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Moez Charfeddine
Benoit Montreuil

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Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone : 418 656-2073
Télécopie : 418 656-2624

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Toward a Conceptual Agent-based Framework for Modelling and Simulation of Distributed Healthcare Delivery Systems

Moez Charfeddine[1,*], Benoit Montreuil[1]

[1] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT) and Département des opérations et systèmes de décision, Pavillon Palasis-Prince, Université Laval, Québec, Canada G1V 0A6

Abstract. Research adopting the agent-based simulation approach in the healthcare domain has increased during the last few years. The healthcare domain is characterised by a high level degree of complexity and uncertainty, and modellers are often confronted to conceptual and methodological issues related to its specific requirements. This paper presents the AOE2 generic framework for agent-based modelling and simulation in distributed healthcare delivery systems. The framework provides modellers of healthcare systems and facilities a reference guideline for carrying out the model development process. The framework components are structured in a three-level categorisation supported by an integration platform called the distributed simulation engine. The first-level components that modellers must define to build their healthcare simulation model are: agents, objects, environment and experience. The AOE2 framework can be a very useful reference helping healthcare delivery system modellers to accelerate the model development process while at the same time minimising the risks of skipping important elements and interactions. Application of the overall framework is illustrated using a field case, the Québec regional COPD (Chronic Obstructive Pulmonary Disease) network.

Keywords. Patient flow modelling, health services, multi-agent systems, simulation, modelling framework and methodology, distributed healthcare delivery systems, logistics and supply chain management.

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* Corresponding author: Moez.Charfeddine@cirrelt.ca

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1 Introduction

The purpose of our research is to elaborate a generic framework for agent-based modeling and simulation in distributed healthcare systems. This framework will provide modellers of healthcare delivery systems (in particular health networks) and facilities (such as hospitals, clinics, etc.) with a reference guideline for carrying out the model development process. The proposed framework integrates, in a general and coherent model, the main concepts and aspects that a modeller needs to consider in order to build an agent based simulator in the specific healthcare domain. Note that depending on the particular objectives for which the simulation model is being built, some of these concepts will have more influence on its detailed design and its components than others.

The paper is structured as follows. Section 2 presents a brief literature review about agent concepts and agent-based modelling methodologies in general, and more specifically about agent based frameworks and simulation studies in healthcare domain. Section 3 introduces the essence of our illustrative field case, a network for dealing with Chronic Obstructive Pulmonary Disease in the Québec region in Canada. Section 4 introduces our generic agent-based framework and defines its different components and concepts. Finally, in section 5, conclusion and future work related to our research are presented.

2 Literature review

Agent-based simulation is an abstracted representation of reality involving the elaboration of a model which reproduces the behaviour of the system through the recourse of representing the decision making entities of the studied system as agents. An agent can be defined as an entity, theoretical, virtual or physical, capable of acting on itself and on the environment in which it evolves, and of communicating with other agents (Jennings et al., 1998). Wooldridge and Jennings (1995) propose the following properties of an agent. i) Autonomy: an agent operates without human being or other direct intervention and neither the actions it realizes nor its internal state are submitted to any control. ii) Reactivity: an agent perceives its environment and reacts in an appropriate way. iii) Pro-activity: an agent must be able to develop behaviours directed by internal goals. iv) Sociability: the agents interact with each other using communication languages and common sociability rules. Agent-based modelling allows the representation of the agent's behaviour within a multi-agent system as well as the existing interactions between them.

Different authors report the benefits and adequacy of applying the agent technology and multi-agent systems to the healthcare domain (see for example Nealon and Moreno, 2003). The reasons mainly cited reside in the complexity and dynamics of a healthcare delivery system or facility, the high degree of uncertainty that characterises the clinical processes and the involvement of multiple distributed service providers and decision makers. In fact, due to their principal characteristics such as autonomy, reactivity, pro-activity and sociability, agents seem adapted to consider these problems and help develop efficient tools and decision systems in the healthcare domain. More specifically, agent-based simulation techniques and multi-agent simulated environments combine these benefits to those of the simulation modelling approach providing researchers, policy makers and managers in healthcare with a powerful tool to pose "What-if" questions and test different scenarios about the implications of their decisions on the care delivery performance.

Research and projects adopting the agent approach to solve healthcare problems have increased during the last few years, but practical implementations in the real world are still very rare. Nealon and Moreno (2003) and, more recently Devi and Mago (2005), reported examples of such systems being developed across the world from which we can mention Guardian, a knowledge based system conceived to deal with the tasks of monitoring and diagnosing cardiac surgery patients requiring intensive care (see Larsson and Hayes-Roth, 1998), and OnkoNet, a system giving patients access to health services via mobile devices (see Kirn, 2003). On another hand, the use of simulation techniques (especially discrete event simulation) is also increasing in the healthcare domain. Jun et al. (1999) presented an extensive literature revue of such applications and classified them into two categories: management of patient flow and resource allocation. In a systematic review of the use and value of simulation in healthcare, Fone et al. (2003) enlarged this classification by adding other categories like infection and communicable diseases, costs and economic evaluation, and screening. However, practical studies using agent-based simulation approaches in healthcare are very rare, and we think that it is attributed to the additional complexity of their implementation compared to more basic discrete event simulation or object oriented models for example. Alternatively, current research focuses on designing and developing solutions and frameworks supporting agent-based simulation approaches in order to use them, lately, for empirical studies and real applications. Some of these frameworks are specific to certain healthcare problems such as patient and staff scheduling (Stiglic and Kokol, 2005). Others are more generic or have a general focus on a healthcare multi-service facility, such as an hospital (see for example Kirn et al., 2003).

One of the early studies that considered the development of an agent-based model in healthcare is attributed to Huang et al. (1995). The authors proposed a three-layered agent based architecture, called AADCare, that aims to support coordinated activities and communication management in healthcare institutions. In this model, the domain layer consists of knowledge databases about the medical speciality, the patient and the resources. The inference layer contains generic rules that defines interactions between the different identified domain components, and finally, the control layer is a “logical meta-level” monitoring the application of inference rules and exploiting the resultant domain facts. A case study of a cancer therapy care process is used to illustrate the usefulness of this architecture. Some frameworks are designed as electronic institutions which define a formalism for modelling organisational structures with multiple distributed locations and actors in a multi-agent system. Examples of such approaches include the Carrel system developed for managing organ and tissue transplants in Spain (Vasquez-Salceda et al., 2003) and its extended version called Carrel+ (Tolchinsky et al., 2006), which uses new argumentation mechanisms to improve the organ selection process for transplantation. The main components of an electronic institution model are 1) the dialogical framework defining different locutions that stands as a standardised language agents can use for their communications; and 2) the performative structure which refers to a network of scenes (each scene can be any meeting place where two or more agents, playing different roles, have to communicate with each other in order to coordinate their actions or exchange information, etc.) as well as to the rules governing the agents participation and progression in these scenes. For more details about the electronic institution, see for example Esteva et al. (2001).

Agent.Hospital (Kirn et al, 2003) is another agent-based framework for distributed applications in healthcare that is designed as a core engine supporting multiple modules each related to a specific healthcare domain such as cardiology, radiology, etc. Agent.Hospital comprises numerous basic agents playing the role of infrastructure service providers to all these modules. For example, the Simulation Environment Agent is responsible for visual modelling and animation, the Directory Facilitator is a kind of repository of the existing services provided by registered agents, etc.

As presented previously, numerous research studies use an agent-based modelling approach to represent systems in the healthcare domain. In the literature, multiple methodologies are proposed to guide the design of multi-agent systems. The main methodologies are Knowledge Engineering based methodologies, Object-Oriented based methodologies and agent-based methodologies (Jennings et al., 1998). In the majority of such methodologies, a design guide is proposed which does not consider the domain of the modelled system. The specification phase is generally directed toward the designv of the multi-agent system. Within certain methodologies such as ADELPHE (Bernon et al., 2001) or TROPOS (Giunchiglia, 2001), a detailed stage is dedicated to the analysis and the specification of needs, integrating more recommendations for implementation. Adapted to manufacturing and logistics systems, a methodological framework for agent-based modeling and simulation is proposed in (Labarthe et al., 2005). This methodological framework starts with domain modelling which is then transposed into conceptual and operational agent-based modelling for simulation implementation. When designing a multi-agent system, it is essential to consider properties of the domain of application. In the following section we propose a framework, and its underlying concepts and components, for developing an agent-based healthcare simulation model.

3 Illustrative field case

Illustration of the overall framework application and further discussions about the different alternatives and the choices to make during the modelling process are provided through a field case focused on a COPD (Chronic Obstructive Pulmonary Disease) regional network around the city of *Québec* in *Canada*.

To be consistent with the terminology used in the context of Quebec’s health system, French acronyms will be used in this article. The English equivalents are shown in table 1 below. Also, location names will be kept in French but formatted in italic characters.

Acronym	French name	English equivalent
ASSS	Agence de Santé et Services Sociaux	Health and social services agency
CSSS	Centre de Santé et Services Sociaux	Health and social services center
CLSC	Centre local de service communautaire	Local community service center
CHSLD	Centre hospitalier de soins de longues durées	Long term care hospital center
SRSRSD	Service régional de soins respiratoires spécialisés à domicile	Regional specialised respiratory home care service
GMF	Groupe de médecins de famille	Family physicians group
UMF	Unité de médecine familiale	Family medical unity

Table. 1. Studied case acronyms

The Chronic Obstructive Pulmonary Disease (COPD) is a non-reversible lung disease in which the lungs are damaged, making it hard to breathe (O’Donnell et al., 2007). COPD includes emphysema and chronic bronchitis. Statistics show that more than 750,000 people suffer from COPD in Canada and that it is the 4th leading cause of death in Canada. In the province of *Québec*, the number of people having the COPD disease exceeds 386 000[1].

[1] The lung association of Quebec, http://www.pq.poumon.ca/diseases-maladies/copd-mpoc/index.php, Accessed in 2008-02-10

Given the importance of the emergencies congestion problem in Québec, a lot of efforts are being made by regional health and social service organizations for establishing an integrated network offering full services for COPD patients. The goal is to improve the availability and continuity of services for COPD patients towards reducing hospital admissions and emergencies visits, and to improve the quality of life for COPD patients.

The regional network is administratively divided into 4 areas, each under the responsibility of a CSSS. These areas are *Vielle-Capitale*, *Québec-Nord*, *Charlevoix* and *Portneuf*. The network covers a territorial area of 19,285 square kilometres. It deserves 57 municipalities, towns and villages. The distant locations within the overall regions suffer from the lack of pulmonology specialists and more generally of medical expertise linked with lung diseases (clinical nurses, etc.).

The COPD affected population must currently travel to hospitals located in *Québec* city for treatment and services. Considering that the regional average age of patients suffering from chronic lung disease is more than 70 years, as well as the difficulties related to their displacement, lack of transportation, their dependence on the availability of family helpers, the patients often require hospitalized care and services due to the deterioration of their health status. Thus a major field objective of our modelling study is to identify avenues having the potential of improving the current situation. These may include the redesign of the network, process reengineering and resource optimisation. A key possible avenue is particularly under investigation. It involves evaluating the impact of developing satellite COPD clinics in each distant area of the region (*Portneuf*, *Charlevoix*, *Québec-Nord*) so as to facilitate the education and follow-up of patients residing in these areas.

4 The generic agent-based framework: presentation and case study illustration

As exposed in section 2, most frameworks in the scientific literature are focusing on the technology that is intended to support a multi-agent system in healthcare. Besides the technology, modellers in the healthcare domain are often confronted with methodological issues related to its specific requirements (see for example Fox et al., 2006). This paper differs from the existing literature because we do not aim to develop a technical framework that defines the implementation of such platforms and by consequence specifies the manner in which modellers should design their agent-based simulation systems. Our framework is concerned with more generalised and methodological issues about the model development process and offers a reference guideline for carrying out this process. It helps answering questions such as Where to start? What to model? and What may be the components of the simulated environment?

In this section, we present our agent-based framework, called AOE^2 as an acronym for Agents-Objects-Environment-Experience, the four main components of the framework. Figure 1 graphically synthesizes the AOE^2 framework for developing healthcare simulation models. The core layer of the framework, called the distributed simulation engine, is an infrastructure platform that is intended to support the functional integration and assembling of all the other components. The second inner layer comprises the main components that modellers must define to build their healthcare simulation model, which are: agents, objects, environment and experience. The third and fourth layers consist, in a hierarchical categorisation, of each of the main components guiding the modellers to more and more details and refinement in the development process. Note that we are not pretending that our categorisation will perfectly fit all existing realities in the healthcare domain, but we believe that this framework can be a very useful reference to guarantee a comprehensive workable modeling, to minimise the risk of skipping important elements, and to practically help save time.

In the following subsections we present all components of the AOE^2 framework. The presentation of some components is more detailed than others. This doesn't mean they are more important in the model development process. We simply put emphasis on what we estimate as more subtle stages in this process and where in depth descriptions should be most pertinent. As an example, we have voluntarily expanded the network component. For each component, we provide a detailed illustration in the field case context. The objective is double. First we aim to facilitate the understanding of the framework. Second we aim to demonstrate the capability of the AOE^2 framework to tackle the complexity, breadth and depth of the modelled field case.

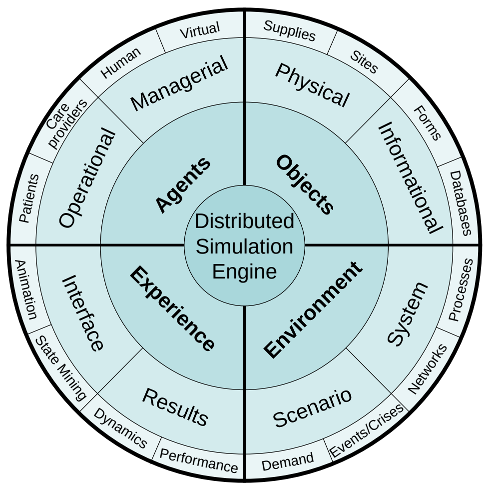


Fig. 1. Overview of the AOE^2 framework

Distributed simulation engine

The distributed simulation engine refers to the infrastructure platform that is intended to support the functional integration and assembling of all the other components. The engine is required to be distributed due to the large scale of the resulting models, often requiring the simulation to be run over a network of computers. Since we are interested in methodological concerns in healthcare domain modelling, and that the distributed simulation engine is a technical component concretely independent of the domain, we here limit ourselves to mentioning that the key elements of a distributed agent-based simulation engine are (for more details, see for example Kirn et al., 2003): an event handler system with clock synchronising, a repository of registered agents and their services, and Models of agent implementation.

Agents

In the healthcare modelling context, we identify two types of agents: operational and managerial. The operational agents correspond to the patients and care providers. The managerial agents represent humans and software managing the modeled health care system. The modeller has first to identify the set of agents in the modeled case. Then he has to characterize them according to their role and various pertinent facets. Finally he has to document the intent and behaviour of each agent.

Operational agents: patients and care providers

Patients represent the principal users of the healthcare system and the core element of the care processes. In contexts where they are paying for the service, patients can also be considered as the clients of the system. Depending on the modelling objectives, patients can be classified according to one or multiple criteria:

a) Demographic characteristics (age, sex, profession, etc.). In general, the demographic characteristics relevant to the modeller are those identified as risk factors regarding the considered diseases or patients group.
b) Patient type. For example, it permits to contrast between regular and new patients.
c) Priority within the system. It can be classified by criticality levels such as normal, urgent, extreme urgency, etc. The criticality level is determined by the urgency of medical intervention which depends on clinical factors such as the severity of the pathology, the risk that the pathology induces others, the presence of multiple pathologies, etc.
d) Clinical needs which comprises:
    - type of service needed (in case of a multi-service network or facility),
    - type of treatment (inpatient or outpatient, chirurgical intervention or/and medication therapy, etc.),
    - type of examination (general, specialised),
    - type of pathology (cancer, diabetes, heart disease, etc.),
    - need for ancillary and paramedic services (laboratory tests, radiology, etc.), and
    - type of visit (simple visit, follow up, cyclic follow up, etc.);
e) Patient trajectory characteristics. This includes the type of arrival (simple arrival, by ambulance, transfer, etc.) and the type of departure (back to home, hospitalisation, transfer, etc.).
f) Patient arrival rules related to scheduling (appointment, walk-in), delayed arrivals, no shows, clinical session of the arrival time (before midday, afternoon, evening) and presence of accompanying persons, etc.

In the context of our case study, Table 2 summarises the elements considered to model patients within the system.

Care providers represent all the agents that are involved in providing care to patients in the healthcare system. Care providers are generally characterised by their skills and competencies. They take one or more roles within the system according to their function in the organisation. Each role implies responsibilities that the agent is committed to do. The main categories of care provider agents are :

a) Medical professionals: physician, surgeon, anaesthetist, etc. Usually, for each patient, we may identify a main medical actor who is responsible for his treatment and who can require the intervention of other medical actors for consultation;
b) Medical assistants: residents, nurse practitioners, etc.;
c) Nursery personnel;
d) Ancillary service providers: radiologist, pharmacist, dietician, physiotherapist, etc.;
e) Technicians: laboratory personnel, special medical machine operators, etc.;
f) Admission and discharge personnel;
g) Clinical support personnel : archive, security, cleaning, transportation, supplying, etc.

Demographic characteristics	• Age : <45 / 45-65 / 65-75 / 75 and more • Sex : Male / Female • Education level : Primary / Secondary / University • Smoking habits : Current smoker / Never smoker / Ex-smoker • Exposure to pollutants : Yes / No • Residence location : *Québec City, Portneuf, Charlevoix, Québec-Nord*
Type of patient	• Main symptoms and signs : Morning cough / Chronic cough / Phlegm cough / Wheeze / Dyspnoea attacks / Dyspnoea grade 2 • Already diagnosed COPD : Yes / No • Having a family physician : Yes / No
Priority within the system	• Four criticality levels : urgent / semi-urgent / non-ambulant / ambulant • COPD severity levels : At risk, Mild COPD, Moderate COPD, Severe COPD.
Clinical needs	• Type of service : General care / Specialized medical care / Medical and clinical follow-up / Education / Hospitalisation / Rehabilitation / Paramedic care / Home care and support / Oxygen material providing • Type of treatment : Outpatient (for ambulant and non ambulant cases) / Inpatient (for semi-urgent and urgent cases) • Type of pathology : emphysema / chronic bronchitis • Need for ancillary and paramedic services : Nutritionist / Physiotherapist / Social worker / Analysis (Laboratory, Bronchodilator reversibility testing, Chest x ray, Arterial blood gas, Other pulmonary function testing) • Type of visit : First visit / Follow-up (for outpatient cases), First visit / Readmission (for inpatient cases)
Patient trajectory	• Type of departure : Back to home / Transfer to continue treatment / Transfer for follow-up
Patient arrival rules	• Appointment rules: With appointment / Without appointment / With or without appointment • Need for a referral from a health professional : Yes / No

Table 2: Patient model characteristics in the COPD network case study

Managerial agents : human and virtual managers

Human managers represent human resources within the healthcare system that assume managerial functions and responsibilities. In this category, we may identify healthcare executives and professionals working in tasks related to finance, accounting, human resources management, operations, supply and logistics, maintenance, etc.

Virtual managers represent healthcare management software systems, modules and agents that are integrated in the healthcare system, responsible for taking specific sets of decisions and providing support to human managers. For example, a virtual managing agent may model a patient queue priority management software. Another may be responsible for scheduling treatment units, insuring the follow-up and the global coherence of the various planning tasks like appointment management, shared resource schedules, etc. Yet another may model a system responsible for collecting, centralising and circulating information in the overall system.

Table 3 shows the agents identified in our COPD network.

Objects

Objects represent physical and informational entities that can be found and used in a healthcare environment. Objects are resources used by agents to accomplish their activities.

Objects are characterised by attributes such as functionalities, available quantity, used quantity, cost, etc.

Care providers	
Medical professionals	General practitioner, Family physician, Pulmonologist
Nursery personnel	General nurse, Clinical nurse (have advanced skills in COPD disease), Linkage Nurse (responsible of referrals between services, one person per activity sector)
Ancillary service providers	Kinesiologist, Nutritionist, Physiotherapist, Social worker, Responsible of analysis, Pharmacist, Occupational therapist, Respiratory therapist
Human managers	
Operation and logistics	Appointments manager
Agency managers	Managers with assigned responsibilities over the COPD care network
Center managers	Specialized unit manager, Hospital director, etc.
Virtual managers	
DSIE System	Computer system for inter-establishments referrals

Table 3: Agents identified in the COPD network field case

Physical objects: supplies and sites

Supplies essentially model all tools, instruments, materials and equipment used in the healthcare system. They include:

a) Medical equipment:
   - Some need to be installed like radiological machines,
   - Others are mobile such as stethoscopes and blood pressure devices;

b) Communication and administrative equipment:
   - Blackboards, phones, personal device assistants (PDA), computers, various furniture, etc.;

c) Transportation equipment:
   - Ambulances, stretchers, wheelchairs, etc.;

d) General-use equipment such as cleaners;

e) Beds;

f) Medicines;

g) Materials and clinical supplies:
   - Consumable or reusable, the latter may require sterilisation.

Sites model the different physical locations and spaces (buildings for example) composing the healthcare delivery system. They are generally assigned to specific organisational units. Sites are characterised by their dimensions and their air quality certification. Their associated resources (agents and objects) determine their capacity limit. Sites can generally be decomposed as a hierarchical structure or mapped as an architectural plan. Depending on the modelling granularity, in top-down order sites correspond to:

a) A country, state, province or region;
b) A healthcare institution, hospital, clinic or centre;
c) A department, unit, service or theatre;
d) A care room, box, office or ward;
e) A care station or bed area.

Other types of sites can also be considered in some specific healthcare models. The most common are patient homes when dealing with home-care services, mobile units, social services providers, governmental administrative entities, as well as fire-stations.

In the contest of the COPD *Québec* regional network, it was decided to take into account the physical objects shown in table 4.

Informational objects : forms and databases

Forms consist of any paper or electronic document that need to be filled out with specific data. Examples are progress notes, order and track tests, prescriptions, track medications, etc.

Supplies	
Medical equipment	Respiratory equipment (Reusable)
Medical equipment	Oxygen equipment (Reusable)
Medical equipment	Spirometry equipment (Reusable)
Sites	
Geographic location	*Quebec City* region and surrounded areas divided into 4 sectors : *Vieille-Capitale* (*Quebec City*), *Québec-Nord*, *Charlevoix*, *Portneuf*
Institution	The following organisational institutions are considered : CSSS, CLSC, CHSLD, SRSRD, GMF
Department / Unit	Clinics, UMFs, Emergency, Hospitalisation units

Table 4: Physical objects identified in the COPD network case study

Computer screens used to enter data, in cases where software applications are used, are also considered as forms.

Databases refer to any source of stored data. The source may be on paper, such as protocols, reference manuals and cardex. It may also be electronic, such as electronic patient charts, scan images and patient records. Databases usually need to be consulted, with search functionalities; updated, for adding new data, deleting and modifying existing data; and secured, insuring that only authorized agents can have access to them.

For the needs of our field study model, the identified key informational objects are summarised in table 5.

Forms
Referring form for COPD patients
Telephonic follow-up form for COPD patients
Databases
Patients medical records
Clinical trajectory plan for COPD patient hospitalisation
Checklist – COPD clinical monitoring
Education plan and material for COPD patients

Table 5: Informational objects identified in the COPD network case study

Environment

The simulated environment component describes the modelled milieu organisationally and behaviourally through its systemic processes and networks, as well as the scenarios of demand, events and crises the system will have to live through.

System: processes and networks

Processes model sets of interrelated activities collectively intending to produce a desired result. The relations between activities define their logical precedence and dependence relationships. The most basic processes, involving a single activity, are often referred to as operations. Activities are executed by agents directly or remotely using telemedicine techniques. They may necessitate or not the presence of the patient. For example, examining a patient clearly requires the patient to be present while analysing test results does not require the patient's presence. As depicted in Figure 2, we can characterise processes in healthcare as follows:

a) Care processes, which are sometimes standardised in protocols such as clinical practice guidelines. Care processes are usually preceded by a patient admission process and followed by a discharge process. In most cases, they can also be divided into sequential phases;
b) Transfer processes, within a healthcare network or between services;
c) Communication processes, structuring the exchange of information;
d) Scheduling processes for admission, resource allocation, etc.;
e) Administrative processes including operation rules and politics;
f) General support processes such as supplying and training;
g) Evaluation processes, involving dashboard, data collecting, etc.;
h) Monitoring processes, involving control, decision making, etc.

Processes are defining the normal, proposed or probable way of functioning. They are action guidelines. However, since the agents are intelligent and pro-active, they may not always follow these processes. Modellers can decide to design agents with closure conformity to the processes or they can allow them to have more or less deviated behaviour. The simulation environment can also include some events or crises (see scenario component in a latter subsection) that may affect the normal progression of one or more processes.

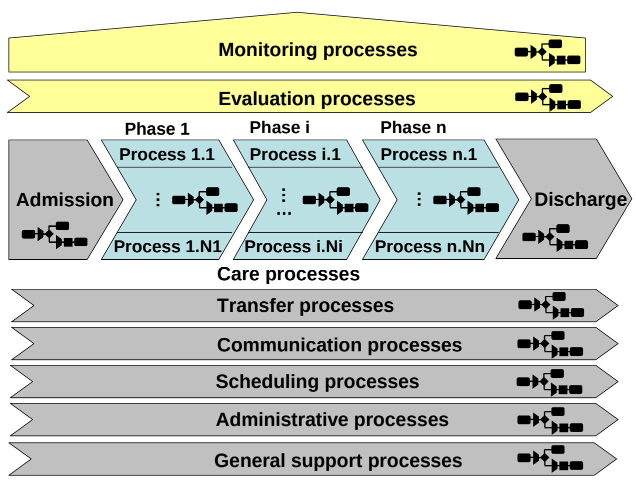


Fig. 2. Overview of a healthcare delivery system processes

In the context of our case study, the following processes were judged important to capture in order to have a sufficient idea (regarding the modelling objectives) about the healthcare delivery system functioning :

- COPD patient caring process;
- COPD patient follow-up process;
- COPD patient hospitalisation process;
- COPD patient transfer process.

Many commercial tools can be used and a range of formalisms exist in the literature process modelling (see for example Aguilar-Savén, 2004)). Figure 3 illustrates an example of COPD patient caring process representation using a simplified formalism.

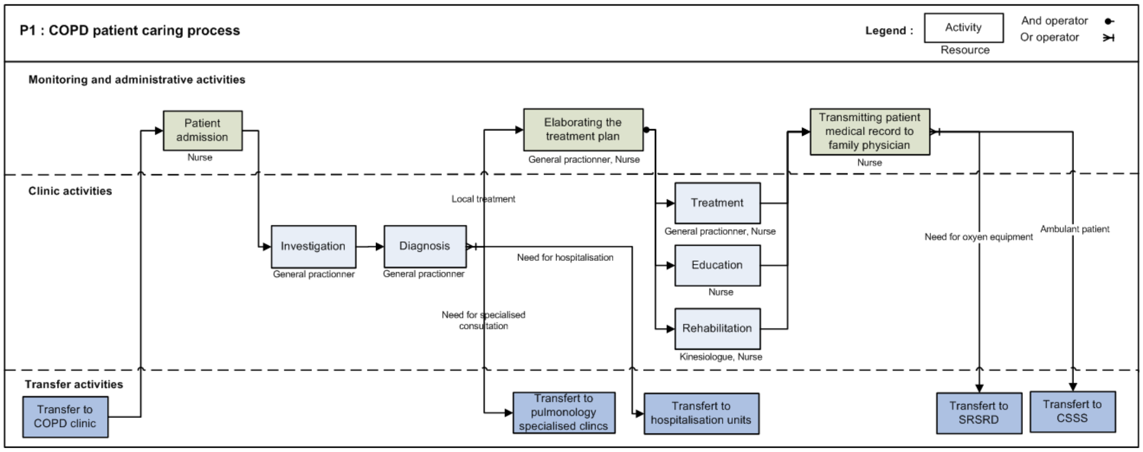


Fig. 3. Representation example of the COPD patient caring process

Networks define the organization of the healthcare delivery system. Networks are composed of nodes and inter-node links. In the AOE^2 framework, nodes correspond to Health Service Centers (HSCs). A HSC refers either to an organisational entity (an emergency center, a hospital, etc.) or an agent (a care provider for example). HSCs are assigned responsibilities in the network. They make decisions and perform processes, using resources to do so. The links represent the relations and flows between the HSCs. Relations generally have a structural connation, while flows capture dynamic functional aspects. We distinguish six types of relations that are usually found in a healthcare network :

- Physical embedding relation, specifying that a HSC is physically located in another.
- Membership relation, specifying that a HSC is organisationally or administratively dependant of another.
- Referring relation, permitting to model service “corridors” between the network HSCs and to specify who can refer a patient to whom.
- Contracting relation, specifying that a HSC deliver services in the network as a subcontractor for another HSC. This is particularly useful to model some supporting services (such as food service, cleaning…) that are often subcontracted to exterior providers.
- Supplying relation, specifying that a HSC (the supplier) provides goods or services to another (its client).
- Collaborative relation, specifying that the two HSCs have to collaboratively and closely coordinate their work to make some tasks or decisions. This is exemplified by the relations between a surgical team during an intervention.

Healthcare flows are generally classified in four main types (see for example):

- Patient flows,
- Physical flows, including mobile assets, supplies, materials and so on.
- Informational flows, including all data, information and documents related to patient (medical record, etc.), supplies and materials (orders for example), and so on.
- Decisional flows, including control, planning & monitoring decisions exchanged within the network.
- Financial flows.

Networks can have an identity of their own in the field, for example a regional first-line network. Networks can become HSCs in higher level networks. In fact all organisational units can be recursively conceived as networks, each with their internal interlinked HSCs. Note that, from a conceptual point of view, a HSC in a network model can refer to an abstract entity (like when we model all private medical clinics or all family physicians in a region as a single HSC) or to a real (physical) instance such as a particular clinic or physician. The former are usually identified by a generic label, the later by their known names. Moreover, depending on the focus of their mission, we can distinguish eight main different types of HSCs, in the same way Montreuil and Lefrançois (1996) and Montreuil et al. (1998) have done for manufacturing and logistic contexts. Table 6 summarizes the currently modelled HSC types.

Type	Responsibility orientation	Processes performed	Examples
Speciality	A medical speciality	All that are part of the speciality	Cardiology, ophthalmology, radiology
Disease	A disease	All required to diagnosis and treat the disease	COPD, diabetes, cancer
Group	A distinct group of diseases or specialties	All required by the diseases or specialties in the group	Cardiovascular diseases
Patient	A type of patient with similar needs	All required by these patients	Elderly people, children, patients at home
Function	An elementary process (function)	Single	Diagnosis, evaluation
Process	A process composed of several elementary functions	Single	Emergencies, intensive care units
Program	A set of activities or procedures to be followed and which are periodically scheduled	All composing the program	Educational centers, Rehabilitation programs
Composite	A combination of other HSC types	All processes required by HSC types	General purpose hospitals

Table 6: Main generic types of health service centers

The network model can be elaborated based on different modelling formalisms largely discussed in the Enterprise modelling research field (see for example Williams and Li, 1999). Inspired by the modelling framework of collaborative manufacturing networks proposed by Montreuil et al. (2000) and Frayret et al. (2001), which was also extended to the case of manufacturing supply chains in a mass customisation context (Labarthe et al., 2005), we propose a new modelling formalism closely adapted to distributed healthcare delivery systems and to the specificity of this domain.

The formalism has been elaborated so as to take into account the complexity of healthcare delivery networks by integrating multiple complementary views and by considering its organizational and behavioural aspects, while at the same time keeping the representation simple and easily understandable. The organizational model illustrates the structure of the healthcare delivery system by describing its HSCs, their respective responsibilities and the relations between them. The behavioural model, for its part, is devoted to detail the exchanged flows within the network and the collaboration modes used by the different HSCs. This permits to understand the behaviour of different actors, their interactions and the overall emergent dynamicity within the healthcare network. The responsibilities of each HSC are depicted using a simplified typology designed for the healthcare domain. Globally, we consider that, depending on their different missions, responsibilities assigned to any agent or organisational entity in the healthcare context can be described by one or a combination of some elementary responsibilities stated in Table 7.

Symbol	Elementary responsibilities	Symbol	Elementary responsibilities
C	Health Care (disease treatment) and health maintenance	D	Investigation and diagnosis
C1	First-line and community care (general practice)	A	Analysis
C2	Medical specialized care	A1	Medical imaging
C3	Chirurgical specialized care	A2	Radiology
C4	Medication	A3	Laboratory
C5	Emergency care	O	Referring and orientation
C6	Hospitalisation	I	Information
C7	Intensive care	M	Providing supplies and / or medicines
C8	Palliative care	N	Providing non medical support services
C9	Psychiatric care	E	Education and teaching (for patient and his family)
C10	Rehabilitation	T	Teaching, training and expertise support (for healthcare providers)
C11	Home care and support	P	Prevention, health promotion and screening
C12	Nursing care	H	Hosting
C13	Paramedic care	R	Medical and clinical research
C14	Medical and clinical follow-up and surveillance	S	Social help

Table 7: Elementary responsibilities groups in a healthcare delivery system

Due to the complexity of the healthcare domain and in order to keep diagrams clear and understandable, multiple views are usually needed to capture the different relations and flows between the HSCs in the network. These different but complementary views enable getting a reliable image of the network and thus meeting the modelling objectives. For example, Figures 4 and 5 have generated to represent the organizational model of the considered COPD regional network. Figure 4 gives an overview of the overall HSCs (as abstracted entities) composing the network and the service corridors that exists between them. The service corridors are modelled through referencing relations in many cases. Figure 5 details how all HSCs involved are physically distributed and how they are organisationally interdependent. Only two examples for Quebec affiliated hospital center and CSSSs are provided in Figure 5.

The level of detail to be reached is assessed according to the objectives of the modelling work. When analysing COPD specialized clinics, it is important to represent each such clinic as well as each HSC closely related to the modelled network, such as the pre-emptive pulmonology specialised clinics. It is also crucial to identify their organisational hierarchy and to localise them properly.

In the case studied, one of our objectives is to analyse the collaboration strategies that may improve the continuity of services between the COPD specialised clinics and the community local centers, the CSSSs. For that reason, we explicitly detail all involved HSCs in each locality in the region. Here this includes *Quebec City*, *Québec-Nord*, *Portneuf* and *Charlevoix*. Moreover, we decided to keep the private medical clinics as aggregated HSCs because we are only interested in the overall flow of patient referred by these actors in the network.

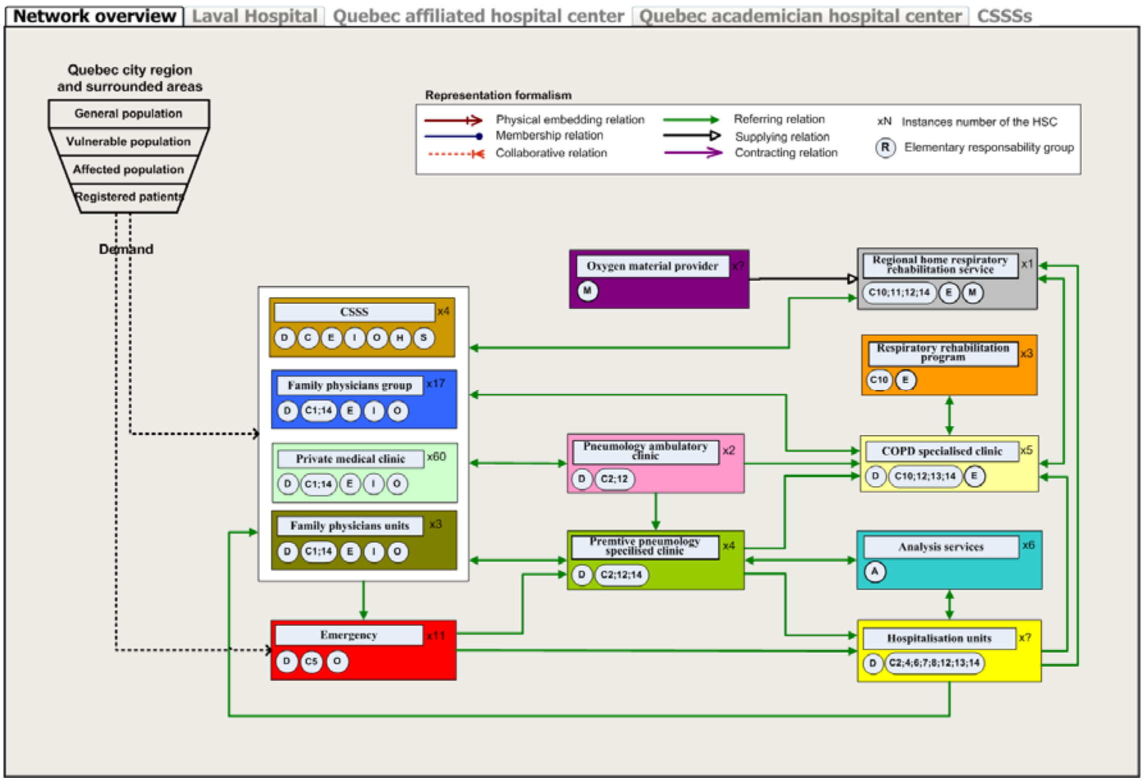
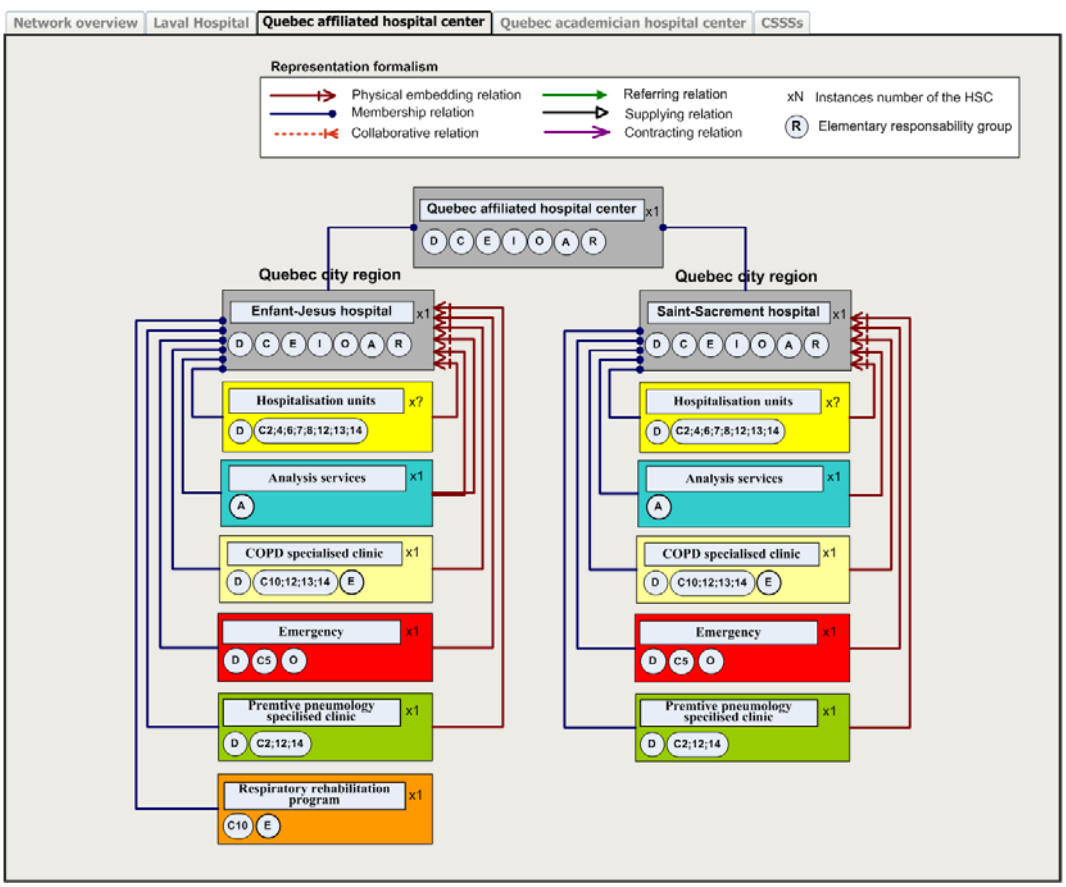


Fig. 4: General structural overview of the COPD regional network



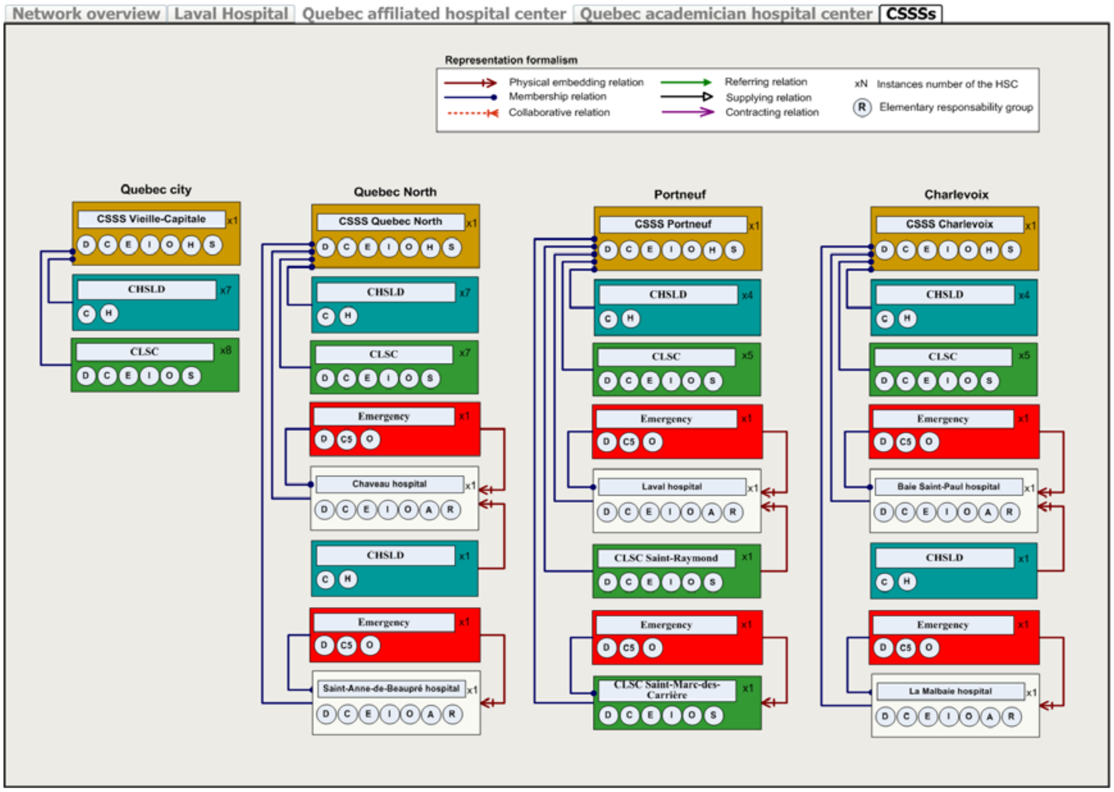


Fig. 5: Examples of detailed structural representation for network HSCs

Figure 6 represents the dynamic functional model for our COPD regional network. In this model, we focus on the patient trajectory and information flow between HSCs. For that purpose, the proposed formalism permits to specify for each HSC multiple information like the type of queue (with or without appointment or mixed), the possible departure options for treated patients (discharge, transfer to another HSC, readmitted for follow-up) or if a referral from another professional of the health system is required. To give an idea about some control mechanisms that are used in the network, it is also possible to mention the criteria or constraints that must be met in order to refer a patient to a HSC. We also put emphasis, in our dynamic model, on the existing collaboration strategies between HSCs. We can see for example that the preemptive pulmonology center and the ambulatory pulmonology center are sharing some human and material resources as well as some processes (or protocols) and information about patients. On another example, we can see that, in this network, the same preemptive pulmonology center gives some human resources and medical expertise support to those of the COPD specialised clinic. Collaboration relations are important to capture since dynamics within the network is in major part emerging from such aspects and many interactions between agents will be derived from them. Finally, we note that the networks can be formal (such as the structure we presented above) or informal. Informal networks include the social networks among colleagues. They often involve mutual assistance or support. They involve the sociability characteristics of intelligent agents and they therefore require more insightful research for adequate modelling.

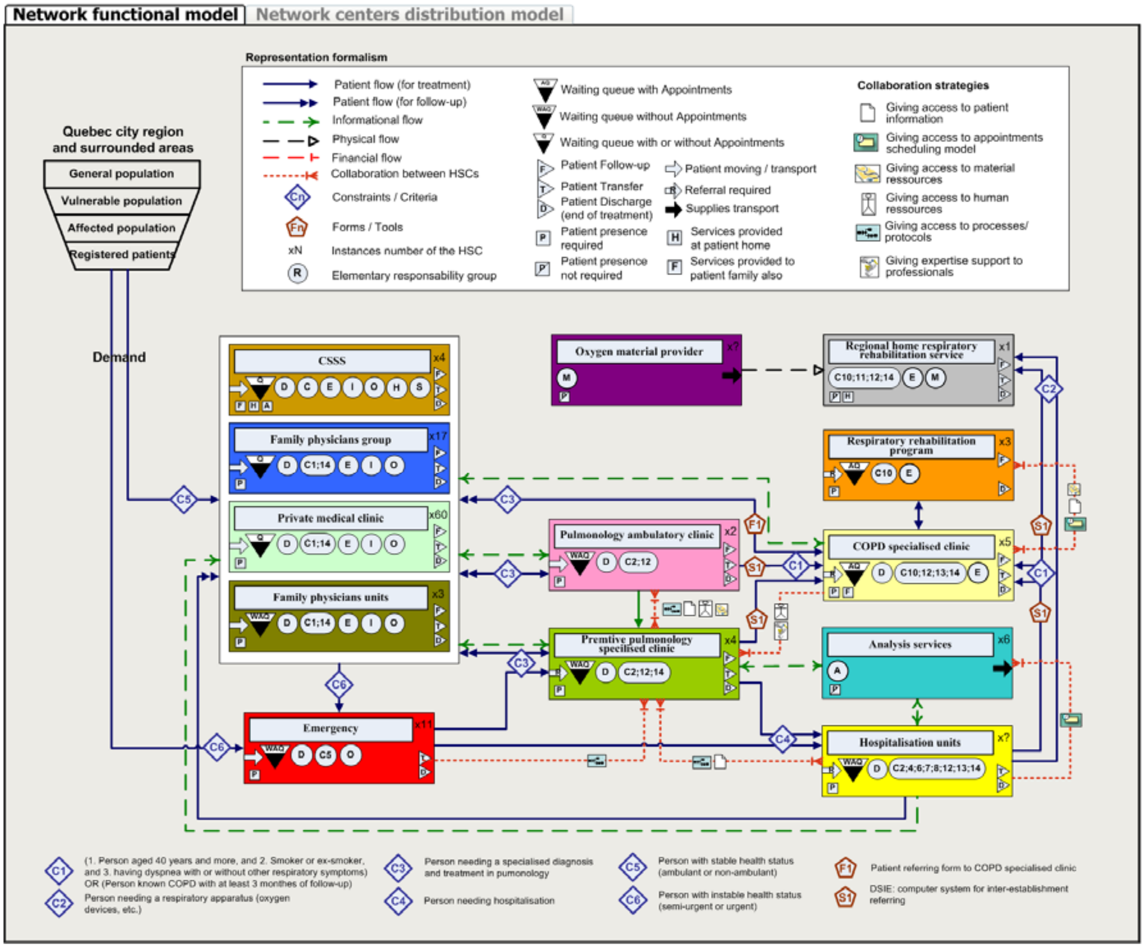


Fig.6 : Functional dynamic overview of the COPD regional network

Networks allow modelling the current organization as well as proposed alternatives. Simulating alternative networks through a As-Is model and a To-Be model allows comparing their relative performance in face of alternative demand-and-events scenarios. In our field case, one of the goals of the decision makers is to evaluate the impact of adding to the current network a satellite COPD clinic in each distant zone (*Portneuf*, *Charlevoix*, *Québec-Nord*) so as to facilitate the education and follow-up of patients residents of these areas. Resources from these satellite clinics would be trained and supported remotely by a group of identified pulmonology specialists from *Québec* city hospitals. The corresponding alternative network is depicted in Figure 7.

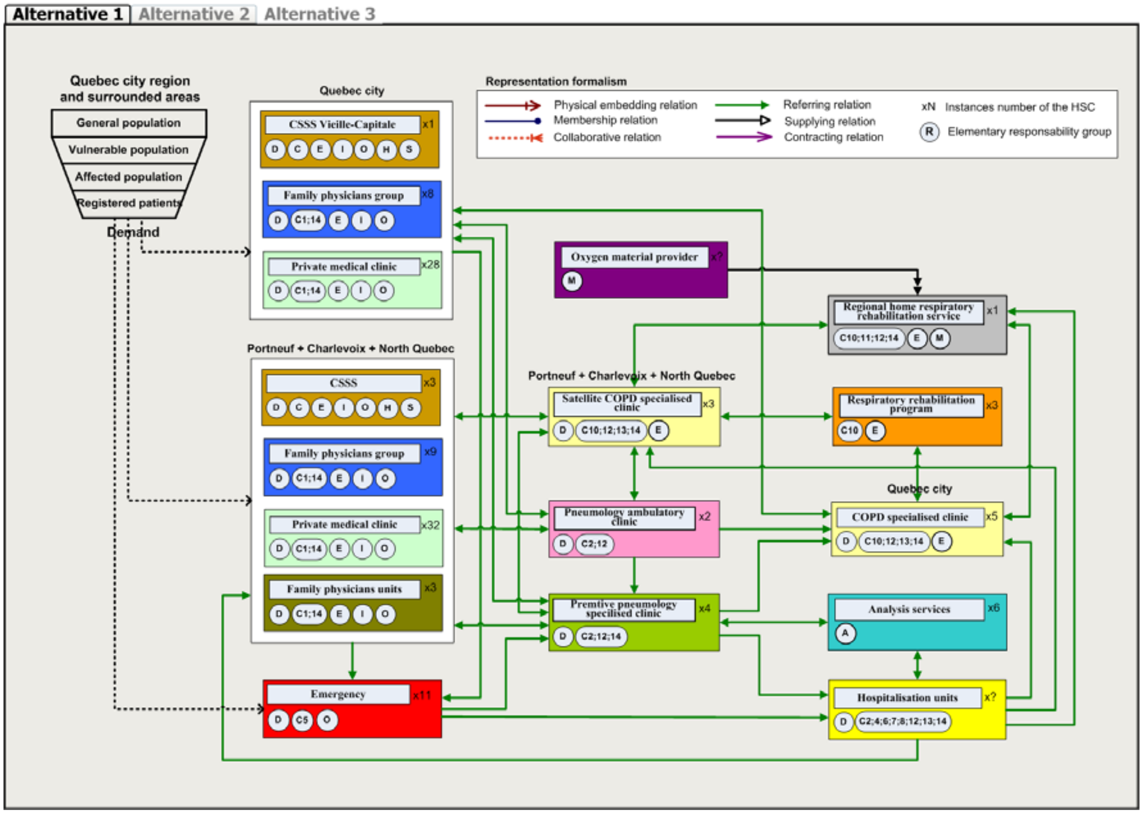


Fig.7: An alternative COPD regional network incorporating satellite COPD centers in remote areas

Scenario: Demand and Events/Crises

In the AOE[2] framework, a scenario contains all the externally specified nature and distribution of demand, event and crisis occurrences to be experienced in specific simulations.

Demand defines the simulation load that the system will undergo. Demand can be modelled at various levels. For example, demand can be expressed as the probability distribution of the quantity of each type of patients arriving, including their time and geographical dispersion. It can be expressed more deeply, for example through the stochastic modelling of health degradation of each individual in a population of potential patients, the implications of this degradation generating the demand in terms of patient arrivals. Beyond the arrivals, demand can also define the stochastic load generated in the system by each new arrival.

Typical statistic parameters defining demand for the CODP network field case are summarised in Table 8. Demand has been modelled through the exploitation of four population levels: general population, vulnerable population, affected population and registered population.

The general population includes the set of persons representing the overall population, distributed by region and having specific demographic characteristics. All these people are indeed potential patients. Each person in the population presenting one or more COPD risk factors has a probability to be considered as vulnerable. We obtain thus the vulnerable population.

The affected population includes the set of really affected persons who are derived from the vulnerable population using probability transitions for each COPD severity degrees : At risk, Mild COPD, Moderate COPD, Severe COPD. Also, we consider that each affected person may have a different behaviour when facing his manifested CODP symptoms. In our model, this behaviour depends on the age, educational level, number of symptoms, and accessibility to the health system evaluated by two factors: having a family physician and residing in a distant region. This permits to identify three main profiles:

1. Persons who are in an advanced stage of the disease and that have high probability of becoming urgent and semi-urgent cases within our health system;
2. Non-ambulant and ambulant persons that are prone to try to contact a health professional immediately or at least within the next three months. These people have generally a higher educational level and a relatively easy access to the health system.
3. Non-ambulant and ambulant persons that are less tempted to call a health professional. A delay varying from three to six months is added in this case before the persons enter the health system.

Moreover, each affected person has a probability of having his health status deteriorated and of thus ending up with a more advanced stage disease, and even to die if he’s already in the severe stage. These probabilities are lower if the person was already diagnosed having COPD disease and is under treatment or followed by a health network member. Note that in a simulation run a person having COPD will not be effectively recognized by the health system until he is diagnosed by a health professional as having COPD.

Once a COPD affected person enters the health system, he becomes part of the registered population. For these people, the health status deterioration probabilities and behavioural profile model are again used to calculate how frequently they will return requesting care from the system.

On another hand, when they are within a HSC within the network, patients have probabilities of needing a reference to another HSC depending on their health status (principally the COPD disease level). Table 9 shows the statistics for the example of HSC hospitalisation units. A margin of error is also added to these transitions probabilities to model the efficiency of the referring system and to enable evaluating its impact.

Probabilities and statistics feeding our demand model are derived from clinical and medical scientific studies about COPD disease and its evolution (Voll-Aanerud et al, 2007a, 2007b ; Carrasco Garrido et al., 2006), field experts evaluation (pulmonology specialists, clinical nurses specialised in COPD, health services managers), official statistics of the Quebec’s health and social services ministry, and data collected using the information system with the collaboration of our partners from Laval hospital in *Québec City*.

General population

- Total population : 648 730 persons
- Demographic characteristics

Residence location	*Sex*	*Age*	*Smoking habits*	*Education level*	*Exposure to pollutants*
Vieille-Capitale : 45,1 %	Women: 52%	<45 : 59,5%	Current Smoker : 28 %	Primary : 17%	Yes : 150%
Portneuf : 7,1%	Men: 48%	45-64 : 26,7%	Never smoker 31%	Secondary : 58%	No : 85%
Québec-Nord : 43,0%		65-74 : 7,8%	Ex-smoker 31%	University : 25%	
Charlevoix : 4,8%		>=75 : 6,0%			

Vulnerable population

- Considered risk factors : Age, Smoking habits, Exposure to pollutants
- 15 to 25 % of smokers develop a COPD disease
- 5 to 10 % of ex-smokers develop a COPD disease
- Persons aged 75 and more have additionally 75% of probability to develop COPD disease
- Persons of age group 65-74 have additionally 40% of probability to develop COPD disease
- Persons exposed to pollutants have additionally 60% of probability to develop COPD disease

Affected population

- 80 to 90% of COPD patients aged 75 and more are in moderate and severe COPD disease levels
- 70 to 80% of patients under 75 years are in the At risk and mild COPD disease levels

- Population having a family physician : 70%

- COPD disease manifestation

Main symptoms	*Number of respiratory symptoms*
Morning cough: 26%	0 : 47%
Chronic cough: 12%	1 : 21%
Phlegm cough: 26%	2 : 14%
Wheeze: 22%	3 : 8%
Dyspnoea attacks: 12%	4 : 5%
Dyspnoea grade 2: 12%	5 : 3%
	6 : 2%

- Deterioration of health status

	At risk → Mild COPD	Mild COPD → Moderate COPD	Moderate COPD → Severe COPD	Severe COPD → Death
Patients not already diagnosed as having COPD	60%	60%	80%	70%
Patients diagnosed with COPD who are under treatment or follow-up	20%	20%	30%	10%

Registered patients

- 1st profile patients (urgent and semi urgent) will immediately go into the system and have 90% of chance to go back.
- 2nd profile patients (non-ambulant and ambulant) will go into the system in less than 3 months, and have 40% of chance to go back.
- 3rd profile patients (non-ambulant and ambulant) will go into the system with a delay between 3 and 6 months, and have 40% of chance to go back.

Table 8: Typical statistics element of the demand model for COPD network case study

Inputs	%	Outputs	%
Emergency referrals	82,4%	Discharged patients (back to home)	36,5%
Premptive pulmonology specialised clinic referrals	14,6%	CSSS referrals	4,8%
Pulmonology ambulatory clinic referrals	2,0%	Family physicians referrals	31,0%
		Premptive pulmonology specialised clinic referrals	18%
		Dead patients	8,7%

Table 9: Example of the transition probabilities for COPD patients treated in HSC hospitalisation units

Events and **crises** model the perturbations that may occur in the simulated environment and that can influence components of the system. Healthcare environments are particularly prone to major events and crises affecting drastically its dynamic load. Events examples include the absence of a physician, a broken device, a lost document, etc. Crises are major events that are normally less frequent but have important disaster consequences. As examples, we can cite an epidemic, a general breakdown of the information system and a strike. Explicit modelling of external events and crises enable modellers to test the performance of the simulated system in terms of reactivity to such circumstances.

In our field case, it was decided to analyse the functioning of the network in case of the stochastic absence of key actors such as the general practitioner assigned to the COPD satellite clinic. It has also been decided to analyse the impact of a new law putting in place further measures to reduce the percentage of smokers within the population of Quebec.

Experience

The experiential component of the AOR^2 framework is directly associated with the simulation modelling objectives. It allows to answer the main question “What do we want to be able to do with our simulation model ?” that can be declined to two auxiliary questions: “What do we want to see and analyze during the simulation execution?” (interface), and “What are the finalities that we want to obtain from it?” (results). These two questions are answered by the modeller through the modelling of interface and result specifications.

Results : Dynamics and Performance

Dynamics refer to observations related to any continuous change, transition or progress of the agents, objects, process activities, and of environment states. Modellers need to define the healthcare system components which they want to observe and whose state evolution along the simulation horizon they want to analyze. These specifications drive the selection of views of simulation results according to the modelling objectives. For example, one may be interested in analyzing the dynamic travel patterns of a medical agent during the simulation in order to understand and then to optimise them. Dynamics analyses are of great utility for analysing the following aspects in healthcare systems, for example:

a) Flows and trajectories (of patients, resources or information);
b) Interactions between agents (cooperation or conflicts phenomena for example);
c) Punctual or short time phenomena (congestions during some periods of a clinic session, reaction immediately after an urgent case arrival, etc.)

In our field case, regarding the objective of the project, it was decided to put particular emphasis on analysing two key dynamic results: (1) the evolution of the patient trajectories (2) the dynamic information flows related to referrals between agents.

Performance is about the statistics and metrics that are to be generated by, and reported after the simulation execution, and that provide insights on the quality, efficacy and efficiency of the healthcare system given the modelled scenarios and systems. We can identify eight main types of performance indicators that are often used in the healthcare context:

a) Outcome indicators, relating to the impact on the health of the treated patients;
b) Time indicators such as patient waiting times, total patient time in the system, etc.;
c) Utilisation rates such as care provider utilisation, equipment utilisation, site utilisation, bed occupation, etc.;
d) Congestion indicators, for example, number of patients in waiting areas, number of patient within the system, etc.;
e) Quality indicators such as patient satisfaction, served patient rates, etc.;
f) Cost indicators such as care provider costs, equipment costs, unit costs, etc.;
g) Stock indicators for supplies, medicines, critical materials, etc.;
h) Complementary indicators for specific needs.

Indicators	Indicator type (unit)
Accessibility indicators	
Delay for taking over users referred to the satellite clinic by a family physician	Time (hour)
Delay for taking over users referred to the satellite clinic by a hospital	Time (hour)
Delay to get an appointment with the family doctor	Time (hour)
Delay to get an appointment with a medical specialist	Time (hour)
Delay for an initial assessment in rehabilitation	Time (hour)
Continuity indicators	
Utilisation rate of the inter-establishments demand for services computer system (DSIE)	Utilisation rate (%)
Number of requests for reference to the satellite clinic	Congestion (number)
Number of requests for reference from the satellite clinic	Congestion (number)
Number of COPD patients hospitalized	Congestion (number)
Number of COPD patients hospitalized for which a summary file is forwarded to the family physician	Congestion (number)
Number of registered patients at the satellite clinic referred to a medical specialist.	Congestion (number)
Services quality indicators	
Rate of COPD patients followed-up by a family physician	Quality (%)
Rate of COPD patients with a treatment plan	Quality (%)
Rate of COPD patients who have benefited from a rehabilitation program	Quality (%)
Rate of hospitalization for registered patients at the satellite clinic	Quality (%)
Number of transmission of the summary record post-hospitalisation to the family physician within a maximum delay of 5 working days following the date of departure	Quality (number)
Number of COPD patients hospitalised through the emergency	Quality (number)
Satisfaction rate of registered patients at the clinic satellite	Quality (%)
Satisfaction rate of physicians who refer patients to the clinic satellite.	Quality (%)
Management indicators for the new regional COPD satellite clinics	
Number of patients referred to the satellite clinic	Congestion (number)
Number of active patients followed-up at the clinic satellite	Congestion (number)
Average duration of follow-up	Time (hour)
Number of appointments made at the clinic satellite	Congestion (number)
Number of appointments with the family doctor	Congestion (number)
Number of appointments with Clinical Nurse	Congestion (number)
Number of appointments with the kinesiologist	Congestion (number)
Number of spirometry tests conducted by the satellite clinic	Quality (number)

Table 10: Performance indicators selected for the case study

Indicators can also be categorised in accordance with the modelling project objectives. For example, in our field case, since we are considering a regional network and that a main objective is to improve integration of the globally offered services to the population, we put strong emphasis on four main indicators categories: Accessibility indicators, Continuity indicators, Services quality indicators, Management indicators for the new regional COPD satellite clinics. These indicators, which are summarized in Table 10 above, were identified and validated with the collaboration of field professionals from Laval Hospital and the Agency for health and social services of the *Québec* region.

Interface: Animation and State mining

The Animation component of the AOE[2] framework refers to the visual representation of the modelled healthcare systems, including the agents, the objects and their environment, dynamically depicting their characteristics, including their properties, abilities, movements and behaviours. Specifications must clearly define the animated interfaces that the final user wants to see and analyse. The configuration of animated interfaces must respect the importance order of its different elements and must present them in simple, vivid, interactive and user friendly manners. For example, a geographic map may be used to present an extended health network while an architectural plan is more suitable for visualising a hospital building. As an illustration, Figure 9 gives the higher level of visual representation considered for our regional COPD network. This geographic mapping is developed using the Google Map API[2], integrated to our modeling platform.

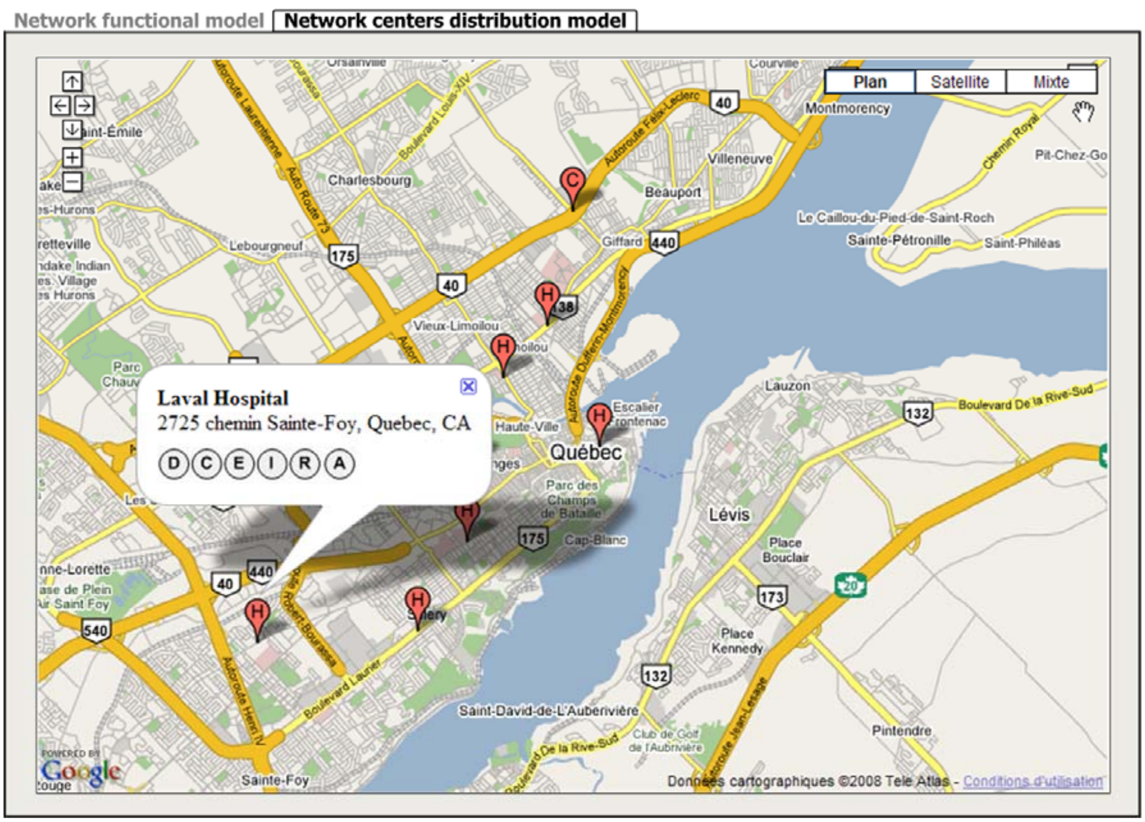


Fig.9 : Illustration example of a geographic visual representation for COPD regional network

State mining defines how deep the user wants to be able to dig into the dynamic state of the various agents, objects, processes, networks, etc., and how he wants to be able to perform this mining. The idea is that through drill-down techniques, it is possible to go from a general view integrating high level elements to more detailed views presenting in more depth a subset

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[2] http://code.google.com/apis/maps/

of these elements. While taking into account the simulation modelling objectives, modellers are required in this step to make a compromise between three main considerations:

a) The level of detail that final users want to reach in their analysis;
b) The navigation complexity between the interfaces, affecting the interface usability;
c) The system development costs.

Conclusion and future issues

In this paper we described a generic framework for agent-based simulation in distributed healthcare systems and discussed different alternatives in modelling each of its components using a real field case, the *Québec* regional COPD network. While other healthcare frameworks focus on technical issues for the design and implementation of agent-based simulation systems, our framework is concerned with more conceptual issues regarding a healthcare model development process and offers a reference guideline for carrying out this process independently of technical choices. Using this generic framework helps to accelerate the model development process for agent-based simulation in distributed healthcare systems and at the same time minimises risks of missing any critical element, concept or interaction. We are now investigating the extension of our agent-based healthcare modelling and simulation research to take into account the following possibilities:

- Developing a generic platform supporting the model development process using our framework;
- Developing and implementing protomodels of healthcare agents and objects, readily available for use and extension by modellers for embedding instances in healthcare simulations;
- Developing modelling techniques and tools adapted to each component of our framework, as for example a medical business process modelling technique for the processes;
- Exploiting our framework to drive empirical simulation-based analyses of focused healthcare case studies.

Concerning the *Québec* regional COPD network field case, a pilot project has been initiated through a collaboration between Laval hospital and Portneuf CSSS to establish a first satellite COPD clinic in Portneuf distant region. Through action research, we collaborate with the project leaders so as to develop an agent-based model and conduct simulation experiments to assess the impact of various design options on expected robust performance. Results from this action research will be the subject of subsequent papers.

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