AGENT-BASED SIMULATION TO SUPPORT DECISION MAKING IN HEALTHCARE MANAGEMENT PLANNING*

Hayden Stainsby[1], Manel Taboada[2] and Emilio Luque[1]
[1] *Computer Architecture and Operating Systems Department (CAOS),University Autonoma of Barcelona, Spain*
[2] *"Tomàs Cerdà" Computer Science School, University Autonoma of Barcelona, Spain*

Keywords: Healthcare operational management, Agent-based modelling, Individual oriented simulation, Emergency department, Decision support systems.

Abstract: Simulation has proved to be a useful tool in healthcare operational management, although up until now does not appear to have reached its full potential within this area. An area in which simulation is increasingly useful is as in aiding decision making of healthcare managers when planning constructing new Emergency Departments or making changes to existing ones. A simulation based on Agent Based Modelling techniques is proposed with an aim to produce a Decision Support System that takes into account the human and social factors present within such departments and that can also be generalised to be used in multiple hospitals. Work on the creation of this model has already began, with many of its concepts and structures presented.

1 INTRODUCTION

Throughout numerous years and a multitude of published work, simulation has been shown to be a very useful tool in healthcare operational management. Why is it then that it has seemingly failed to rise to the same level of importance as in other equally large fields such as supply chain management and the manufacturing industry. While many papers have been published on the topic, few have given detailed reports on the completed implementation of the simulation discussed(Fone et al., 2003).

A number of theories have been presented as to the reason for the current state of simulation in healthcare operational management. Many of these reasons are social or educational barriers rather than technical issues, some healthcare modellers have gone so far as to say that constructing the model may be the easiest part of implementing simulation in healthcare(Lowery, 1996).

One of the reasons simulation may have failed to gain a strong foothold in this area is the apparent dehumanising factor of simulation. Healthcare managers are also trained doctors, and the idea of reducing patients to numbers in a pool or tokens in a queue goes strongly against their training.

Another reason is the so-called "not invented here" syndrome(Brailsford, 2007). The vast majority of models described in the literature are created in conjunction with staff from the relevant department of a hospital, a practice that is advocated by most if not all healthcare modellers. However this can leave the model with a history that may give other institutions the impression that they're using a rehashed, second hand model. This can restrict the spread of what may be a valid generalised model further than the institutions for which is was originally created.

When it is considered that in many countries healthcare is nationalised and ultimately all hospitals are part of a single system under a single strategic leadership, it would appear unlikely that every one of these institutions is so different as to require its own individual model. To be certain, every institution has its differences, but these differences should be able to be described as differences in parameters and using a simulation as a component of a Decision Support System (DSS) in a new hospital should be a case of tuning it for its new environment rather than beginning the system analysis from scratch.

Emergency Departments, just like the hospitals they are within, are under increasing pressure to handle additional patients with the same or a reduced level of staffing. At the same time both technological and organisational changes are being proposed

*Supported by the MEC-Spain under contract TIN2007-64974.

Stainsby H., Taboada M. and Luque E. (2010).
AGENT-BASED SIMULATION TO SUPPORT DECISION MAKING IN HEALTHCARE MANAGEMENT PLANNING.
In *Proceedings of the Third International Conference on Health Informatics*, pages 436-441
DOI: 10.5220/0002739304360441

to improve the efficiency of these departments, but implementing these changes can be both costly and dangerous if their full effects are not completely understood. One recent study of the impact of technological changes on the running of an emergency department(Ayatollahi et al., 2009) showed that while the effects had been mostly positive, the introduction of computerised systems into the department had also caused additional problems, specifically in the learning phases and when the computer system experienced downtime.

This example highlights the need for modelling and simulation to try and measure the impact of these kinds of work flow changes in a specific department before they are implemented, not just technological changes but changes to staffing levels, patient numbers and arrival distribution, or operational procedures would all be cases where a DSS could be used to assist in planning for such occurrences. The type of Decision Support System that can be provided by computer simulation, and more specifically by Agent-Based Simulation, is perfectly suited to balancing the advantages and disadvantages of proposed changes, giving healthcare managers a better position from which to make these important decisions.

2 PRIOR WORK

As mentioned in section 1 there are a number of examples of the use of simulation in healthcare operational management in the literature. Within this area the types of models the simulations are based on can be split into two categories; department focussed models and hospital or region wide models.

The department focussed models most often use a technique called Discrete Event Simulation (DES), which involves simulating only the important events with a system. This is often characterised by a series of tokens that wait in turn for a server which process them before they continue on to the next part of the system.This method can be particularly well suited to predicting average waiting times of patients in emergency department settings(Connelly and Bair, 2004).

The hospital or region wide models are more generalised simulations that focus on the system as a whole. A popular simulation technique whose use in healthcare operational management began more recently than DES is System Dynamics (SD), which is often used to simulate these larger systems. An SD simulation does not model individuals, but rather the quantity of patients or resources in pools which represent combined waiting rooms, hospital beds, or some other place of rest for that entity. SD simulations can illustrate how changes in one department can have negative effects on other, apparently unrelated departments(Taylor and Dangerfield, 2005).

Another increasingly popular modelling technique is Agent-Based Modelling (ABM). This technique is used in biological simulations at both the macro level - for example the movement of a fish school(González et al., 2009) - and the micro level - cell behaviour(Walker et al., 2004) - as well as in the social sciences(Cederman, 2002). While ABM shows a lot of promise in being able to model the individual aspects of patients and hospital staff, up to this point the authors have been unable to find any reference to prior work involving the use of ABM in healthcare operational management.

3 DECISION SUPPORT SYSTEM

Making decisions about the current and future operations of even a small sized emergency department is a complicated and ever-changing task. One assistive measure in these circumstances is a Decision Support System(Wang et al., 2009). Such a tool, supplied with the correct input data can provide insight into the inner workings of a real world system that can be difficult, if not impossible to glean using traditional methods.

A DSS can take many forms, however its purpose is the same; given information from a current or proposed system and configured based upon the expectations of the user, a DSS should be able to process that information and present it in a form which aids the decision making process. This tool may be comprised of a single programatic aid, or a number of tools working in consort, although in this final case an additional layer may be required to package the information from all tools into a single coherent interface.

One example of a tool that is often employed as a Decision Support System component is simulation. A simulation, given correct configuration and input data can allow the user to discover the interrelated effects of changes in various parts of the system without the need to try these changes in a live environment, a definite advantage when the live system is so important.

The most effective Decision Support Systems are those were the users are the ones who gain the most advantages from the tool being in place.

The measure of the effectiveness of a Decision Support System is the advantages that it gives to the user of the system. In the case of a hospital emergency department this would be the manager or department head who is planning improvements to an existing department, or possibly even designing a new department. The goal of such a tool is to allow the individual to be able to adjust the the input parameters themselves and receive timely feedback on the effects of these changes in a form that they can easily interpret.

In order to provide meaningful output, a simulation based DSS must be able to describe a number of physical and abstract entities. Physical entities can be divided into two groups, the individuals, or agents, and the environment in which they interact. Individuals represent the patients and hospital personnel, while the environment is the emergency department itself and possibly operationally adjacent sections of the hospital. The abstract entities refer to the social and economic factors that are as just important as metrics such as how many patients can be processed by the triage department per hour.

A Decision Support System centres around answering questions in order to aid healthcare managers make the best informed decisions possible. Obviously asking the correct questions is an important part of the process, and in most cases these questions can be divided into two groups.

The first group are the simplest and require more interpretation on the part of the user of the DSS. These are the "what if...?" questions. Answering these questions is an attempt to divine what will happen to the system as a whole if one or more changes are made to the parameters that define it. In this case examples may be:

- *what if an additional triage nurse is present during the busiest period of the day?*; or
- *what if a flu epidemic raises the number of patients seeking treatment by 40%?*

While a manager may be able to answer some of these questions based on their own experience, there is the possibility that these changes will have additional and unexpected consequences which are more likely to be revealed by the process of simulation.

The second group of questions are much more complex, requiring both a better understanding of the system as well as additional definitions within the Decision Support System. These questions involve the optimisation of the system given certain parameters and indices. The additional definitions in the DSS are the indices involved, these may be concrete numbers such as total cost of personnel or may be much more fuzzy concepts such as patient satisfaction. Once these indices have been defined it is important to also define what value for these indices is considered optimal. Then the user of the DSS may ask how to optimise the system based on a group of indices, or how to optimise a given index while keeping another above a certain threshold.

These optimisation tasks can be incredibly time consuming on the part of the Decision Support System, especially when some of the indices under examination are represented differently from others. A system comprising of both quantitative and qualitative indices makes a simple formula based solution impractical and the required processing power usually increases dramatically. It is important to take into consideration that a DSS must provide timely feedback to a user.

When seen in the realm of healthcare operational management the system response time must allow the user to adjust variables and receive feedback while they are working, this will allow them to more easily understand the relation between what they have changed and the effects that change has on a system. To achieve this degree of responsiveness when simulating a large complex system it is quite likely that High Performance Computing (HPC) techniques, as provided by Cloud Computing, will form an integral part of the solution.

Decision Support Systems can be useful tools in aiding the decision making process, however it is important that they are easily usable by the people who are seeking answers from them and also must be able to produce results within acceptable time frames.

4 MODEL OF AN EMERGENCY DEPARTMENT

In order to solve the previously discussed problems a number of strategies are being used to create a general and validate-able model. Firstly the model is being constructed in a modular fashion. The model itself is comprised of a number of smaller sub models that comprise each of the main arenas of interaction for the individuals present in the system. The orientation of these sub models within the larger model is shown in figure 1.

Within the emergency department itself there are four main areas for interaction as shown in figure 1; Administration, Triage, Diagnosis / Treatment, and the Waiting room. There is also a fifth sub model that represents the laboratory tests, although this need not be modelled with the same level of precision at this time as it's unlikely to involve such complex human-human interactions, this multi-paradigm model type is explored further in section 4.1.

Five classes of individuals have been defined. These five classes are patients (ρ), companions of patients (ς), administrative staff (α), nurses (η), and doctors (δ). The individuals within these classes are also heterogeneous with respect to one another, which

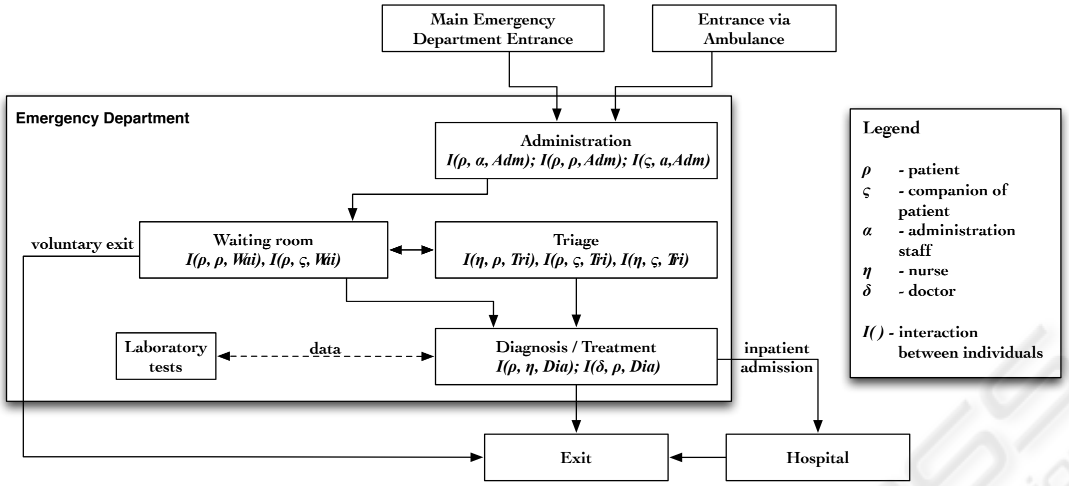

Figure 1: Overview of agent interaction stages within an emergency department.

is to say that each individual classified as a nurse also has their own properties unique to themselves amongst other nurses.

Interactions between two individuals is denoted by the function $I(x,y)$, where x and y represent the class of individual. The order is meaningful in the case of the interaction, the individual stated first (x in this example) is the initiator of the interaction. So an interaction between a doctor and a patient, initiated by the doctor would be denoted by $I(\delta,\rho)$.

The environment where an interaction takes place may well change the form and outcome of the interaction. When describing an interaction within the entire emergency department as a whole we extend the interaction function to include a location attribute as well, $I(x,y,\langle loc\rangle)$. To extend our previous example of an interaction between a doctor and a patient and specify that it is occurring within the diagnosis and treatment sub model we would define it like this, $I(\delta,\rho,Dia)$.

It is important at this stage to remember that what is being represented is the interactions between real people in real environments, a less technical description of the function defined here would be to say:

> *A doctor approaches a patient waiting in a bed in the diagnosis area to begin a discussion of the level of pain they are experiencing due to what appears to be a broken leg.*

The extra information given here is not lost in the model, nor the representation in function form, it is provided within the agents. It is an attribute of the patient that they have a broken leg and an attribute of the doctor that they are approaching the patient in order to discuss the level of pain resulting from this injury. Further details of the models of individuals are discussed in section 5.

4.1 Modular Design and the Multi-paradigm Approach

As stated previously, the model of the emergency department is made up of a number of smaller sub models. These design structure provides a number of advantages. The first is in breaking down the problem into smaller and more manageable sections. Each section has been separated out based on the interactions involved within it, more specifically which hospital staff are involved. While all staff will have a generalised idea of how the emergency department works the bulk of their knowledge is necessarily focussed on their own area. By dividing the sub models in this way the process of system analysis is simplified because staff from different areas can be interviewed separately, constructing each sub model in turn rather than trying to build everything at once.

This scheme of building each sub model separately also offers the advantages of unit testing, a popular method for separately verifying individual modules of code used in software engineering. Each sub model is built and then tested using sample or statistical data to verify that it is accurate within itself. This greatly reducing the time spent hunting for erroneous parts of the model if the whole model output is not what is expected once all the separate sub models have been attached to one another.

The third advantage of using a modular design for the model is the ability to create a multi-paradigm model in order to take advantage of modelling techniques that best suit each part of the system(Stainsby et al., 2009). The laboratory tests are a good example of where this brings an advantage. Because the focus of the model is the interactions the patient has while in an emergency department the laboratory is lacking in any significant form of interaction. From a patient's point of view, a sample is taken and at some point later it will be ready for collection. Each of these samples could be modelled as an individual, but this is really an unnecessary use of resources given that a laboratory sample has neither personality nor memory. In this case it may make much more sense to create a sub model defined by tokens waiting in a queue for their turn to be processed, the output of this is then returned to another part of the model where it is likely to invoke the action of an individual.

Each sub-model has various attributes and outputs which together form the larger picture of the reality of an Emergency Department. Therefore the sub-models may be made up of economic, logistic, and social models, as well as other information required to solve the optimisation questions of the DSS.

4.2 Social and Human Behavioural Factors

Social factors are an important part of all human interaction. A person may react differently to the exact same situation depending on their current state of mind, the environment they're in or a range of other factors. Many simulations do not take human factors into account, this can lead to results that are unable to fully represent all parts of an emergency department that are effected by human decisions.

Research has shown that social and behavioural factors can play an important role patient decision making with regard to healthcare, from as early in the process as whether or not they choose to seek out care to begin with(Brailsford et al., 2006). The complex social and psychological factors that drive the desires and beliefs of people are made many times more complex when they interact with others around them, it is these interactions that are important during the time a patient spends in an emergency department.

By using an agent-based model human behaviour can be modelled at the individual level, rather than the combination and average of all human behaviour across the simulation. This becomes more important when the interactions at one stage may effect the manner in which an individual acts in another stage, possibly creating behaviour changing feedback loops.

4.3 Generality of the Model

One of the possible reasons for the lack of mainstream take-up of simulation as a decision support tool in hospital emergency departments discussed previously is the idea that a model built for one department is not applicable to another. For this reason the model being developed is being done so in concert with more than one partner hospital. This has a two fold effect on the same issue.

The first is that by working with more than one department the differences and similarities will quickly become obvious, suggesting which parts of the model may be given default values and which need to be implemented as parameters so as to be easily changeable by the user at a given site. When it is said that some parts may be given default values, that may be easily changed in the future to accommodate different emergency departments in different hospitals. When it comes to creating the simulator this is already good programming practice and should not cause too many problems.

The effect is that the model can be shown to be applicable to more than one department from the beginning of its lifecycle. This reduces the perceived ownership and single use nature of the model just by it being used by multiple departments at the beginning of its life cycle.

5 MODELS OF AN INDIVIDUAL

While the modular nature of the model described in the previous section creates an architecture of models within a model, the use of Agent-Based Modelling creates yet another level. When using ABM each individual is essentially an instance of a model. The number of models used to describe the agents and their complexity depends on the level of detail required.

Each individual may be modelled using almost any modelling or control technique available, from simple algorithmic or boolean decision making to methods often not seen in modelling such as subsumption architecture. In fact it is quite possible to create individuals that are in fact controlled by their own Agent-Based Models, although logically this cannot go on forever.

In the model described in section 4, the actions of each individual are controlled by a Finite State Machine (FSM). The form of each FSM is dependent on the class of the individual (patient, companion of a patient, administrative staff, nurse, or doctor). Within each of these five classes the behaviour of an individual is determined by certain attributes which are assigned to them, giving each one their own individuality.

These models of individuals also govern the manner in which individuals interact, both with other individuals and with the environment in which they reside.

In the same manner as the indices used to define aspects of the real world system when using a Decision Support System, the attributes of an individual may not all be of the same type, nor may they all be static during the course of the simulation. Some values may be numeric in nature, such as how much blood a patient has lost, others may require fuzzy states to more accurately represent naturally occurring, non-numeric conditions such as human concentration.

These factors can be defined as either mutable or immutable attributes, representing factors that may or may not change during the course of the simulation respectively. Mutable attributes may represent such factors as the level of pain or stress experienced by an individual at a given moment or the short term memory of an individual with regard to their experiences within the simulated period. Immutable attributes may represent the level of training a nurse or doctor has, or the individuals ability to communicate based on their competence in the local language, these form the properties of the agent which are unlikely to change during the course of the simulation.

6 CONCLUSIONS

In the field of healthcare operational management it has been shown that simulation can be a useful tool. A number of examples exist in the literature, although the lack of results from complete implementations shows that simulation in this area has not reached its full potential.

A number of requirements for a general and verifiable simulation are presented. Starting from these requirements a new model has been created specifically to work towards creating a tool that can be used as a basic component of a Decision Support System which will be easily usable to healthcare managers to gain insight into the inner workings of current or planned emergency departments.

A key feature of this project is the use of Agent-Based Modelling techniques to both take into account the important social and psychological factors that come into play during human interactions in high stress environments such as emergency departments, but also to aid to reducing the dehumanising appearance of simulation tools from the point of view of healthcare managers.

The work on this model continues to proceed based on ongoing investigation and partnership with a number of hospitals.

ACKNOWLEDGEMENTS

We would like to thank Montse Edo for the detailed and invaluable assistance provided in describing the operations of the triage department where she works. Without the help afforded, this work would not have been possible.

REFERENCES

Ayatollahi, H., Bath, P. A., and Goodacre, S. (2009). It in the emergency department - what is the impact of technology? *Proceedings of the International Conference of Health Informatics (HEALTHINF)*, pages 454–457.

Brailsford, S. (2007). Tutorial: Advances and challenges in healthcare simulation modeling. *Proceedings of the Winter Simulation Conference*, pages 1436 – 1448.

Brailsford, S., Sykes, J., and Harper, P. (2006). Incorporating human behavior in healthcare simulation models. *Proceedings of the Winter Simulation Conference*, pages 466–472.

Cederman, L. (2002). Endogenizing geopolitical boundaries with agent-based modeling. *Proceedings of the National Academy of Sciences of the United States of America*, 9(3):7296–7303.

Connelly, L. and Bair, A. (2004). Discrete event simulation of emergency department activity: a platform for system-level operations research. *Academic Emergency Medicine*, 11(11):1177–1185.

Fone, D., Hollinghurst, S., Temple, M., and Round, A. (2003). Systematic review of the use and value of computer simulation modelling in population health and health care delivery. *Journal of Public Health*, 25(4):325–335.

González, J., Dalforno, C., Suppi, R., and Luque, E. (2009). A fuzzy logic fish school model. *Procc. ICCS 2009, LNCS*, 5544:13–22.

Lowery, J. (1996). Introduction to simulation in health care. *Proceedings of the Winter Simulation Conference*, pages 78 – 84.

Stainsby, H., Taboada, M., and Luque, E. (2009). Towards an agent-based simulation of hospital emergency departments. *Services Computing, 2009. SCC '09. IEEE International Conference on*, pages 536 – 539.

Taylor, K. and Dangerfield, B. (2005). Modelling the feedback effects of reconfiguring health services. *Journal of the Operational Research Society*, 56(6):659 – 675.

Walker, D., Southgate, J., Hill, G., and . . . , M. H. (2004). The epitheliome: agent-based modelling of the social behaviour of cells. *Biosystems*, 76:89–100.

Wang, J., Gwebu, K., Shanker, M., and Troutt, M. (2009). An application of agent-based simulation to knowledge sharing. *Decision Support Systems*, 46:532–541.