Multi-Agent Decision-Making Support Model for the Management of Pre-Hospital Emergency Services

Adil Chennaoui and Marc Paquet

***Abstract*—This article focuses on the theme of modeling and that of decision-making support in complex systems. We are interested more precisely in multi-agent decision-making support models. This work, carried out in collaboration with "Urgences-santé de Québec", is applied to the design of a decision-making support system dedicated to the management of pre-hospital emergency services. For this system we propose a model based on reactive agents and a generic architecture.**

***Index Terms*—Decision-making support, multi-agent system, planning, pre-hospital emergency services, simulation.**

I. Introduction

The complexity of artificial systems and the critical importance of a better understanding of the complexity of natural systems impose to develop new approaches of problems modeling and their resolution [1]. In this article, we are interested in designing decision-making support systems of pre-hospital emergency services. In order to construct and analyze multi-agent models, we have appealed for the knowledge of the expert.

The modeling based on agents is one of the most popular modeling techniques due to the richness of the agent paradigm. It allows to easily represent qualitative and quantitative processes and to interact heterogeneous entities with various architectures. However, the primary motivation of its use is related to the goal of modeling: Understanding the relationship between individual behavior and collective behavior [2].

This work is mainly carried out in an application setting related to the problem of management of pre-hospital services in the "Urgences-Santé de Québec" Corporation (U.S.). This corporation is responsible for providing pre-hospital emergency services to the Montreal and Laval with a population over 2.4 million inhabitants in an area of 500 km^2. The corporation employs paramedics working continuously round the clock, 7 days a week to cover a vast area whose vehicles have only three deposits [3].

An overview of the literature shows that a series of articles deal with the topic of the emergency services management. In summary, each article deals with a very specific problem in this area, either is the production and scheduling of paramedics [4]-[6] or the demand management in pre-hospital services, or vehicles / ambulances management [7]-[14]. To the best of our knowledge, no article deals with the issue of pre-hospital emergency services management in all these aspects with a comprehensive and integrated resolving approach.

The model that we propose in this article presents a new and a more effective approach of management and optimization of the pre-hospital emergency services integrating its various components. This approach integrates the scheduling planning, replacements management, vehicles fleet management, the deposits capacity management, the covering of the demand and the management of special events.

The solution we propose is composed of two main parts. The first part is a reactive multi-agent model integrating several algorithmic components. The second part corresponds to a decision-making support architecture that facilitates to the user the intervention in the resolution process and the visualization of results.

Our model was tested in "Urgences-santé de Québec" and we will be presenting the results of tests done on real data.

II. Emergency Pre-Hospital Services

In addition to be a part of the continuous service category, pre-hospital emergency services require a high and consistent quality. From this perspective, both efficiency and responsiveness remain two crucial points of work done. Thus and in order to be able to answer all calls received from paramedics in a limited time (less than 9 minutes for calls of Priority 1 in U.S.), we must have in station all the necessary and sufficient resources (paramedics , vehicles, etc.) 24/7.

These resources are determined by estimating the service request and may change any moment during the day. In light of these facts, it makes complete sense to seek a high quality of an integrated services management that reaches the best concordance between the offer of pre-hospital services and their real demand.

A. Standards of Service

It is essential to give a brief overview of key factors influencing the management of pre-hospital services which is the demand for services. This will help understanding the importance of an accurate evaluation of the demand in term of paramedic care needs. This work is limited to explaining the service standards used in U.S.

An example of objectives of performance pursued by paramedics is presented in Table I:

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TABLE I: EXAMPLE OF PERFORMANCE STANDARDS

TERRITORY	MINIMAL OBJECTIVE	TARGETED OBJECTIVE
URBAN	80% OF URGENT CALLS IN LESS THAN 8 MIN	90% OF URGENT CALLS IN LESS THAN 8 MIN
SUBURBAN	80% OF URGENT CALLS IN LESS THAN 15 MIN	90% OF URGENT CALLS IN LESS THAN 15 MIN
RURAL	80% OF URGENT CALLS IN LESS THAN 30 MIN	90% OF URGENT CALLS IN LESS THAN 30 MIN

U.S. establishes a code of rules and priorities for the allocation of calls. The priority level of a call depends on the severity of the condition of those to be rescued. At each priority level correspond a maximum delay of arrival, available staff and transport standards.

The following chart shows the relationship between the number of vehicles available in the area and the average response time [15], [16]:

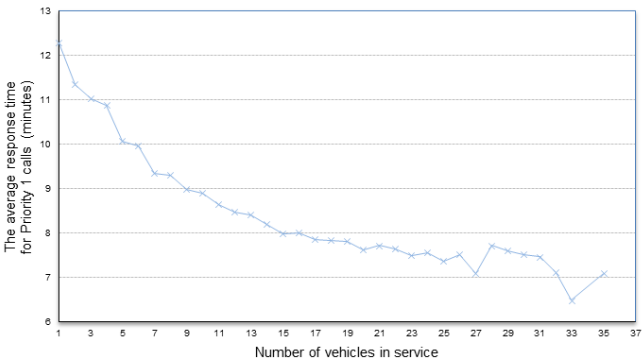

Fig. 1. The relationship between the response time and the number of vehicles in service for Priority 1 calls (2011).

According to Fig. 1, we can see that the average response time decreases exponentially with the increasing of the available number of vehicles. This is a significant constraint which directly influences the estimation of the demand.

B. Logistic

To cover a large territory, vehicles (ambulances represent 70%) have only three deposits. Managing the fleet of vehicles and the capacity of the host operating centers remain the major logistic constraints. For instance, we would like to cite:

- The maximum number of vehicles (ambulances) may be operating in the same time.
- The capacity of physical locations: It is necessary to limit the number of simultaneous departures of a same operational center to about 8 vehicles.
- The delay maintenance of a vehicle between two quarter services.
- The maximum number of vehicles able to start their shift at the same time: This number is limited in order to avoid problems of traffic in operational centers caused by the carrying capacity of the operational centers.

C. Ambulance-Technicians

Over 850 paramedics are employed by U.S [8]. Some of them work full time, others work part-time. Some have regular jobs with strict working conditions, others do not. The paramedics are not all of the same skill levels. Work rules are governed by a relatively strict and complex collective agreement, but also by several work habits deeply rooted in the culture of the company and therefore difficult to change [17].

D. Other Constraints

In addition to the rules related to the service request, to paramedics and logistical constraints, the emergency services are influenced by a multitude of factors, such as:

- Road traffic
- Climatic conditions,
- Festivities, etc…

In conclusion, this introduction helps becoming acquainted with environment and issues related to pre-hospital services management. This complex problematic involves estimating demand of service, the management of ambulance men and vehicles' fleet, as well as taking into account several constraints related to work context.

III. RESOLUTION APPROACH

Our approach is based on the paradigm of reactivity where the decision cycle is incremental and iterative. The time of an elementary cycle is the sum of the time required to detect the change and understand the situation, to decide what action to take and finally implement the agreed actions (Fig. 2). The goal is not the absolute pursuit of optimality, but rather to better satisfy all the constraints in the studied environment in order to achieve our goals. This should lead to improve the system overall performance, which will be validated by a continual confrontation of the model with the reality:

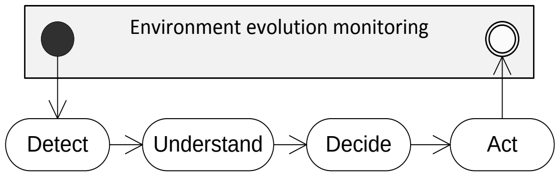

Fig. 2. Steps of a reactive management strategy of pre-hospital services.

Based upon analysis of the problem structure and its characteristics, a multi-agent system was selected and it is defined as: a system composed of a set of autonomous and intelligent entities that coordinate their knowledge to achieve a goal or resolve a problem [9]. A multi-agent sys-tem is not a simple addition of agents, but is a pooling of several intelligences and an integrated management of a set of features leading to an intelligence much greater than the sum of pooling intelligences to achieve the following objectives:

- To better meet the demand of pre-hospital care.
- Optimize the management of human resources especially in terms of paramedics scheduling planning and replacements management.
- Optimize the management of vehicles (ambulances) and operational centers.

This is mainly visible in the design where an independent definition of each agent (planning agent, replacement agent, agent, demand management agent, vehicles management agent, etc…) is not sufficient to define the complete system. The aspect of organization, communication, interaction and of the environment is even more important:

The design of a reactive multi-agent model to resolve the problem of pre-hospital services management is analogous to defining a decision-making support process whose goal is to provide a stable solution in time and space, from the problem statement that has its own topology and its own dynamics.

The environment is defined as the input layer of the loop of this decision making. It formalizes the topology and variations of the problem that have to be perceived by the agents it contains. The emerging organization is the output of the system and the mechanism of decision-making is defined through the agents and their interactions. These interactions can be separated into two distinct categories. On one hand, agent-agent interactions compose the direct branch of the decision making loop [10]. On the other hand, agent-environment interactions characterize the feedback loop filter and thus its process of decision making. The environment is modified by both the dynamics of the problem and the dynamics of decision making related to the interactions and the actions of agents (see Fig. 3).

The Fig. 4 proposes to schematize a multi-agent system in the four quadrants diagram based on the definitions of the agent concepts, interaction, environment, organization, institution and standard [11]:

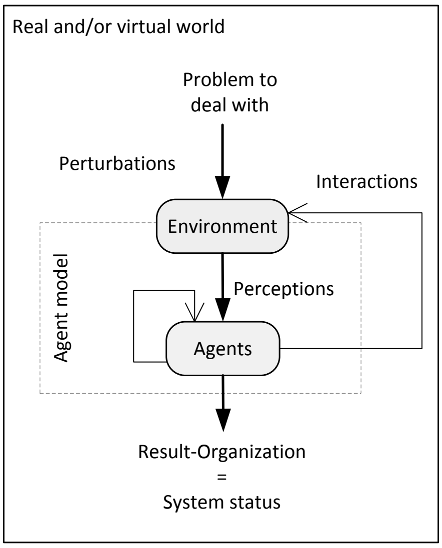

Fig. 3. Principle of reactive agent resolution based on the environment.

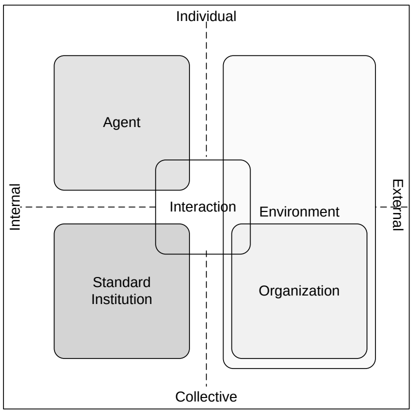

Fig. 4. Concept of multi-agent systems on the four quadrants.

IV. Methodology and Application

We have chosen the methodology O-Mase [12] to model our system which is an extension to MaseE. The multi-agent system is considered as a social organization. Each agent is a member of this organization and plays a specific role according to its capacity. This organization is mainly composed of models of: goal, organization, roles, ontology, agent, protocol and agent state).

This methodology allows designing a multi-agent system according to an organizational vision based on meta-models. One of the biggest advantages of this methodology lies in its broad coverage of the development process of multi-agent systems. Indeed, it allows following the evolution of the model right from the definition of the objectives up to the design and final implementation of the application (Fig. 5) and therefore increasing and facilitating the industrialization of multi-agent systems [15]:

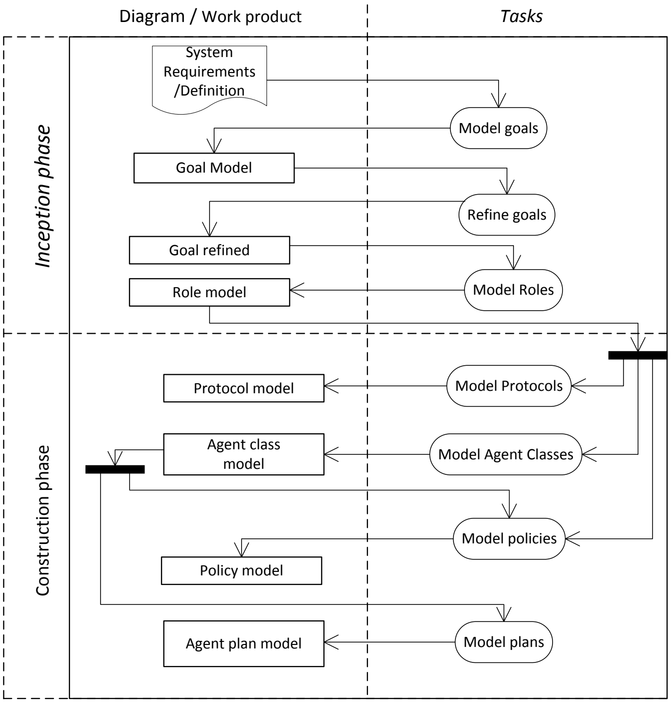

Fig. 5. O-MASE modeling process.

This method is divided into two main phases: the initiation phase and the construction phase. The following diagram shows a portion the goals defined:

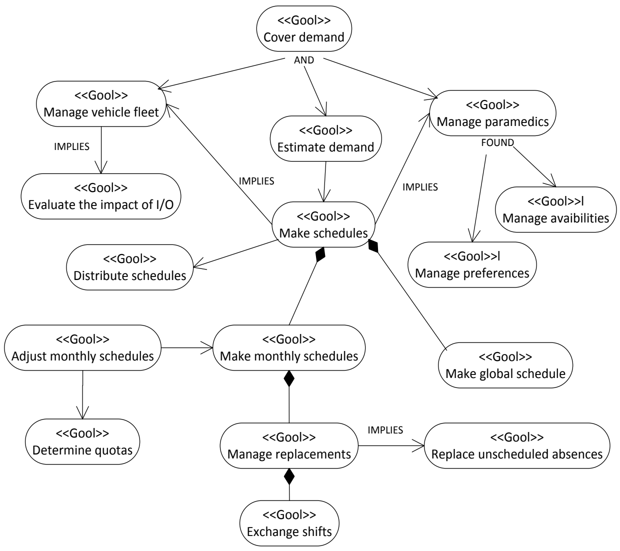

Fig. 6. Goal model.

For each identified objective, we associate a role. Each role will be composed of tasks designed to achieve a goal. This is achieved through state diagrams - transition that will allow describing the roles and relationships between them.

Afterwards, we generate a domain diagram that is used to describe the relationships between the various entities, attributes, and the overall organization.

The agent diagram used to describe the agents, the allocation of roles, the capabilities of each agent and finally the services provided.

The agents' model is a class diagram. The attributes of an agent are the roles that he can play and the relationships between agents represent conversations.

In this model (see Fig. 6), some agents are endowed with optimization algorithms and problem resolution. For instance, the planning agent integrates a scheduling algorithm of paramedics. The general formulation of its optimization function is thereby presented:

$$Minimize \quad \sum_{k\in K} f\left(\overline{X_k}\right) = \sum_{k\in K}\sum_{n\in N} C_n\left(\overline{X_k}\right) \bullet P_{nk}$$

Subsequently, this function must be minimized under certain hard constraints. An example of a hard constraint is the satisfaction of the demand:

$$\sum_{i\in I} X_{ij} = R_j, \quad \forall j \in J$$

The elements of this matrix are defined as follows:

$$X_{ij} = \begin{cases} 1, \text{ if the quarter } i \text{ is allocated to the period } j \\ 0, \text{ otherwise} \end{cases}$$

Terms and variables used in the modeling of the problem are defined as follows:

I, the set of indices i representing quarters;

J, the set of indices j representing periods of work;

K, the set of indices k representing schedules;

N, the set of soft constraints;

X_{ij}, the decision variable indicating whether the quarter i is allocated to period j;

$\overline{X_k}$, the schedule k,

$C_n\left(\overline{X_k}\right)$, the Function that quantifies the compliance of the soft constraint n by the schedule k, R_j the total number of quarters to be allocated to the period j.

The general process of decision-making is composed of three modules (see Fig. 7):

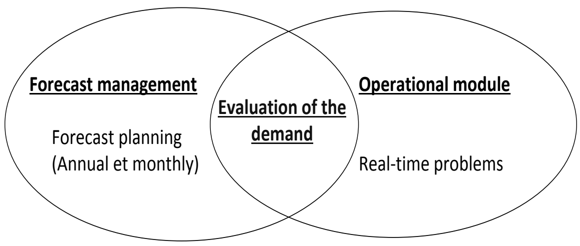

Fig. 7. Modules of decision-making process of pre-hospital services.

The three modules relative to the pre-hospital services management model are:

- The evaluation of the demand;
- The forecast planning on long term and short term.
- Operational management concerning real-time problems.

The following diagram (see Fig. 8) helps visualizing the steps of our decision making process and identifying the triggers and the data associated to each step:

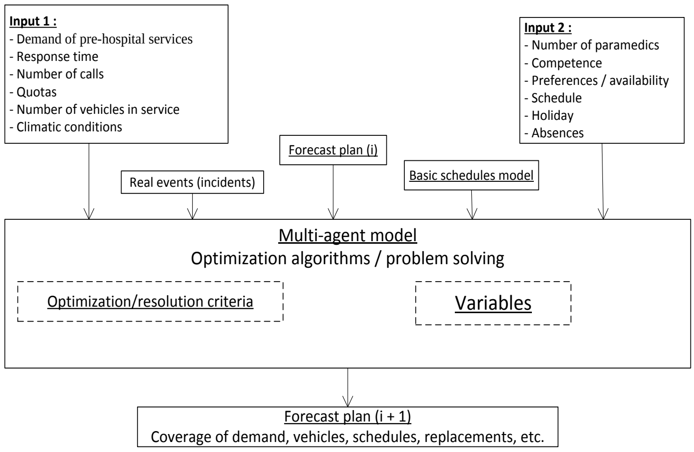

Fig. 8. Protocol problem resolution and trigger factors.

Indeed, our model is translated into an intuitive web application, its architecture inspired from [13] is illustrated in the following Fig. 9:

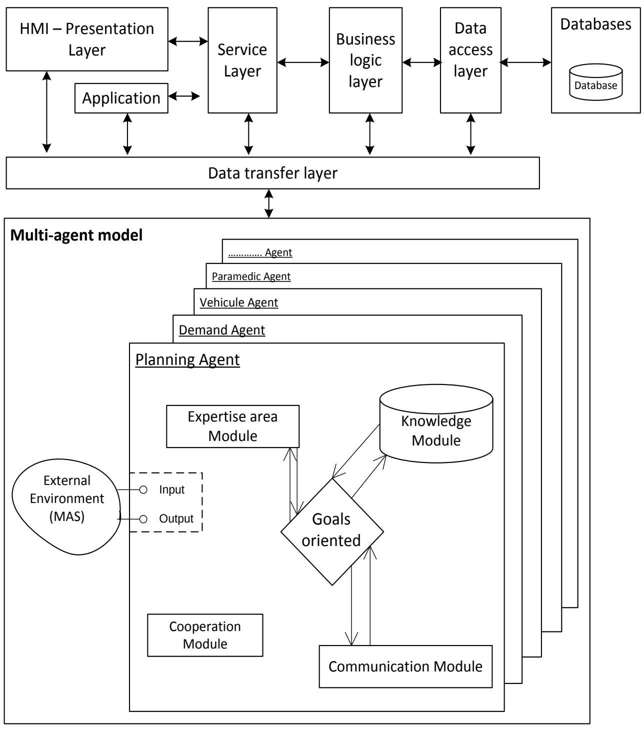

Fig. 9. The application architecture.

This application includes a Human-machine interface (HMI) facilitating to the user to intervene in the resolution process and visualize the results.

This system was tested in "Urgences-santé de Québec" and generally allowed to obtain and satisfying solutions, with acceptable computation time on a computer desktop Intel Core Duo CPU E6850 at 3.00 GHz and 3.48 RAM. We present the results of the carried tests on real data.

V. RESULTS

In this section, the preliminary results obtained by our model are presented. Concerning the demand covering, it is quite simple to evaluate the quality of the results. However, with regard to other elements such as planning quality, evaluation is less simple to do.

We have created a list of measures allowing the user to assess the quality of the overall solution. These measures are:

- Coverage of the demand
- Number of hours-vehicles
- Number of hours-men
- Number of schedule
- Number of vehicles
- Number of additional vehicles
- Execution time

We considered that these statistics are those necessary and / or useful to be able to assess the quality of a solution, in respecting both the demand and the vehicles fleet, etc… but especially in its implementation potential in U.S.

The three tests in this section are based on several parameters (for instance):

- Three scenarios that include real data of the demand of pre-hospital services for the year 2012 and special events.
- Paramedics 596
- A maximum number of 123 vehicles
- A banking schedule generated by the system [3]
- Stopping criterions used accordance with the iterations number without improving the best known solution

Table II shows the resolution time of each test:

TABLE II: TABLE OF RESOLUTION TIME

	TEST 1	TEST2	TEST 3
TIME	00:10:18.63	00:10:18.78	00:33:39.80

By changing the scenario of the problem we aim to resolve, we can see that the execution time differs from one test to another. The Fig. 10 shows the result based on the assessment of the Sunday demand for the test solution 1:

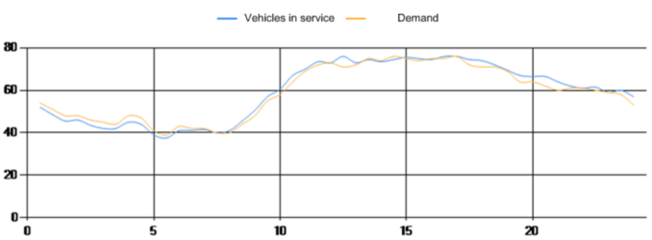

Fig. 10. Comparison of the offer and demand for the test solution 1 (Sunday).

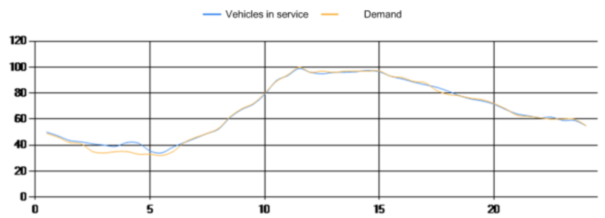

Fig. 11. Comparison of the offer and demand for the test solution 1 (Wednesday).

Fig. 10 shows that the solutions generated by our model have a good coverage of demand compared to the offer of each of the tests. And we come up to the same conclusion for the day Wednesday of each test scenario. The Fig. 11 shows the comparison between the offer and demand of results obtained in Test 1:

Despite the change in demand, our model gives good results for the coverage of demand in all the three tests. Table III shows the distribution of results for the three tests based on the type of schedule:

TABLE III: DISTRIBUTION OF SCHEDULE BY TYPE FOR THE THREE TESTS

TYPE	TEST 1	TEST2	TEST 3
614 / 10H	40	40	40
714 / 12H	410	404	412
814 / 10H	26	20	20
1014 / 8H	120	132	124
TOTAL	596	596	596

These results are presented in detail in our system as a description report of hours per solution.

The summary of other results is presented in Table IV:

TABLE IV: SUMMARY OF THE OTHER RESULTS

ELEMENT	RESULTS
HOURS-VEHICLES	568.483
HOURS-MEN	1.136.967
NUMBER OF SCHEDULE	596

The main strength of our method is the rapidity of resolution. In the short term, we see our model as an excellent simulation tool of scenarios, modifications and improvements to existing structures and management processes at U.S.

VI. CONCLUSION

The objective of our work was to design and produce a reactive multi-agent decision-making support model in a simple way and according to an integrated approach. Pre-hospital emergency services have proven to be an interesting scope to implement these ideas, since it involves the modeling of a complex system.

The proposed model was able to answer the majority of both organizational and operational management constraints of pre-hospital services in U.S. We believe this objective has been achieved and our model provides satisfactory solutions on desktop machines quickly and its flexibility allows testing and evaluating a large number of scenarios. The solutions offered are of good quality and take into consideration the constraints of management (demand, vehicles and paramedics). We now aim to extend the application of our work to other areas to better enrich this experience and develop it further.

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