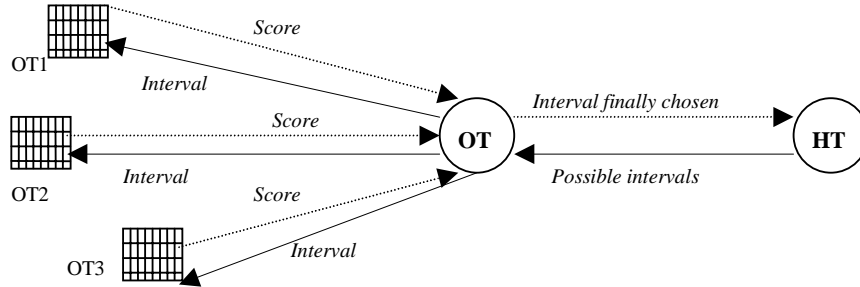

Figure 6. MP receives the data of the available doctors, nurses and anaesthetists

Figure 8. Selection of the best-fitting time interval

theatre's schedule, and it is computed as follows. If the operating theatre is not free in the given interval, the score is 0. If the given interval fits perfectly in a free space in the operating theatre's schedule (i.e. there are not free slots just before and after the interval), the score is 3, because no unusable intervals are generated. If there are empty slots right before and after the interval, the score is 1. If there is an empty slot in one side of the interval but the other side is not free, the score is 2. In the example, the scores obtained by the interval 03:30-04:30 are 2, 0 and 0, whereas the scores obtained by the interval 05:00-06:00 are 0, 3 and 3. Therefore, OT would notice that the best option is to perform the operation from 05:00 to 06:00 in any of the two available operating theatres (2 and 3). All this process is shown in Figure 8.

Assume that operating theatre 3 is selected. Then, OT would complete the previous contract-net protocol by sending an *accept-proposal* to operating theatre 3 and a *reject-proposal* to the other two operating theatres (figure 9). Then, the agent in charge of the schedule of operating theatre 3 would update it by marking the interval 05:00-06:00 as *occupied*, and would inform OT of this updating. Then, OT can send the selected operating theatre and time interval to the hospital team co-ordinator.
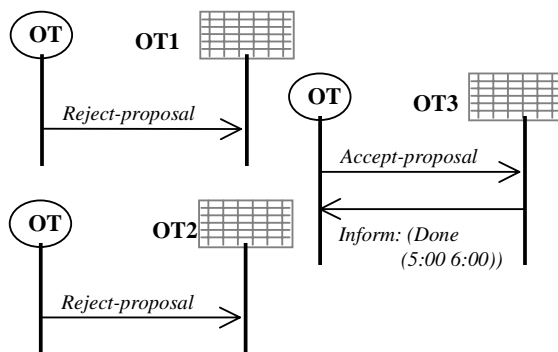
HT sends the interval of the operation to MP, who passes it to D, A, and N (along with the number of each type of staff members that have to be selected to perform the operation). Thus, in the example it would tell D, A and N that the operation is going to take place from 05:00-06:00, and that 2 doctors, 3 anaesthetists and 2 nurses must be selected in that interval. Each of these three agents follows the same "scoring" procedure in order to make this selection: it will choose those staff members whose empty slots match better with the selected interval. In the example, the best scores are obtained by doctors 4 and 6 (3 points), anaesthetists 1 (3 points), 2 and 6 (2 points) and nurses 2 and 3 (2 points). Therefore, the schedule of these 7 people would be updated to reflect that they have been assigned to the transplant operation, and they would be told of this assignment by their personal agents. Then, D, A, and N will tell MP which people have been chosen, and MP will send this information to HT. Finally, HT will be able to send a message to T with the complete information: interval in which the operation is going to take place, operating theatre and medical personnel assigned to the operation (see Figure 10).
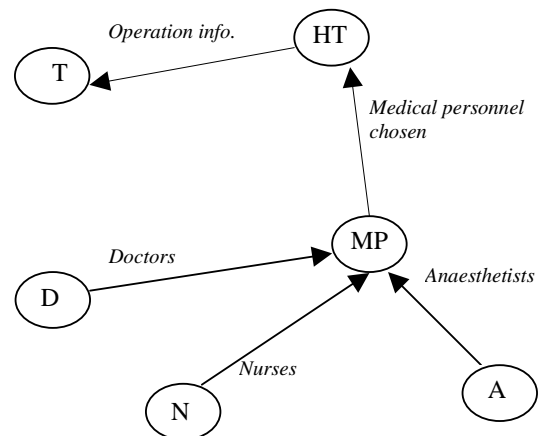

Figure 9.Updating the operating theatre schedule

Figure 10. Final messages in the co-ordination process

The information provided by the system is shown in figure 11. At the top of the window we have the answer given by the system in the previous request. At the bottom, we can see the result if we repeat the same request. In the second case, the operation will be performed between 3:30 and 4:30, in operating theatre 1, by doctors 1 and 5, anaesthetists 2, 4 and 5, and nurses 1 and 4.
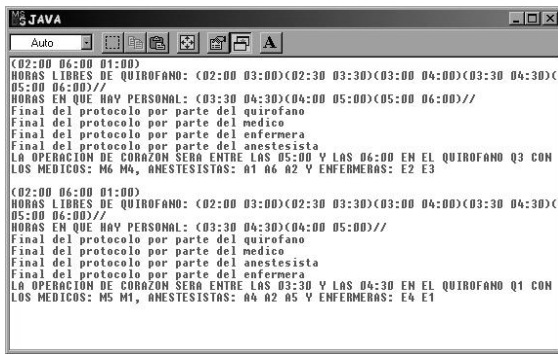

Figure 11. Scheduling two heart transplants

After booking these two transplants, the timetables of the medical staff are the ones shown in figure 12. The two transplant operations are represented by numbers 1 and 2.

	D1	D2	D3	D4	D5	D6		A1	A2	A3	A4	A5	A6
2:00							2:00						
2:30							2:30						
3:00							3:00						
3:30	2				2		3:30		2		2	2	
4:00	2				2		4:00		2		2	2	
4:30							4:30						
5:00			1		1		5:00	1	1				1
5:30			1		1		5:30	1	1				1
6:00							6:00						

	N1	N2	N3	N4	N5	N6		O1	O2	O3
2:00							2:00			
2:30							2:30			
3:00							3:00			
3:30	2			2			3:30	2		
4:00	2			2			4:00	2		
4:30							4:30			
5:00		1	1				5:00			1
5:30		1	1				5:30			1
6:00							6:00			

Figure 12. Timetables of doctors, anaesthetists, nurses, and operating theatres after booking two heart transplants

In the case in which it is not possible to set up the transplant operation with the given time requirements, MT will warn T of this failure and will explain its cause (lack of operating theatres, lack of medical personnel, impossibility of joining the medical team, or impossibility of matching the medical team with the available operating theatres).

4. Cancellation of transplant operations

Due to external factors, a transplant operation may be cancelled. As the global co-ordination tasks are performed in parallel different problems may arise. For instance, the patient is not in the city, so he/she cannot arrive on time to the hospital; the patient is ill, thus a transplant operation is not recommended; the organ has been damaged during its manipulation (extraction, transport), etc.

In those cases, the personnel and operation theatre must be informed in order to allow them to be assigned to other tasks (urgencies, other transplants, ...).

Our system records the identification of each member of a surgical team that has been assigned to a transplant, as well as the operation theatre and the scheduled time when the operation is going to take place. Once the system (in particular, agent T) has been informed about the cancellation of a transplant operation, the hospital team co-ordinator (HT) automatically sends a message to the co-ordinators of doctors, nurses and anaesthetists with the time and place of the transplant cancelled. These co-ordinators look for the people (doctors, nurses, anaesthetists, respectively) that must be notified about the change, and send a message to the agents that control their schedules. In addition, HT sends a message to the operating theatres co-ordinator (OT) informing in which place and time an operation is not going to be done.

Consider again the previous example (figure 12). Let us suppose that at 1:00 we are told that the transplant scheduled between 3:30 and 4:30 (number 2) has to bee cancelled. As we know, this operation was going to be performed by doctors 1 and 5, anaesthetists 2, 4 and 5, and nurses 1 and 4. The information that identifies an operation is its interval of time and the operation theatre where it is performed. Thus, this is the information that T knows and passes to the other agents. However, D, A, N and OT will only send cancellation messages to the agents involved in the operation. In figure 13 there is a diagram with the messages sent.
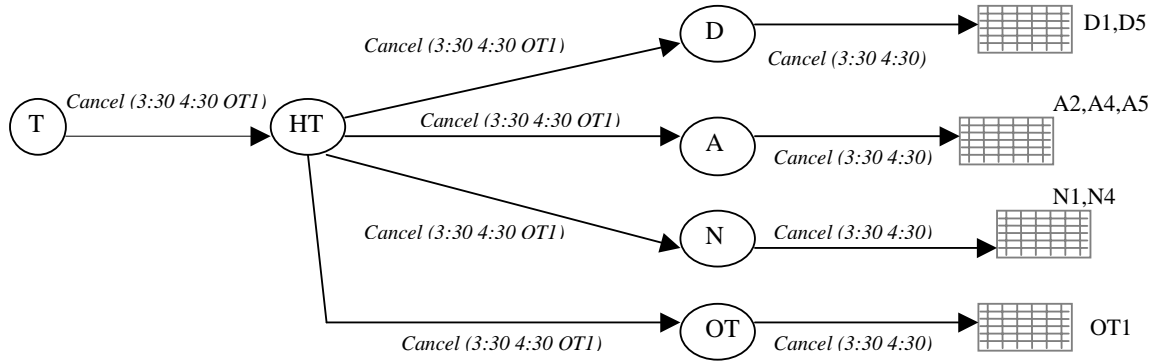
Figure 13. Cancellation messages

5. Discussion and future work

The Multi-Agent System described in this paper has been implemented in Jade ([Bellifemine et al. 01], [Bellifemine et al. 99]). Jade (Java Agent Development Framework) is a software framework that simplifies the implementation of multi-agent systems through a middle-ware that complies with the FIPA specifications. FIPA (Foundation for Intelligent Physical Agents [HP:FIPA]) is a non-profit association that provides internationally agreed specifications for developing agent-based applications. For example, FIPA has defined the FIPA ACL (Agent Communication Language), which is the one used in Jade.

Jade provides a set of tools that support the debugging and deployment phases in the construction of agent-based systems. In figure 14, we can see the graphical interface with the information about the agents that are running in the system.
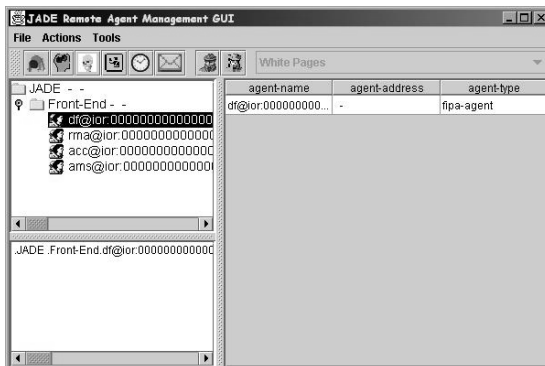
Jade also provides an especial agent, called *sniffer*, which is able to show a graphical representation of the messages flowing in the system (see figure 15). This agent is a very useful tool in the development of multi-agent systems, as it permits to keep tracking of all the information exchanged by the agents.
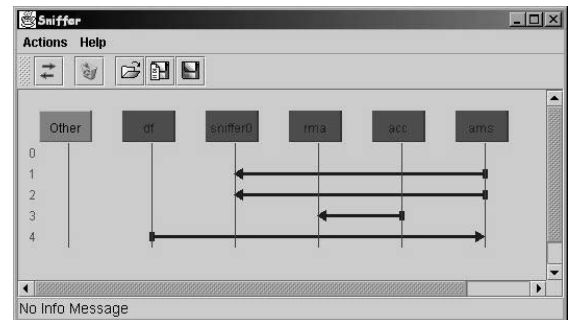

Figure 15. Sniffer agent

We have performed different simulations in which all the agents were running in the same computer. The response time of the system, in the case of trials of the size of the example used in this paper, is less that 10 seconds. This speed allows us to treat all the requests sent to a hospital separately, and not in parallel. In this way we can avoid many problems that should be tackled if several requests were being treated at the same time (e.g. two requests trying to use the same operating theatre at overlapping time intervals). As shown in the previous section, the system is also capable of cancelling previously scheduled operations, and modifying the schedules of the people that were involved in that operation

Figure 14. Jade graphical interface

accordingly. The system could be easily extended to allow more types of organs or medical personnel.

The way of assigning operating theatres and people to the transplant operations, which tries to keep the empty spaces in their schedules as large as possible, does not take into account that the work should be evenly distributed between all the members of the staff. The medical team co-ordinator (MT) should use a different strategy in order to achieve this goal.

It is interesting to notice that the co-ordinating techniques developed in this work could be used in any other domain in which it is necessary to arrange the use of material resources (such as operating theatres) and different types of human resources (such as doctors or nurses) to solve a particular problem under given time constraints.

In the Multi-Agent Systems Group [GruSMA] at Universitat Rovira i Virgili, we are also developing MAS that tackle the issues of finding the most appropriate recipient of an organ and finding the most efficient route to send it to the recipient's hospital. Our main aim in the future will be to join these three MAS to have a full transplant co-ordination system.

Acknowledgements

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