The organ allocation process: a natural extension of the Carrel Agent Mediated Electronic Institution

Javier Vázquez-Salceda [a], Ulises Cortés [a],
Julian Padget [b], Antonio López-Navidad [c],
Francisco Caballero [c],
[a] *Technical University of Catalonia.*
c/Jordi Girona 1 & 3. 08034 Barcelona, Spain.
E-mail: {jvazquez,ia}@lsi.upc.es
[b] *Department of Computer Science. University of Bath. Bath, BA2 7AY. United Kingdom.*
E-mail: jap@cs.bath.ac.uk
[c] *Banc de Teixits.Hospital de la Santa Creu i Sant Pau. c/ St. Antoni M. Claret, 167. E08025 Barcelona, Spain.*

In this paper we extend the formalization of *Carrel*, a virtual organization for the procurement of tissues for transplant, to deal also with organs. We focus on the organ allocation process to show how it can be formalized with the ISLANDER specification language and we also present the first version of a mechanism to federate several geographically-distributed Carrel platforms with the objective of addressing some of the technical issues in the establishment of a pan-European tissue and organ distribution service.

1. Introduction

Organ transplants are among the most complicated medical procedures performed today. Organ transplantation from human donors are becoming common life-saving therapies and the only option available when there is major damage to or a malfunction in an organ. Today, most donated organs and tissues come from patients who are pronounced brain dead as result of disease or injury. At the time of writing, more than one million people in the world have successfully received an organ, and thereafter, in most cases, been able to lead normal lives. But while these operations are becoming more commonplace, there is a major shortage of organs. At the time of writing, ten people die daily due to the shortage of transplantable organs, while a new name is added to the transplant waiting list every 18 minutes.

Organ	Allowable time from Donor to Recipient
Heart	4 to 5 (hours)
Lung	5 to 6 (hours)
Heart-Lung	4 to 6 (hours)
Pancreas	12 to 15 (hours)
Liver	12 to 18 (hours)
Kidney	15 to 18 (hours)

Fig. 1. Cold ischaemia time for solid organ transplantation

Over the years, transplant techniques have evolved, knowledge of donor-recipient compatibility has improved and so have immuno-suppressant drug regimes, leading not only to an increase in the different kinds of organs that can be transplanted, but also in the range of transplants, moving beyond organs (heart, liver, lungs, kidney, pancreas) to tissues (bones, skin, corneas, tendons). The allocation process for tissues is quite different from that for organs, because of the time organs can be preserved outside the human body (see table 1).

Tissues are clusters of relatively homogeneous cells, so the optimal temperature for preservation of all the cells composing the tissue is almost the same. Thus, tissues can be preserved for several days (from seven days in the case of corneas to years in the case of bones) in tissue banks. For tissues, the allocation process is demand-driven, triggered when there is a recipient with a need for a certain tissue, at which time several tissue banks are searched for a suitable piece.

Organs, on the other hand, are very complex structures with several kinds of cell types each with different optimal preservation temperatures. That fact leads to quite short preservation times (hours), no need for an organ bank, and an allocation process that is supply-driven, triggered when a donor appears, taking the form of a search for a suitable recipient in some number of hospitals.

AI Communications
ISSN 0921-7126, IOS Press.

1.1. *The need of software systems for the organ and tissue management*

As explained in [22], the increasing rate of success of tissue transplants, that is literally a *second chance at life*, is leading to an increase in the number of requests and this volume is starting to overwhelm the human coordinators at hospitals who are responsible for managing the transplant process, and furthermore is leading to tissue loss, because available tissues are not being assigned before they exceed their *shelf life* as a result of the length of time it is taking to process requests.

In the case of organs, successful transplants have also led to an increase in demand for organs for transplantation purposes. However, there is not an increasing volume of donations to match the demand and this is creating lists of transplant candidates or *waiting lists*. Typically, there is one list per kind of organ. Because of the organ shortage, the process of managing and distributing the organs that are available is complex and often surrounded by controversy. Much research has been done to enable the definition and implementation of policies for donor identification (to increase the number of available donors) [10], organ allocation (to find a suitable recipient for each organ) [20,7,16] and in extraction, preservation and implant procedures (to increase the chances of success).

The relative scarcity of donors has led to the creation of international coalitions of transplant organizations. This new, more geographically distributed, environment makes an even stronger case for the application of distributed software systems to solve:

– *the data exchange problem:* exchange of information is a major issue, as each of the actors collects different information and stores it in different formats. The obvious, and easily stated, solution is the definition of standard data interchange formats.
– *the communication problem:* countries typically use different languages and terminologies to tag the same items or facts. Either a standard notation or a standard ontology or even a translation mechanism is needed to avoid misunderstandings.
– *the coordination issues:* in order to manage requests at an international level, there is the need to coordinate geographically distributed surgery teams, and to coordinate piece delivery at an international level.
– *the variety of regulations:* an additional issue is the necessity of accommodating a complex set of, in some cases conflicting, national and international regulations, legislation and protocols governing the exchange of organs [20,7]. These regulations also change over time, making it essential that the software is adaptable.

The first two points can largely be resolved by standard software solutions. For instance, the EU projects `RETRANSPLANT` and `TECN` have largely focused on the creation of a) standard formats for the storage and exchange of information about pieces, donors and recipients among organizations, b) telematic networks, or c) distributed databases . Another project `ESCULAPE` uses conventional software to help in checking tissue histocompatibility.

In the USA the United Network for Organ Sharing (UNOS) is supporting tools like ULAM [19] that are used for the simulation and analysis of national cadaveric kidney and kidney-pancreas allocation policies for transplantation to permit comparison of multiple liver allocation policy proposals so that the policies can be tested prior to implementation.

The third point (coordination) is harder to solve with conventional software. But a sound, if relatively new, approach is the use of *software agents*. An *Agent* is a computer program capable of taking its own decisions with no external control (*autonomy*), based on its perceptions of the environment and the objectives it aims to reach [23]. It not only reacts to the environment (*reactivity*) but also *pro-actively* takes initiatives. The *social ability* of agents allow them to group together (in *agencies*) sharing common objectives and dividing the tasks in order to achieve those objectives. All these useful attributes suggest that multi-agent systems are well-suited for solving coordination issues.

It is the last point (variety of regulations changing over time) which underpins our case for the use of so-called *electronic institutions*, whose purpose is to provide over-arching frameworks for interaction of agents capable of reasoning about the norms governing individuals' actions, in the same way as physical institutions and social norms do in the real world (see §2). Electronic institutions and the norms that govern them are the key to a system that is able to adapt automatically to changes in regulations.

In summary, our proposal addresses all four issues identified above, by the use of multi-agent technology, not only for coordination and regulation but also for serving as a language interface among teams using different terminology, and actively distributing the information to be shared.

1.2. Organization of the paper

In §2 we introduce our point of view of electronic institutions as *social structures* and the use of norms. In §3 we give a description of *Carrel* our electronic organization for the procurement of human organs and tissues for transplantation purposes. Here, we focus on the organ allocation process to show how it can be formalized with the ISLANDER [4] specification language. In §4 we discuss the main characteristics of *Carrel* and finally present some conclusions in §5.

2. Electronic Institutions

Building a Multi-Agent System (MAS) is a complex task, as developers need to find an acceptable balance between the *autonomy* that agents should have in order to act in unforeseen circumstances, and the *control* the designer wants to have over emergent behaviour in order to ensure that the system will achieve its goals. One way to tame the complexity of building a MAS is to create a centralized controller, that is, a specific agent that ensures coordination. *Coordinator agents* are agents which have some kind of control over other agents' goals or, at least on part of the work assigned to an agent, according to the knowledge about the capabilities of each agent that is under the *Coordinator Agent*'s command. However this approach is not good, as this special agent becomes a *bottleneck* in the information flow. An alternative is to distribute not only the work load but also the control among all the agents in the system (*distributed control*). That means to *internalize* control of each agent, which has now to be provided with reasoning and social abilities to make it able to reason about intentions and knowledge of other agents plus the global goals of the society in order to be able to coordinate successfully with others and also to resolve conflicts when they arise. However, as Moses and Tennenholtz state in [13], in those domains where the cost of a conflict is dear, or if conflict resolution is difficult, completely independent behaviour becomes unreasonable. Therefore some kind of structure should be defined in order to ease coordination in a *distributed control* scenario. A good option taken from animal interactions is the definition of *social structures*.

Social structures[1], define a social level where the multi-agent system is seen as a *society* of entities in order to enhance the coordination of agent activities (such as message passing management and the allocation of tasks and resources) by defining structured patterns of behaviour. Social structures reduce the danger of combinatorial explosion in dealing with the problems of agent cognition, cooperation and control, as they impose restrictions to the agents' actions. These restrictions have a positive effect, as they:

- avoid potential conflicts, or ease their resolution
- make easier for a given agent to foresee and model the other agents' behaviour in a closed environment and fit its own behaviour accordingly.

An *Agent-Mediated Electronic Institution* (*e-institution* for short) is kind of *social structure* where the interactions among a group of agents are governed by a set of explicit norms expressed in a language representation that agents can interpret.

The roots of this idea come from the study of human organizations. Most human interactions are governed by conventions or rules of some sort, having their origin in society (emergent) or the laws (codification of emergent rules) that society has developed. Thus we find that all human societies, even the most primitive ones, have some kind of *social* constraints upon their members in order to structure and regulate the relations among their members. Some of these constraints are quite informal (taboos, customs, traditions) while some others are formally defined (written laws, constitutions). In fact, modern human societies have defined collections of expected behavioural patterns that have an effect in specific scenarios (such as a shop, bank, a conversation, a lecture or an exclusive club).

Douglas North[2] refers to this *corpora* of constraints as *institutions*. In his studies [15], North has analyzed the effect of institutions on the behaviour of human organizations (including human societies) and he concludes that institutional constraints ease human interaction (reducing the cost of this interaction by ensuring trust), shaping choices and making outcomes foreseeable. By the creation of these constraints, the organizations and the interactions they require can each grow in complexity while interaction costs remain static or are even reduced. Having established these institutional constraints, every competent participant in the institution may act—and expect others to act—according to a list of rights, duties, and protocols of interaction.

The main reason grounding the creation of institutions is to create *trust* when the parties know very lit-

[1] They are also called *Artificial Social Systems* by Shoham, Moses and Tennenholtz in [13,18]

[2] Douglas North received the Nobel Prize in 1993 for his studies on the role of institutions in the performance of organizations.

tle about others. No institutions are necessary in an environment where parties have complete information about others (*e.g.* a village market where vendors and buyers know each other and interact on a periodical basis). However, in environments with incomplete information (*e.g.* international commerce), cooperative solutions (based on trust) could break down unless institutions are created to provide sufficient information for individuals to create trust and to police deviations.

The same statements and ideas can be brought to the field of agents. An *e-Institution* is the modelling of an institution through the specification of its norms in some suitable formalism(s) that can be followed by agents. One of the hypotheses of the field is that the essence of an institution, through its norms and protocols can be captured in a precise machine processable form (this key idea forms the core of the nascent topic of institutional modelling). The main objective is to create a *safe* environment where agents can trust in other agents, as any violation of a norms may lead to a compensating sanction.

The effect of norms on agents should not be seen as a constraint but a guide which reduces the complexity of the environment, because the option space is pruned, and hence allows the agent to make better use of its (limited) resources.

3. An Institution for the distribution of organs and tissues

The Carrel agent platform models an *organization* that receives a tissue request from one hospital and then tries to allocate the *best* tissue available from all the known tissue banks. Within this organization different entities play different roles that are determined by their goals at any particular moment. Figure 2 depicts all the parties that interact with the Carrel system. There are a) the hospitals that create the tissue requests, b) the tissue banks, and c) the national organ transplantation organizations, that own the agent platform and act as observers (in the figure the organizations in Spain are depicted: the Organización Nacional de Transplantes[3] (ONT) [17] and the Organitzaciò CATalana de Transplantaments[4] (OCATT)). In the proposed system all hospitals, even those running a tissue bank, must make their requests through Carrel in order to ensure a fair distribution of pieces and to ease the tracking of all pieces from extraction to the transplant, as the ONT and OCATT require for organs (that is, no *insider* trading).

[3]National Transplant Organization
[4]Catalan Transplant Organization

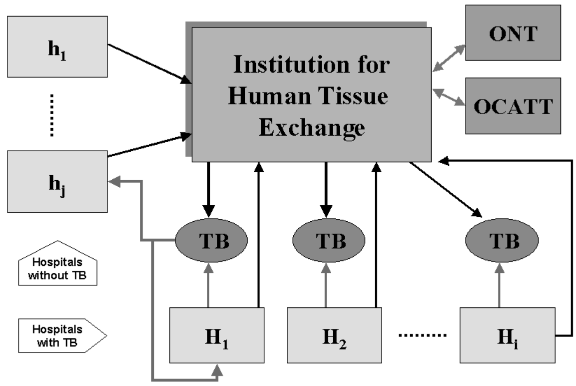

Fig. 2. Carrel: An Agent Mediated Institution for Tissues Assignment

The role of the Carrel institution can be summarized in the following tasks:

- to make sure that all the agents which enter into the institution behave properly (that is, that they follow the behavioural norms).
- to be up to date about all the available pieces in the tissue banks, and all the recipients that are registered in the waiting lists.
- to check that all hospitals and tissue banks fulfil the requirements for interacting with Carrel.
- to ensure that the commitments made within Carrel are fulfilled.
- to coordinate the piece delivery from one facility to another.
- to record all incidents relating to a particular piece.

The participation of hospitals in Carrel is based on the notion of membership. That is, hospitals belong to Carrel and respect the negotiation (assignation) rules, and the agents that represent them inside Carrel are unable to break these conventions. A Hospital interacts with Carrel through the Transplant Coordination Unit Agency (*UCTx*). This agency (depicted in figure 16) serves as interface between the surgeons and Carrel. When a surgeon needs a piece, he makes his request through the UCTx system, which analyzes the information entered, adds information about the recipient and finally creates a *Finder Agent*, which goes to the institution looking for a suitable piece.

The information required by the *Finder Agent* to look for a piece in *Carrel* is entered in an electronic *Sealed Envelope*. The envelope contains the following information:

- *Urgency level*, that works as an electronic postage stamp and sets the urgency level of the request (in Spain: normal, urgency-1 or urgency-0)

– *Hospital identification*, a certificate issued by the Certification Authority associated with Carrel [2], to allow the authentication of the sender of each request to ensure that only *Finder Agents* with requests from authorized hospitals can enter and negotiate.
– *Tissue information* (type, parameters, *etc.*) and *recipient data* (age, sex, laboratory analysis, *etc.*).
– The *selection function* which is composed of a set of rules, each one being a constraint the selected piece (*e.g.* a cornea) must satisfy. Some of these rules will typically come from the policy of the transplant unit of the hospital, while the rest will be introduced by the surgeon, who can set the constraints needed for a given recipient. A rule of the *selection function* can contain:
    ∗ predicates about the piece: predicates that describe the constraints the selected tissue has to satisfy, such as the age of the donor or the dimensions of the piece itself.
    ∗ predicates about the tissue bank: predicates that can set constraints about the tissue bank preferred by the surgeon or the hospital.
    ∗ predicates about the cost of the piece: a predicate that can set a maximum cost for the piece. This cost only covers piece extraction and preservation, and is paid through a clearing house by the hospital which receives the piece. There is no price associated with the piece itself.

3.1. *Extending the Carrel institution*

In order to extend the Carrel system presented in [22] to handle organ as well as tissue distribution, we must augment it for the organ allocation process. In most of the official organ allocation organizations, the process is composed of two phases:

1. Each hospital informs the organization about patients that have been added to or removed from the waiting list of that hospital, or patients either to be added to or removed from the national-wide Maximum Urgency Level[5] Waiting List.
2. When a donor appears, the hospital informs the organization of all the organs suitable for donation in the form of *offers* sent to the organ allocation organization, which then assigns the organs.

[5] In Spain the Maximum Urgency Level is called Urgency-0

This process can be modelled formally by specifying interactions between agents. To give a formal description of the interaction among agents in the Carrel system we will follow the same formalism used for the case of tissues [22]. The ISLANDER formalism [4] views an agent-based electronic institution as a type of *dialogical system* where all the interactions inside the institution are the composition of multiple dialogic activities (message exchanges). These interactions (called *illocutions* [14]) are structured through agent group meetings called *scenes* that follow well-defined protocols.

However, instead of creating a separate model for the organ allocation process, we will extend the model for the tissue allocation process. Some of the scenes that were defined for the case of tissues will be shared for organs by extending their functionalities, and a few new scenes are created. The resulting set of scenes is the following:

– *Reception Room*: the scene where all the external agents identify themselves in order to be assigned the roles they are authorized to play. If these agents are carrying either a request for one or more tissues or an offer of one or more organs, then this information is checked to make sure that it is well-formed.
– *Consultation Room*: the scene where the institution is updated about any event or incident related to a piece. Agents coming from tissue banks update the institution about tissue availability, while agents coming from hospitals update the institution about waiting lists and information on piece (organ or tissue) reception, transplant operations and the health of recipients.
– *Exchange Room*: the scene where the assignation process is made. In fact, there are specific exchange rooms for managing tissue requests (*Tissue Exchange Room*) and for organ offers (*Organ Exchange Room*).
– *Confirmation Room*: the scene where the provisional assignments made in either a *Tissue Exchange Room* or a *Organ Exchange Room* are confirmed or cancelled because of the arrival of another request with higher priority. In case of the confirmed ones, a delivery plan is built.

Another key element of the ISLANDER formalism is the definition of agent *roles*. Each agent can be associated with one or more roles, and these roles define the scenes the agent can enter and the protocols it should follow (the *scene protocols* are defined as multi-role conversational patterns). There are two kinds of roles:

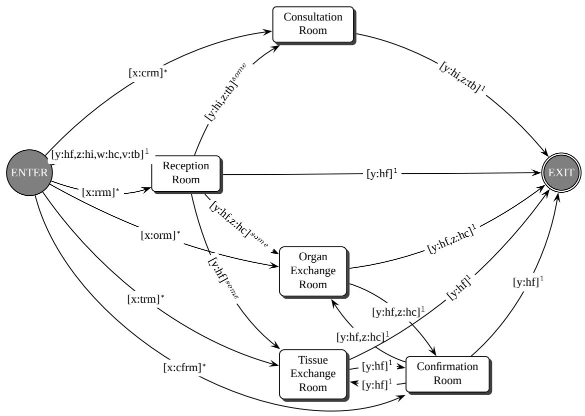

Fig. 3. The Carrel Institution performative structure

the *external roles* (roles for incoming agents) and the *institutional roles* (roles for agents that carry out the management of the institution). The external roles are the following:

***Hospital Finder Agent* (hf):** agents sent by hospitals with tissue requests or organ offers that are seen from the point of view of the institution as requests for finding an acceptable tissue or recipient, respectively.

***Hospital Contact Agent* (hc):** agents from a certain hospital that are contacted by the institution when an organ has appeared for a recipient that is on the waiting list of that hospital. The agent then enters the institution to accept the organ and to receive the delivery plan.

***Hospital Information Agent* (hi):** agents sent by hospitals to keep the Carrel system updated about any event related to a piece or the state of the waiting lists. They can also query the Carrel database.

***Tissue bank notifier* (tb):** agents sent by tissue banks in order to update Carrel about tissue availability.

The institutional roles consist of one agent to manage each scene and one agent to coordinate all the scene relationships. Thus we have: *Institution Manager* (im) which coordinates the scene managers *Reception Room Manager* (rrm), *Tissue Exchange Room Manager* (trm), *Organ Exchange Room Manager* (orm), *Confirmation Room Manager* (cfrm) and *Consultation Room Manager* (crm).

3.2. The performative structure

The connected graph of scenes constitutes the *performative structure*. It is a network of scenes that defines the possible paths for each agent role. In accordance with its role, an agent may or may not be permitted to follow a particular path through the performative structure.

With all the scenes and roles identified in the previ-

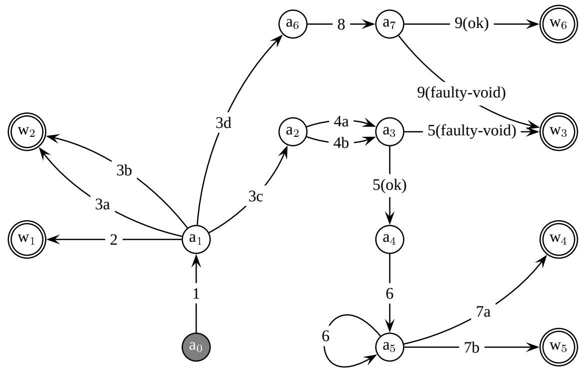

Fig. 4. The conversation graph for the Reception room

Msg♯	Illocution
1	`(request (?x hf|hc|tb) (?y rrm) (admission ?id_agent ?role ?hospital_certificate))`
2	`(deny (!y rrm) (!x hf|hc|tb) (deny ?deny_reason))`
3a	`(accept (!y rrm) (!x hi) (accept_hi))`
3b	`(accept (!y rrm) (!x tb) (accept_tb))`
3c	`(accept (!y rrm) (!x hf) (accept_hf))`
3d	`(accept (!y rrm) (!x hc) (accept_hc))`
4a	`(inform (?x hf) (?y rrm) (petition_tissue ?id_hospital ?urgency_level ?time_to_deliver ?piece_type (?piece_parameters) (?info_recipient)))`
4b	`(inform (?x hf) (?y rrm) (petition_organ ?id_hospital ?time_for_availability ?piece_type (?piece_parameters) (?info_donor)))`
5	`(inform (!y rrm) (!x hf) (petition_state ?id_petition ok|faulty))`
6	`(inform (?y rrm) (?x hf) (init_exchange ?piece_type ?id_exchange_room))`
7a	`(request (?x hf) (?y rrm) (tissue_exchange_entrance_request !id_exchange_room))`
7b	`(request (?x hf) (?y rrm) (organ_exchange_entrance_request !id_exchange_room))`
8	`(inform (?x hc) (?y rrm) (called_for_organ ?id_hospital !id_petition))`
9	`(inform (!y rrm) (!x hf) (called_state !id_petition ok|faulty))`

Fig. 5. The illocutions for the Reception room

ous section, the performative structure can be drawn, as depicted in figure 3. Nodes are the scenes listed above plus *enter* and *exit* nodes in order to define start and end points in the diagram. Arcs are labelled with tags *variable:role*, where variable is an agent$_i$ and role is one among the identified roles for the Carrel system. The diagram in figure 3 shows, for instance, that scene managers go directly from the *enter* node to the scene they should manage (the * means that they are the ones creating the scene), while all the external agents must proceed through the *Reception Room* scene in order to be registered and then be directed to the proper scene according to their roles.

3.2.1. *Authentication of external agents*

As explained above, in the *Reception Room* external agents enter and are registered inside the platform. In this room an authentication mechanism based on electronic certificates ensures that external agents come only from authorized organizations (which previously received the electronic certificate to be used). Once the sender has been identified and authorized, the external agents are then directed to the proper room according to their roles.

The protocol of this scene can be seen in figure 5: An agent$_i$ makes a request for admission (1) that can be accepted (messages 3a, 3b, 3c, 3d) or refused (message 2, exit state w_1). Depending on the role of agent$_i$:

- it is directed to the *Consultation Room* (exit w_2),
- if it brings a request from a hospital, a checking of such request is done (messages 4 and 5). Then agent$_i$ waits until a proper *Exchange Room* is available to do the assignation (messages 6 and 7a for tissues, 6 and 7b for organs).
- if it was called by the institution to receive an organ offer, the information it brings about the recipient is checked and, if all is correct, then is directed to the *Organ Exchange Room* that sent the call.

3.2.2. *Registering the recipients and the available pieces*

In order to manage the assignation of organs and tissues, the Carrel institution should be kept up to date about: a) all the available tissues for transplantation, b) the state of hospitals waiting list for each kind of organ, and c) the whereabouts about all pieces that have been assigned by Carrel.

The *Consultation Room* allows agents coming from hospitals or tissue banks to keep Carrel updated about all the facts mentioned above. The protocol of this scene is shown in figure 7. The incoming agents can

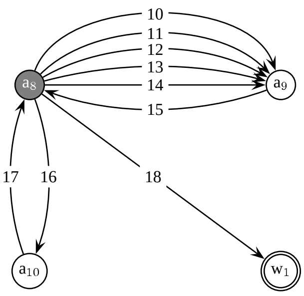

Fig. 6. Conversation graph for the Consultation room

Msg♯	Illocution
10	`(inform (?x hi) (?y crm) (piece_arrival ?id_hospital ?id_tissue_bank ?id_piece (?state)))`
11	`(inform (?x hi) (?y crm) (transplantation_eval ?id_piece ?id_recipient ?date (?info_transplantation)))`
12	`(inform (?x tb) (?y crm) (tissue_bank_update ?id_tissue_bank ?id_piece (?specifications)))`
13	`(inform (?x hi) (?y crm) (waiting_list_update ?id_hospital ?id_piece ?id_recipient ?time_in (?info_recipient) ))`
14	`(inform (?x hi) (?y crm) (maximum_urgency_level_update ?id_hospital ?id_piece ?id_recipient ?urgency_level ?time_in (?info_recipient) ))`
15	`(inform (!y crm) (!x hi|tb) (notification_ack !id_piece ok|error))`
16	`(query-if (?x hi) (?y crm) (?query))`
17	`(inform (!y crm) (!x hi) (query_results (?results)))`
18	`(request (?x hi|tb) (?y im) (end))`

Fig. 7. Illocutions for the Consultation room

perform notifications (messages 10 to 14) and are informed if the notification is successful (message 15). The agents coming from hospitals—which represent the Hospital Transplant Coordinator [3]—can also perform queries (message 16) about historical facts (*e.g.* statistics on, say, successful cornea transplants over a certain period). The queries are answered (message 17) with the level of detail that is permitted for a certain role, as all access to the database is controlled through a *Role-Based Access Model* [9]. When the incoming agents have performed all the queries and notifications, they exit the Carrel system (message 18).

3.2.3. *Allocating organs*

For organ assignment, a new scene, the *Organ Exchange Room* has been added. Numerous factors influence the probability of success in solid organ trans-

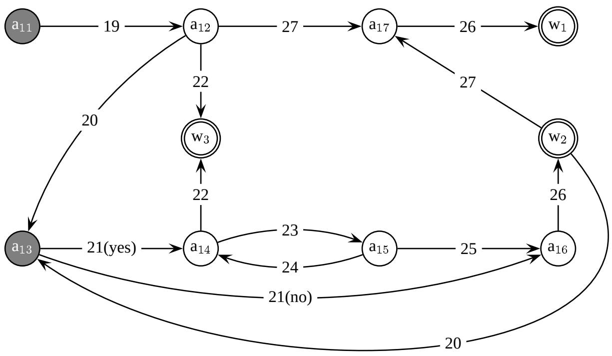

Fig. 8. The conversation graph for the Organ Exchange room

Msg♯	Illocution
19	`(query-if (?x hf) (?y orm) (recipient_for_organ ?id_petition))`
20	`(query-if (?x orm) (?y hc) (call_for_recipient ?id_recipient !id_petition ?time_for_availability ?piece_type (?piece_parameters) (?info_donor)))`
21	`(inform (!y hc) (!x orm) (call_answer !id_petition ?id_hospital))`
22	`(inform (?x orm) (?y hf) (recipient_found !id_petition !id_recipient !id_hospital))`
23	`(query-if (?x hc) (?y orm) (change_recipient (!id_previous_recipient ?id_new_recipient ?change_reason)))`
24	`(inform (!y orm) (!x hc) (accept_change))`
25	`(inform (!y orm) (!x hc) (reject_change reason))`
26	`(request (?x hf|hc) (y im) (exit ?exit_reason))`
27	`(inform (?x orm) (?y hf) (recipient_not_found reason))`

Fig. 9. The illocutions for the Organ Exchange Room

plantation. Both patient and graft survival can be influenced by factors such as race, histocompatibility, immune responsiveness, age, sex, body habitus, primary disease, cause of donor death, and other characteristics of the candidate and donors. It should be possible for each hospital to create a set of rules, see for example the rules in figure 10, for cadaver solid organ transplantation that maximizes the number of additional years of patient life system wide or that maximizes the number of years of transplant function.

The protocol of this scene, depicted in figure 9, can be divided in two parts:

– the arrival of an Agent$_i$ (hospital *Finder Agent*) with an offer of an available organ (states a_{11} and a_{12}), waiting for a notification that a proper recipient has been found (message 22, exit state w_3) or not (message 27 leading to a request for exit through state w_1).
– the loop of the scene manager looking for recipients. Based on the information of the waiting lists stored in Carrel's database, the scene manager sends a call to a hospital (message 20) where there is a suitable recipient. Then an Agent$_j$ (hospital *Contact Agent*) enters the scene to answer the call, saying whether it accepts the organ or not (message 20). Sometimes Agent$_j$, representing the hospital Transplant Coordinator, expresses the intention to use the organ in a different recipient (message 23), a change that, depending on the reasons given, can either be accepted or rejected (messages 24 and 25). If the scene manager and Agent$_j$ agree, then Agent$_i$ is notified of the recipient, otherwise Agent$_j$ exits the scene and the loop starts again with a call to another hospital for another recipient.

The search and assignment processes by the scene manager are driven by knowledge of donor-recipient compatibility that is coded in the form of rules such as those for kidneys shown in Figure 10. Rules 1 to 8 are related to size compatibility, either considering age ranges (rules 1 to 7) or weight differences—here the criterion permits a 20% variation above or below. Rules 5 to 7 consider quality of the kidney [6] and assess not only the limit that is acceptable but also the transplant technique to be used (to transplant one or both kidneys). Rules 9 to 10 are examples of diseases in the donor that do not lead to discarding the organ for transplantation, if a proper recipient is found (in the example, a recipient that has had also the same kind of hepatitis B or C in the past). Finally, rules 11 to 13 are examples of rejection rules [7], as determined by current medical knowledge.

It is important that such policies not be hard-coded in the system, as such rules evolve with practice (for instance, some years ago donors with any kind of hepatitis were discarded). Expressing the knowledge in the form of rules is a technique that allows the system to be adaptable to future changes in medical practice.

Another restriction which must be encoded into the system is the allowable time between retrieving the organ from the donor and transplanting the organ into a recipient (see table 1).

[6] *Glomerulosclerosis* is a negative decay factor in kidney filtering behaviour, while *Creatinine Clearance* is a measure of the amount of serum creatinine the kidney can filter

[7] The rules in figure 10 are ordered and grouped only for display purposes. The order has no precedence meaning (for instance, rule 11 should precede any other).

```
1- (age_donor <= 1)
     -> (age_recipient < 2)

2- (age_donor > 1) AND (age_donor < 4)
     -> (age_recipient < 4)

3- (age_donor >= 4) AND (age_donor < 12)
     -> (age_recipient > 4) AND
        (age_recipient < 60)

4- (age_donor >= 12) AND (age_donor < 60)
     -> (age_recipient >= 12) AND
        (age_recipient < 60)

5- (age_donor >= 60) AND (age_donor < 74) AND
   (creatinine_clearance > 55 ml/min)
     -> (age_recipient >= 60) AND
        (transplant_type SINGLE-KIDNEY)

6- (age_donor >= 60) AND (age_donor < 74) AND
   (glomerulosclerosis <= 15%)
     -> (age_recipient >= 60) AND
        (transplant_type SINGLE-KIDNEY)

7- (age_donor >= 60) AND
   (glomerulosclerosis > 15%) AND
   (glomerulosclerosis <= 30%)
     -> (age_recipient >= 60) AND
        (transplant_type DUAL-KIDNEY)

8- (weight_donor = X)
     -> (weight_recipient > X*0.8) AND
        (weight_recipient < X*1.2)

9- (disease_donor Hepatitis_B)
     -> (disease_recipient Hepatitis_B)

10-(disease_donor Hepatitis_C)
     -> (disease_recipient Hepatitis_C)

11-(disease_donor VIH)
     -> (DISCARD-DONOR)

12-(glomerulosclerosis > 30%)
     -> (DISCARD-KIDNEY)

13- (HLA_compatibility_factors < 3)
     -> (DONOR-RECIPIENT-INCOMPATIBILITY)
```

Fig. 10. Example of some selection rules for kidneys

3.2.4. Allocating tissues

The *Tissue Exchange Room* is the place where negotiation over tissues is performed. The protocol of this scene is shown in figure 12: Agent$_i$ (hospital *Finder Agent*) asks the scene manager for tissue offers (tissues matching the requirements included in their petition). Then the scene manager gives a list of available tissues (message 29) that is evaluated by the external agent$_i$ (message 30). With this information the scene manager can make a provisional assignment and solve collisions (two agents interested in the same tissue). When this provisional assignment is delivered (message 31) then agent$_i$ exits the scene to go to the *Confirmation Room* represented by state w_2. There is an alternative path for the case when there are no available pieces matching the requirements described in the petition (message 9 with null list). In this case agent$_i$ requests an exit permission from the institution (message 32, exit state w_1), including the reason for leaving. The reason provided is recorded in the institution logs to form an audit trail for the relevant authorities to inspect. For further information about this negotiation process see [2].

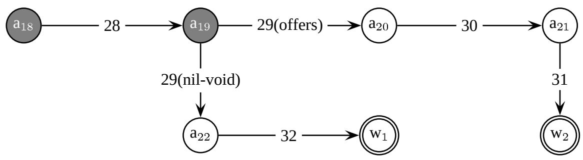

Fig. 11. The conversation graph for the Tissue Exchange room

Msg♯	Illocution
28	`(query-if (?x hf) (?y trm)(offer_list ?id_petition))`
29	`(inform (!y trm) (!x hf) (offer_list !id_petition (list (?id_piece1 ?info_piece1) ... (?id_piecen ?info_piecen))))`
30	`(inform (?x hf) (?y trm) (weighted_list !id_petition (list (!id_piece1 ?weight) ... (!id_piece1 ?weight))))`
31	`(query-if (?y trm) (?x hf) (piece_offer (?id_petition ?id_piece ?cost_estimation)|void))`
32	`(request (?x hf) (y im) (exit ?exit_reason))`

Fig. 12. The illocutions for the Tissue Exchange Room

3.2.5. Confirming the assignation

In the *Confirmation Room* scene, the provisional assignments made in a *Tissue Exchange Room* or an *Organ Exchange Room* are either confirmed or withdrawn. Figure 14 shows the protocol of this scene: the agent$_i$ can analyze the assigned piece data and then accept or refuse it (message 33). If the agent$_i$ accepts the piece and no higher-priority requests appear during a certain time window then the provisional assignment is confirmed and a delivery plan is given to the agent$_i$ (message 34), and then it exits the Carrel system (exit state w_2). When there is a request with higher priority that needs the piece provisionally assigned to agent$_i$ a conflict arises. To resolve the conflict the scene manager notifies the agent$_i$ that the assignment has been withdrawn (message 35) and that he is then entitled to a fresh request for another piece, if available, (message 36) to be negotiated again in the *Exchange Room* whence it came.

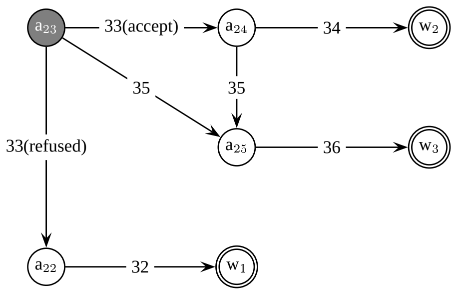

Fig. 13. Conversation graph for the Confirmation room

Msg♯	Illocution
32	`(request (?x hf) (y im) (exit ?exit_reason))`
33	`(inform (?x hf) (?y cfrm) (piece_eval ?id_petition ?id_piece accepted|refused))`
34	`(inform (?y cfrm) (?x hf) (piece_delivery ?id_petition ?id_hospital ?id_tissue_bank ?delivery_plan))`
35	`(inform (?y cfrm) (?x hf) (piece_reassigned_exception ?id_petition ?id_piece ?reassignment_reason))`
36	`(query-if (?x hf) (?y cfrm) (another_offer_list ?id_petition))`

Fig. 14. Illocutions for the Confirmation room

3.2.6. The Multi-agent architecture

The agent architecture that supports the *institutional roles* (see figure 15) shows one agent managing each of the scenes: the **RR Agent** for the *Reception Room*, the **CR Agent** for the *Consultation Room*, an **ER Agent** for each *Exchange Room* (either the ones for organs or the ones for tissues), and a **CfR Agent** for the *Confirmation Room*. Also there is an agent (the **IM Agent**) playing the *institution manager* role.

In order to assist these agents, two agents are added for specific tasks: the **Planner Agent**, to build the delivery plans that are needed in the *Confirmation Room*, and the **DB Agent**, which handles access control to the internal database. For solid organs the **Planner Agent** has to consider the constraints imposed by the conservation of those pieces as described in table 1.

3.3. Extending the UCTx

Adapting the UCTx agency in order to assist not only in the tissue allocation process but also in the organ allocation process is not difficult. In the case of tissues, it is the surgeons who are responsible for creating the tissue requests through their **Surgeon Agent** [3]. In the case of organs, however, it is the *Hospital Transplant Coordinator* who is responsible for issuing organ

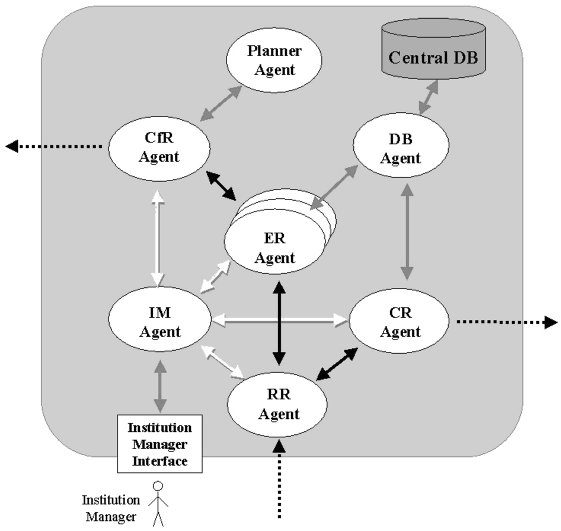

Fig. 15. The multi-agent architecture of a Carrel platform

offers to the institution or answering a call for recipients. So the architecture presented in [3] (depicted in figure 16) is not modified but rather the **Coordinator Agent** functionality is extended.

3.4. A network of Carrel institutions

In the preceding sections the Carrel system has been described as an institution that works alone, managing all the requests and offers coming from the hospitals. However a distributed system is needed in order to manage the allocation problem at an international level, which is one of the aims of our scheme.

To do so, we propose the creation of a federation of geographically-distributed Carrel platforms. Hospitals and tissue banks register themselves with the *nearest* platform and interact as described in previous sections.

As a result, the search process may become distributed through the platforms exchanging information among themselves via their **DB Agents**. The process is the following:

– The **DB Agent** of a certain platform$_i$ receives a query, either from an *Organ Exchange Room*, a *Tissue Exchange Room* or the *Consultation Room*
– It accesses the local database.
– If the information is not available locally, then it sends part of the query to other **DB Agents** in other Carrel platforms.
– All the differences in terminology are solved at this point by the use of domain ontologies shared

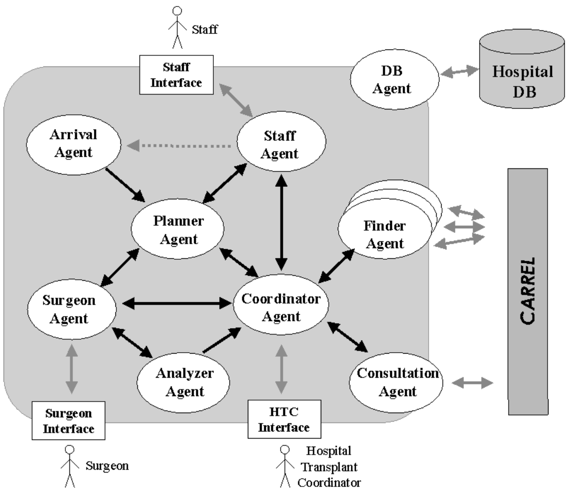

Fig. 16. The multi-agent architecture for the UCTx system

by all the platforms that define a common exchange format for the information.

All *Carrel* platforms are aware of the existence of the other platforms. The communication among agents of different platforms is done through the mechanism the FIPA specification establishes for communication among Agent platforms [5].

4. DISCUSSION

The current systems of organ procurement and allocation works reasonably well, but significant improvements in both its fairness and its effectiveness could be made. We present here an Agent-Mediated Electronic Institution for the distribution of organs and tissues for transplantation purposes. The policy that we are implementing here follows the Spanish model for organ and tissue procurement and Spanish regulations for allocation but we believe that this model is general enough – and very successful– to used as an example.

Our aim with this work is not only to apply multi-agent technologies to model the organ and tissue allocation problem but we also have devoted significant effort to formalization, following the recommendations in [6] about the need for formal design methods when applying agents to the medical domain in order to ensure the *safety* and *soundness* of the resulting system. In our case we have chosen a formalism called ISLANDER [4], based on the dialogical framework idea, to get an accurate description of the interactions among the agents. By means of such formalism we have been able to design a system that combines the strengths of agents with the advantages of formal specification.

As far as we know, there are very few references in the literature to the use of agents in the transplant domain. [21] and [12] describe single agents to solve specific tasks needed for this domain (respectively, a receiver selection algorithm based in multi-criteria decision techniques and a planner of transport routes among hospitals for organ delivery). [11] proposes a multi-agent system architecture to coordinate all the team members involved in a transplant. [1] also proposes a static hierarchical agent architecture for the organ allocation problem, but no formalism is used in the development of the architecture, and no mechanism is presented to make the architecture adaptive to changes in policies or regulations.

5. CONCLUSIONS

Public interest in the utility and fairness of solid organ and tissue transplantation is among the motivations of this work. Transplants protocols as above explained have many characteristics that suggest the appropriateness of a multi-agent solution:

– they are safety critical;
– they involve large amounts of data;
– the data are diverse in source and format;
– complex inferences must be made from combinations of data;
– co-ordinated activity across numerous agencies may be indicated; and finally,
– strong legal and ethical obligations underpin the interactions between agencies as ONT or OCATT.

Carrel is an agent-based solution meant to help policy makers in designing, implementing and verifying organ allocation policies (like for example [8]) so that, say, graft survival rates can be maximized. Finally, we summarize the properties of our proposal, which we believe might help to address concerns about what *fair* distribution might mean:

– Experimentation with allocation policies *before* deployment, for example:
  ∗ Old-for-the-old
  ∗ Children first
  ∗ Allocation based on waiting time

  or combinations of the above and other schemes.
– The *Carrel* system may help to speed up the allocation process of solid organs for transplantation and in this way to improve graft survival rates. Recall the temporal constraints imposed by the conservation of those pieces (see table 1)

– The federation of several platforms of this kind, as described in §3.4, would make it possible to extend the benefits of such a system to a larger geographical area (*e.g.* from country to country) easing the communication among the different Organ Exchange Organizations. This will allow the unification of policies in the European Space.

Future work aims to explore other alternative formalisms to describe multi-agent systems in complex domains. As part of that exploration we aim to expand the PRO*forma* [6] formalism, which is well-suited to model decision support systems for domains with uncertainty, to include agent communication and the definition of multiple roles (in the sense that each role has a different view of the problem to solve).

Acknowledgements

U. Cortés, and J. Vázquez-Salceda would like to acknowledge the IST-2000-28385 Agentcities.NET and the IST-1999-10176 A-TEAM projects. The views in this paper are not necessarily those of Agentcities.NET and A-TEAM consortia.

References

[1] A. Aldea, B. López, A. Moreno, D. Riaño, and A. Valls. A multi-agent system for organ transplant co-ordination. In S. Quaglini, P. Barahona, and S. Andreassen, editors, *Proceedings of the 8th. European Conference on Artificial Intelligence in Medicine, Portugal, 2001*, Lecture Notes in Artificial Intelligence 2101: Artificial Intelligence in Medicine, pages 413–416. Springer-Verlag, 2001.

[2] U. Cortés, A. López-Navidad, J. Vázquez-Salceda, A. Vázquez, D. Busquets, M. Nicolás, S. Lopes, F. Vázquez, and F. Caballero. Carrel: An agent mediated institution for the exchange of human tissues among hospitals for transplantation. In 3^{er} *Congrés Català d'Intel.ligencia Artificial*, pages 15–22. ACIA, 2000.

[3] U. Cortés, J. Vázquez-Salceda, A. López-Navidad, and F. Caballero. UCTx: A multi-agent system to assist a transplant coordinator unit. *Applied Intelligence. Accepted*, 2003.

[4] M. Esteva, J. Padget, and C. Sierra. Formalizing a language for institutions and norms. In John-Jules Meyer and Milinde Tambe, editors, *Intelligent Agents VIII*, volume 2333 of *Lecture Notes in Artificial Intelligence*, pages 348–366. Springer Verlag, 2001. ISBN 3-540-43858-0.

[5] The Foundation for Intelligent Phisical Agents, `http://www.fipa.org/repository/fipa2000.html`. *FIPA Specifications*, 2000.

[6] J. Fox and S. Das. *Safe and Sound*. MIT Press, 1^{st} edition, 1999.

[7] U.S. Government. 42 cfr part 121, organ procurement and transplantation network; final rule. 63 Federal Register 16295, at 16332, April 1998.

[8] M. Hild. Fair kidney allocation based on waiting time. Social Science Working Paper 1117, California Institute of Technology, 2001.

[9] A. Lin. Integrating policy-driven role-based access control with common data secutiry architecture. Technical Report HPL-1999-59, HP Laboratories Bristol, 1999.

[10] Antonio López-Navidad. Professional characteristics of the transplant coordinator. *Transplantation Proceedings*, (23):1607–1613, 1997.

[11] A. Moreno, A. Valls, and J. Bocio. Management of hospital teams for organ transplants using multi-agent systems. In S. Quaglini, P. Barahona, and S. Andreassen, editors, *Proceedings of the 8th. European Conference on Artificial Intelligence in Medicine, Portugal, 2001*, Lecture Notes in Artificial Intelligence 2101, pages 374–383. Springer-Verlag, 2001.

[12] A. Moreno, A. Valls, and A. Ribes. Finding efficient organ transport routes using multi-agent systems. In *IEEE 3rd International Workshop on Enterprise Networking and Computing in Health Care Industry (Healthcom)*, L'Aquilla, Italy, 2001.

[13] Y. Moses and M. Tennenholtz. Artificial social systems. *Computers and AI*, 14(6):533–562, 1995.

[14] P. Noriega. *Agent-Mediated Auctions: The Fishmarket Metaphor*. Number 8 in IIIA Monograph Series. Institut d'Investigació en Intel.ligència Artificial (IIIA), Bellaterra, Spain, 1997. PhD Thesis.

[15] D.C. North. *Institutions, Instutional Change and Econonomic Performance*. Cambridge Univ. Press, Cambridge, 1^{st} edition, 1990.

[16] Commitee on Organ Procurement and Transplantation Policy, editors. *Organ Procurement and Transplantation: Assessing Current Policies and the Potential Impact of the DHHS Final Rule*. National Academy Press, Washington, USA, 1999.

[17] Organización Nacional de Transplantes. `http://www.msc.es/ont`.

[18] Yoav Shoham and Moshe Tennenholtz. On social laws for artificial agent societies: Off-line design. *Artificial Intelligence*, 73(1-2):231–252, 1995.

[19] S.E. Taranto, A.M. Harper, E.B. Edwards, and J.D. Rosendale. Developing a national allocation model for cadaveric kidneys. In J. A. Joines, R.R. Barton, K. Kang, and P. A. Fishwick, editors, *Proc. of the 2000 Winter Simulation Conference*, pages 1955–1962, 2000.

[20] UNOS. Unos statement of principles and objectives of equitable organ allocation. *Seminars in Anesthesia*, 14:142–166, March 2000.

[21] A. Valls, A. Moreno, and D. Sánchez. A multi-criteria decision aid agent applied to the selection of the best receiver in a transplant. In J. Braz, M. Piattini, and J. Filipe, editors, 4^{th} *International Conference on Enterprise Information Systems (ICEIS-2002)*, Ciudad Real, Spain, 2002. ICEIS Press.

[22] J. Vázquez-Salceda, U. Cortés, and J. Padget. Formalizing an electronic institution for the distribution of human tissues. In *Artificial Intelligence in Medicine*, volume 27, pages 233–258. Elsevier, March 2003.

[23] M. Wooldrige and N.R. Jennings. Intelligent agents: Theory and practice. *The Knowledge Engineering Review*, 10(2):115–152, 1995.