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A MODELLING AND SIMULATION FRAMEWORK FOR INTELLIGENT CONTROL OF EMERGENCY UNITS IN THE CASE OF MAJOR CRISIS

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ABSTRACT

A modelling and simulation framework for the performance evaluation of emergency units and intelligent control in the case of major crisis is proposed in this paper. Taking into account new challenges related to the optimization of the patient care pathway in the emergency unit in the context of major crises, we propose a flexible tool that can be used by health-care practitioners as a decision aid in various situations under the shape of a digital twin of the emergency unit. The modelling framework is based a modular model with specific representation of care pathways and resources activities. Various arrival processes are modelled in order to comply with the periodic variations observed in data history as well as exceptional massive arrivals that may be related to major crisis. A practical experiment is provided in order to determine the best available leverages to optimize the operations of the system.

1 INTRODUCTION

1.1 Context

The research field related to crisis management in health-care has received an increasing attention during the last decade. Organization of modern health-care systems in the context of a major crisis (earthquake, tsunami, terrorist attack) is crucial to manage all victims to give care as soon as possible and save as many lives as possible. In this context, new patient clinical pathways are created to face the drastic demand in case of such event; among those, the emergency unit is on the first line when a massive number of victims is brought to the hospital.

This work has been conducted in collaboration with a network of emergency units from various hospitals of the Saint-Etienne (France) territory, allowing the creation of a modular model of patient care pathway in the emergency unit. The goal of the project is twofold: (i) Propose an emergency unit digital twin using a flexible modelling and simulation framework to be connected to each hospital information system in order to retrieve the current state of the system; (ii) Propose a decision aid tool for the head of the emergency unit in order to react quickly in the event of massive arrivals of patients, related to recurrent situations (yearly epidemic) or exceptional situations (natural disaster, and in our case study, terrorist attack).

1.2 Literature Review

Discrete-Event Simulation (DES) has been widely used in the literature for modelling health-care systems for various purposes: performance evaluation, optimization, demand forecast… Comprehensive literature reviews (Jun et al. 1999; Fone et al. 2003; Günal and Pidd 2010) are available to obtain a complete landscape of the scientific contributions using such tool. In particular, DES has numerous advantages to model and analyze emergency units which are considered as complex systems with many special features such as: preemption of tasks, variable arrival rate of entities in the system, variable shift scheduling of human resources. Also, such system contains highly stochastic yet easily observable processes (Centeno et al. 2001; Miller et al. 2003; Glaa et al. 2006). Although a lot of articles describe specific yet complex models to achieve realistic results (Takakuwa and Shiozaki 2004; Duguay and Chetouane 2007), some studies propose generic models supposed to be transferred to other hospitals (Sinreich and Marmor 2004). Simulation has also been used to propose control strategies for emergency services taking into account costs (Prodel et al. 2014) or patient satisfaction (Pehlivan et al. 2013).

1.3 Scientific Contribution

The main contribution of this article consists in providing a flexible performance evaluation framework for emergency units connected to the information system of the hospital in order to automatically set up the model and simulate activities of the unit depending on predefined scenarios. Such approach allows hospital manager to: (i) monitor the activity of the emergency unit using a dynamic connection with the information system of the hospital; (ii) test the impact of long-term organizational decisions to improve the performance of the system depending on a certain set of settings; (iii) anticipate a major change in the unit activity and choose the best decision to optimize the operations of the unit during a crisis. The framework is flexible thanks to an underlying modular model that can be customized depending of the organization of the service under study.

This paper is organized as follows: the emergency unit modelling and simulation framework is described in Section 2 along with the contributions of the approach regarding the demand of health-care practitioners. Section 3 describes the underlying modular formal model of the emergency unit based on UML. The design of experiment and numerical results are presented in Section 4. Finally, conclusions and perspectives are given in Section 5.

2 EMERGENCY UNIT MODELLING AND SIMULATION FRAMEWORK

2.1 Architecture of the Framework and Features

In this paper we propose a new framework for the modelling and simulation of emergency units, as illustrated in Figure 1. The framework itself consists in a modular simulation model connected with a process analyzer tool, allowing the design of experiments based on requirements of the health-care practitioners. The simulation model is modular rather than generic, in order to be used in every hospital of the network. To do so, a formal model of the patient process and of the resources activities is proposed (Section 3). The modelling and simulation framework is fed with two types of data: (i) the hospital information system, which provides the initial state of the model through the number of patients in the three care pathways depending on the health state of the patient and of the nature of his/her injuries, and through the capacity of resources (doctors, nurses, care givers, boxes and some diagnosis facilities such as imaging device); (ii) the arrivals forecast which may be available at certain time depending on several factors:

- GP network alert: the French GPs Sentinelles network provides a continuous surveillance of health indicators in order to detect epidemics of influenza and gastroenteritis.
- Crisis alert: the emergency unit is alerted in advance (few hours) when a major crisis occurs, related to a natural disaster, a major car accident or a terrorist attack for example. In that case, it is possible for the health-care professionals to take actions before the massive arrival of patients (such as activating the white plan, a French disaster plan intended to provide more resources towards medical sanitary civil defense).

- Transfer of patients from another hospital of the network: in the event of a massive arrival of patients in a specific hospital, the emergency network encourages collaboration between emergency units in order to balance the load of all units.
- Heavy load in other services of the hospital: if medical units of the hospital are full, it is impossible to transfer patients from the emergency unit. In that case, the patient must remain in the short stay unit of the service.

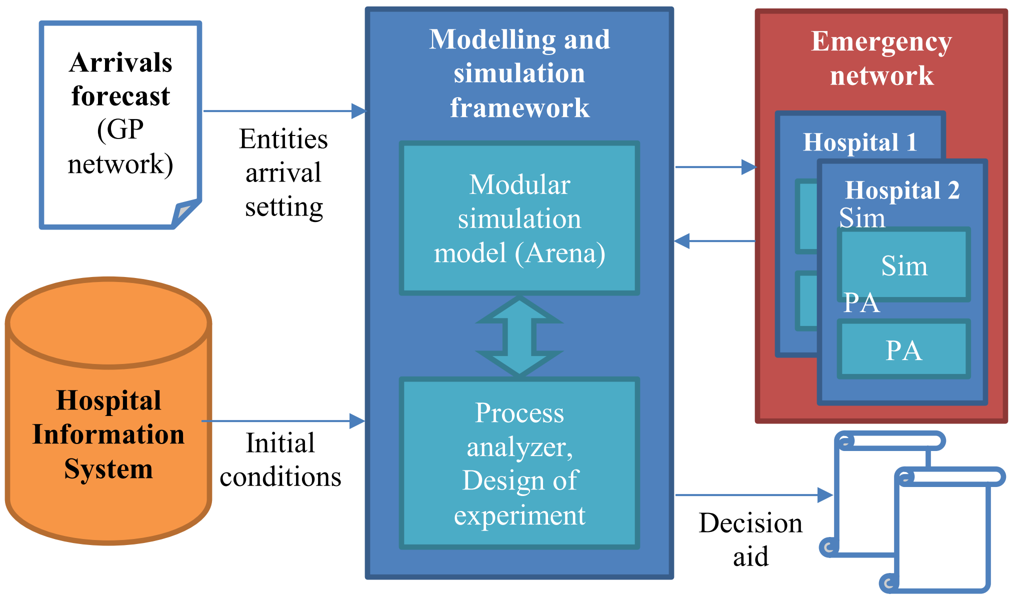

Figure 1: Architecture of the emergency unit modelling and simulation framework.

Once the simulation model is initialized, the framework is ready to be used. The following execution modes have been designed, following the recommendation of the health-care professionals:

- **Provide a "best scenario" and "worst scenario"** depending on patient arrival and initial setting in order to anticipate the length of stay of patients in the unit depending on the care pathway and the resource occupancy.
- **Provide a comprehensive design of experiment** featuring main decisions to take in order to reduce patient length of stay and service occupancy rate at the level of the hospital: we consider that the internal organization of the emergency unit is already optimized, all available actions to decrease patient length of stay are related to tasks requiring external expertise (surgeon notice) or resources/paraclinical examinations (hospital beds, MRI, biological examination).
- **Provide a decision board in the case of a crisis** in order to determine quickly the best actions to take in order to treat as many patients as possible. The simulation model can be set up in order to inject a higher number of patient in critical state. In that case, additional actions are available, such as reducing the conditioning of the patient after his/her arrival in the unit.

2.2 Contributions of the framework

The framework has been conceived and tested in close collaboration with health-care professionals in order to be as close as the real system as possible. Also, the framework is intended to be used regularly by the head of the emergency unit. In this context, the following contributions constitutes true innovation in the use of DES for emergency unit analysis, modelling and simulation:

1. **A modular formal modelling of patient care pathway and resources activities:** the model has been formally defined using UML and is organized around different views (related to entities and resources activities) and modules (related to the different care pathway of patients in the unit). The concept of a generic model has been abandoned as it required custom modifications depending on the system under study.
2. **A decision tool based on dynamic arrival process of entities to model patient admission:** since the framework has been developed in order to deal with (i) regular arrivals, (ii) exceptional but predictable arrivals and (iii) massive arrivals related to major crisis, the arrival process of the simulation model has been defined in order to follow a variable Poisson process close to the regular variations of patients arrival during a day and during a week, but also supplementary arrival processes have been integrated to model special behaviors. Practitioners and hospital managers can use the tool as decision aid: in the case of a major crisis, practitioners will be able to decide among various leverages the most efficient one for the present situation (e.g. extraordinary transfer of additional beds for a certain period).
3. **An automatic setup of the framework using a connection with the hospital information system:** the model is intended to be automatically setup in order to take into account the number of patients in the system, the occupancy of resources, and the history in order to predict future arrivals in the week.

2.3 Hypothesis

The following assumptions are fixed by the hospital organization and are integrated in the model:

(H1) Three care pathways are modeled as personalized modules: (i) low priority patient (non-severe) with a care pathway including low technicity tasks (bandage, plaster), denoted **UF**; (ii) low priority patient fast care pathway, denoted **UFR**; (iii) high priority patients, requiring strong medical expertise and eventually additional expert notice and examinations; life-threatening emergencies are included in that care pathway, denoted **UG**.
(H2) For all external resources of the emergency unit, waiting times are modelled using an observations in the service: since such resources are shared among different medical units, it is not possible to model precisely the capacity and occupation of such resources. Data provided by the hospital information system is not reliable and should not be used as-is in the simulation model. All tests are replicated using two distributions: triangular (when durations are based on minimum, maximum, and most observed values) and exponential (when durations are based on an average and expected to be very long). The following resources requests have been modelled in this way: MRI (Magnetic Resonance Imaging), surgeon notice, biological tests analysis and interpretation, beds in medical services of the hospital (for the follow-up of patients). Such hypothesis is justified by the fact that in the case of major crisis, supplementary resources could be requested (such as additional beds, or external practitioners); in that case, we want to simulate the impact of having a reduced waiting time for external resources, and subsequently decide whether activating an emergency plan.
(H3) Arrivals are generated every four hours in the model using a variable Poisson distribution. Exact arrivals time are then randomly generated over the four-hour time slot using a uniform distribution. The duration of the time slot (four hours) have been chosen following the evolution trend of patients arrival in the emergency unit (morning: 8am-12pm, afternoon: 12pm-4pm, evening: 4pm-8pm, 8pm-12am, night: 12am- 4am, 4am-8am). According to health practitioner, such modelling approach is sufficient to simulate arrivals variability. A shorter interval could be implemented for very specific arrival patterns requiring additional hypothesis.

3 MODULAR FORMAL MODELLING OF THE EMERGENCY UNIT

3.1 Formal Modelling using UML

In order to provide a clean and modular representation of the various activities of the emergency department, we use the modelling framework MedPRO based on UML state charts described in (Augusto and Xie 2014): this approach is based on a meta-model with three different views: process view (care pathways of patients), resource view (activities of relevant resources), and organization view (dependencies and organization of resources). The resulting meta-model can be instantiated for a specific health care system and be converted into executable model for simulation. In this study, we focus on process view (three care pathways of patients in the emergency department) and on resource view (activities of doctor, intern, nurse and care giver). This method has been efficiently used for other services such as the pharmacy department logistics (Augusto and Xie 2007).

The Process view is presented in Figure 2, whereas the Resource view related to a Doctor and a Nurse are presented in Figure 3 and Figure 4. Due to space limitations, we will not present the diagrams related to the Intern (highly similar to the model of the doctor) and to the Care giver (responsible for numerous unique tasks dependent on the nurse activities). All diagrams are state charts: entry points are modelled using a filled circle whereas exit points are modelled using empty circles. States model activities performed on/by the patient/the resource. Blue states means that the task in present in both process and resource view. Orange states means that the task is synchronized among different resources.

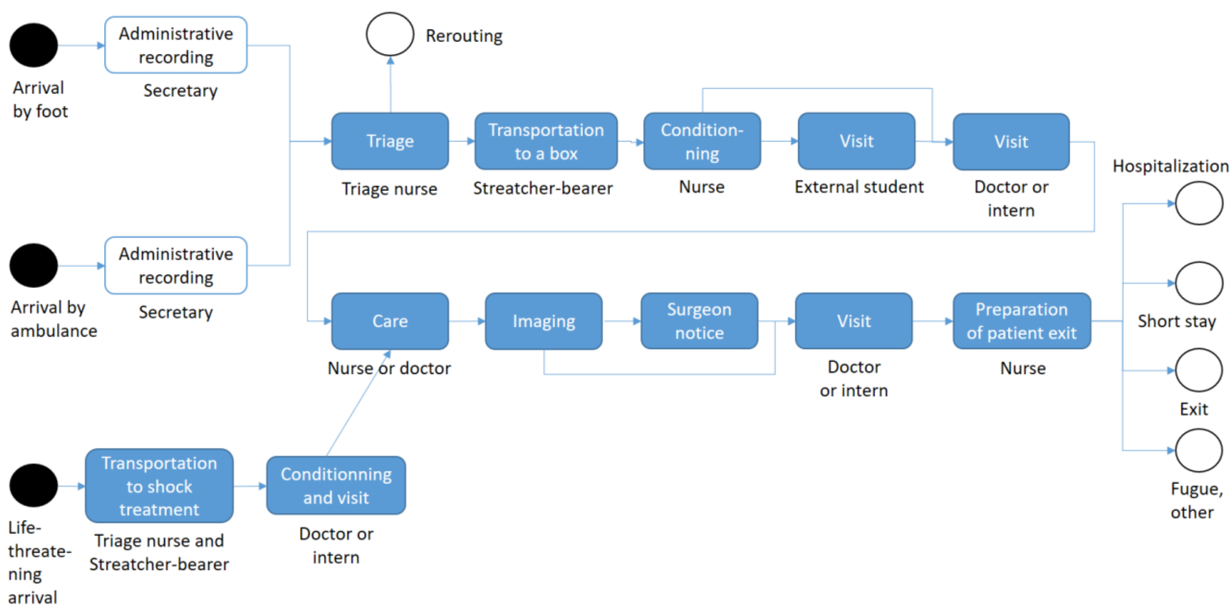

Figure 2: Process view – Patient care pathway.

The patient care pathway is described in Figure 2. The patient may arrive in the emergency unit either by foot or by ambulance. We distinguish arrivals of patients in critical state (life-threatening emergency). The regular pathway is modelled in the following way: after a triage performed by a dedicated nurse (triage nurse), the patient is transported to a box by a stretcher-bearer and is conditioned by a nurse. Eventually, a first visit is performed by a junior doctor (external student). The main visit is then performed by a doctor or an intern, depending on the required experience. The patient is given care by a nurse or a doctor (when high level technical care is required). Additional paraclinical examinations are requested such as Imaging (CT scan or MRI) and eventually a surgeon notice. Based on the paraclinical examinations, a second visit is performed by a doctor or an intern, and finally the patient is prepared by a nurse for departure to a medical unit of the hospital, the short stay unit of the emergency department, or return to home. Fugues may also happen. For patient in critical state, the patient is directly transferred to a dedicated box for shock treatment, and the conditioning is performed as soon as possible by a doctor.

Activities of a doctor are presented in Figure 3. In the MedPRO approach, activities of resources are grouped together using the concept of "missions". In the case of the doctor, we enumerate five missions: (1) Read the medical record of waiting patient at the beginning of the doctor shift. (2) When a new patient arrives, a visit is performed and tasks are given to other workers such as nurses. In case of complex care, the doctor is solicited, otherwise he/she realizes a synthesis of the clinical examination performed during the visit. (3) When requested paraclinical examinations are available, the doctor performs a synthesis and a second visit, before giving recommendations for patient routing (including paper work, phone calls…). (4) When a new patient arrives (life-threatening emergency), the doctor performs the visit at the same time as the conditioning and reads the medical record of the patient afterwards. The following tasks are identical as in mission (2). (5) The doctor takes a break after a certain period of work.

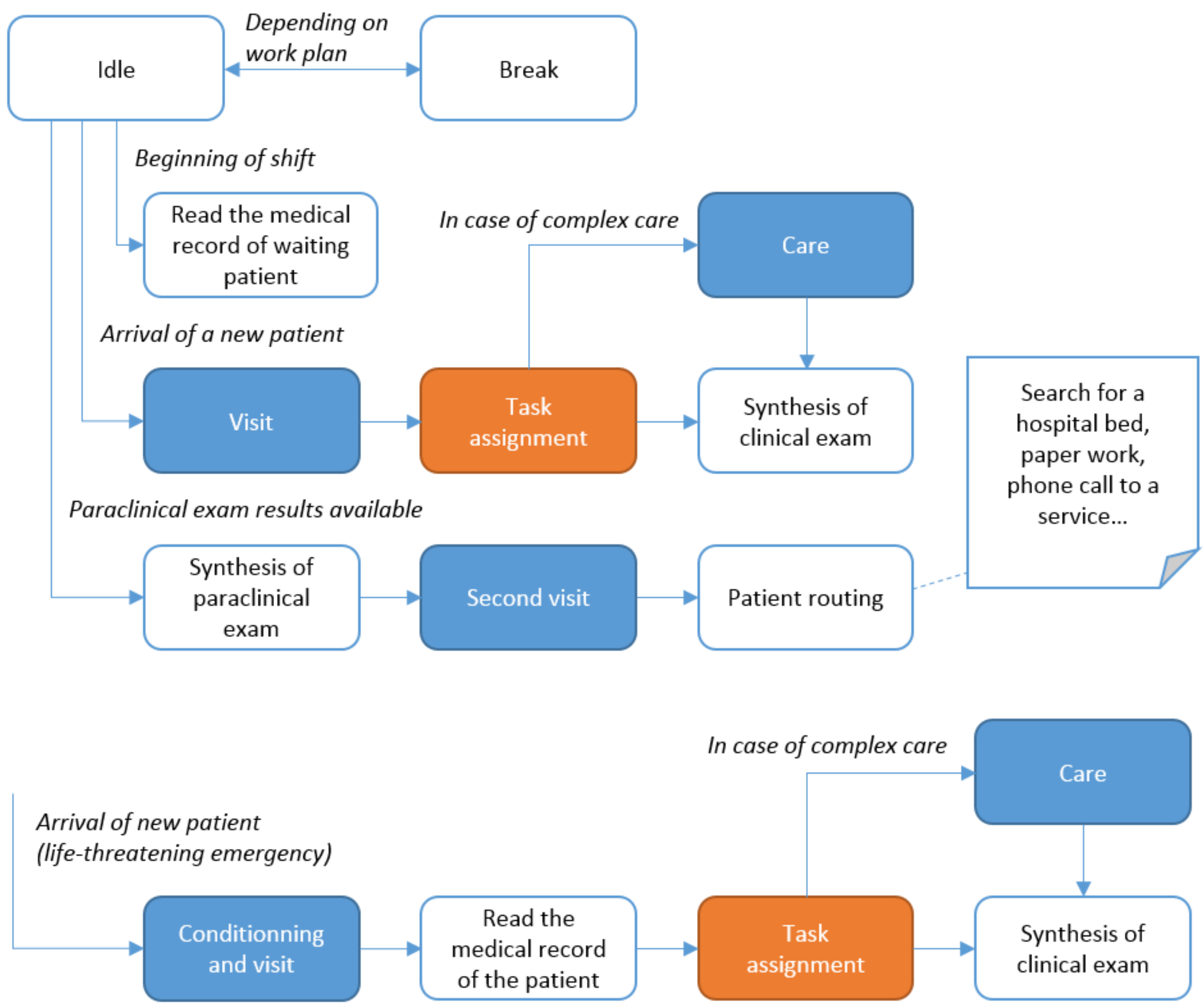

Figure 3: Resource view – Doctor.

Activities of a nurse of the emergency unit are presented in Figure 4. Missions are: (1) Regular visit of all patients (based on a predefined schedule). (2) When a patient arrives, the nurse is responsible for his/her conditioning. Then the nurse is given instructions by the doctor, prepares the treatment and gives care to the patient. (3) When a patient is about to leave, some paper work is required. (4) When the second visit of a patient is finished, the nurse prepares the patient for a transfer out of the emergency unit.

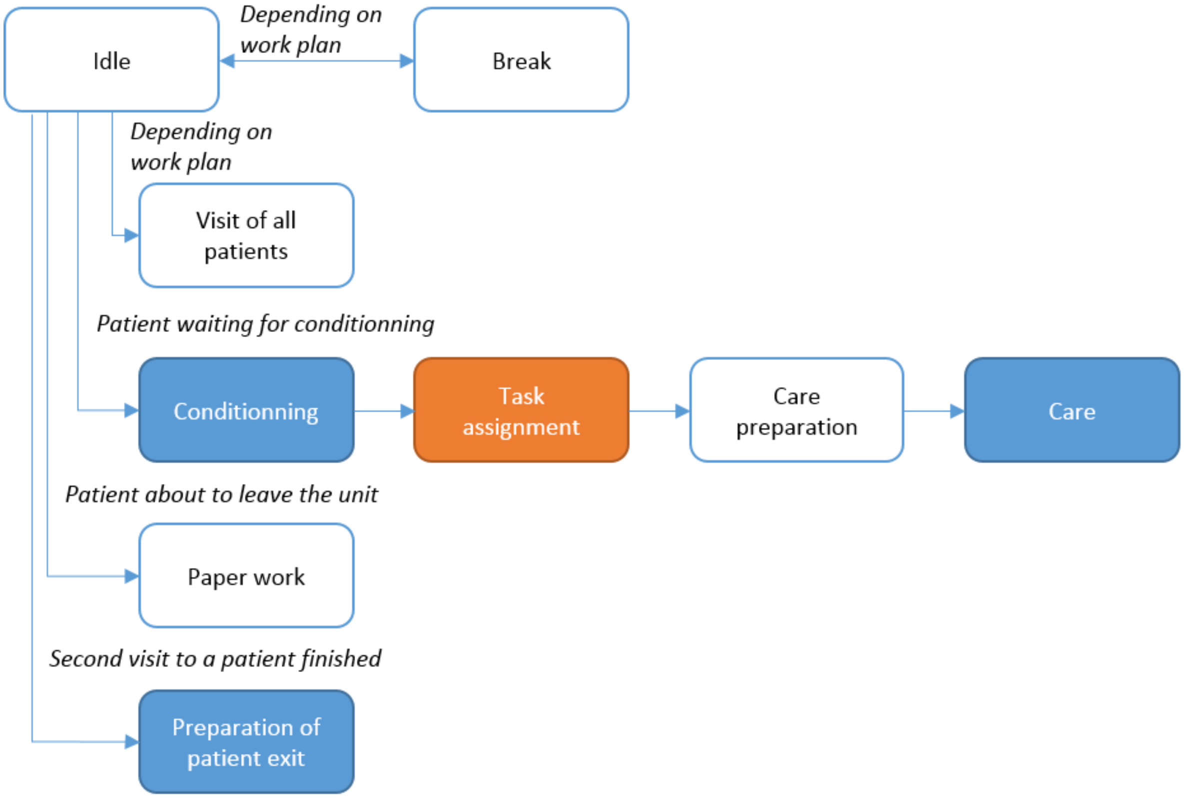

Figure 4: Resource view – Nurse.

3.2 Data Collection

Data collection was performed using the hospital information system for the following values: patient arrivals, total length of stay, type of patient (low criticity (fast and normal track), medium criticity and life-threatening emergency), number of requested paraclinical examinations per patient. On the other hand, processing times were collected by interviewing doctors, nurses, care givers and interns since the related data in the hospital information system were not reliable enough. For each activity and for each type of patient, we collected a minimum duration, a maximum duration and a most observed duration in order to use triangular distributions. For waiting time of paraclinical examinations, minimum, maximum, most observed and average values were collected to use both triangular and exponential distributions. We did not estimate theoretical distributions since we could not get enough data to ensure statistical validity.

4 NUMERICAL RESULTS

4.1 Model Validation

The model has been validated by the head of the emergency unit and the appropriate modules have been selected to mimic the behavior of the real system. The model has been implemented using ROCKWELL Arena® 14.5. To validate the model, a validation scenario has been established using as input a real dataset of patient stays in the emergency unit over a year. A setting corresponding to the real system has also been calibrated. The following key performance indicators have been selected to validate the simulation model: (i) the average length of stay of patients in the various care pathways (UFR, UF, UG) (ii) the distribution of length of stay, and (iii) the number of patients in the service each four hours.

4.2 Design of Experiment and Simulation Settings

A design of experiment has been established with several objectives, as described in Section 2.1 (execution modes) and presented in Table 1:

1. Compare three base scenarios: best case, worst case, and validation scenario.
2. For a regular behavior of the system, determine the best decisions to optimize the operations of the emergency unit.
3. For an exceptional conditions (massive arrival of patients in the emergency unit following a crisis), determine the best decisions to minimize patient length of stay and avoid massive crowding of the system.

Table 1: Design of experiment (A,B,C: exponential waiting time; D,E: triangular waiting time *).

Scenario	Replication count	Replication length	Waiting time before hospitalization*	Waiting time before hospitalization for vital patients*	Waiting time for surgeon notice*	Waiting time for imaging results*	Waiting time for imaging results for vital patients*	Inclusion of psychiatric patients	Inclusion of additional patients	Arrivals (1:real,0:Poisson)	Conditioning duration for vital patient (min,mod,max)			% of vital patients	Additional arrivals of patients	Inter-arrival of additional patients
A-1 Ideal	10	8640	120	25	15	30	15	NO	NO	0	24	30	36	1.73	0	30
A-2 Real	10	8640	240	45	60	90	30	YES	YES	0	24	30	36	1.73	0	30
A-3 Valid	10	8640	240	45	60	90	30	YES	YES	1	24	30	36	1.73	0	30
B-1 (D-1)	10	8640	180	45	60	90	30	YES	YES	0	24	30	36	1.73	0	30
B-2 (D-2)	10	8640	240	25	60	90	30	YES	YES	0	24	30	36	1.73	0	30
B-3 (D-3)	10	8640	240	45	60	30	30	YES	YES	0	24	30	36	1.73	0	30
B-4 (D-4)	10	8640	240	45	60	90	15	YES	YES	0	24	30	36	1.73	0	30
B-5 (D-5)	10	8640	240	45	15	90	30	YES	YES	0	24	30	36	1.73	0	30
B-6 (D-6)	10	8640	240	45	60	90	30	NO	YES	0	24	30	36	1.73	0	30
B-7 (D-7)	10	8640	240	45	60	90	30	YES	NO	0	24	30	36	1.73	0	30
B-8 (D-8)	10	8640	180	25	60	90	30	YES	YES	0	24	30	36	1.73	0	30
B-9 (D-9)	10	8640	240	45	15	30	15	YES	YES	0	24	30	36	1.73	0	30
C-1 (E-1)	200	816	180	25	15	30	15	NO	NO	0	24	30	36	17.30	1	60
C-2 (E-2)	200	816	240	45	60	90	30	YES	YES	0	24	30	36	17.30	1	60
C-3 (E-3)	200	816	120	25	60	90	30	YES	YES	0	24	30	36	17.30	1	60
C-4 (E-4)	200	816	240	45	60	90	30	YES	YES	0	8	10	12	17.30	1	60
C-5 (E-5)	200	816	120	25	60	90	30	YES	YES	0	8	10	12	17.30	1	60
C-6 (E-6)	200	816	120	25	60	30	15	YES	YES	0	8	10	12	17.30	1	60

The settings of the design of experiment are summarized in Table 1. Apart from the number of replications and the replication length, the following parameters are varied in the design of experiments: paraclinical exam waiting time (parameters 3, 4, 5, 6, 7); arrival of supplementary patients (parameters 8, 9); arrival distribution (parameter 10); conditioning duration for vital patients (parameter 11); ratio of life-threatening emergencies (parameter 12); finally, for crisis scenarios, we also introduce potential additional arrival of patients with specific inter-arrival time for exponential distribution (parameters 13 and 14). Three groups of scenarios are defined : A for base scenario comparison, B for optimization of the system, C for decision aid in the event of a crisis. All scenarios are replicated twice to test the impact of triangular distributions instead of exponential for waiting times. Actions corresponding to the scenarios are related to the impact of: (B-1) Reducing waiting time for a bed; (B-2) Reducing the waiting time for a bed for vital patients; (B-3) Reducing waiting time for imaging exam; (B-4) Reducing waiting time for imaging for vital patients; (B-5) Reducing waiting time for surgeon notice; (B-6) No psychiatric patients in the unit; (B-7) No daily additional patients; (B-8) Reduction of total waiting time for a bed; (B-9) Combination of (B-3) and (B-5). In the case of a crisis management we simulate a massive arrival of vital patients during four days in the unit: (C-1) Ideal system, no action taken; (C-2) Real system, no action taken; (C-3) Reducing waiting time for a bed; (C-4) Reducing patient conditioning duration; (C-5) Combination of (C-3) and (C-4); (C-6) Combination of (C-5) and reducing waiting time for imaging. Such actions are related to the activation of emergency plans that can be triggered by health practitioners.

For scenario groups A and B, replication length is equal to one year and the number of replications is equal to 10. For scenario group C (related to crisis management), the replication length is equal to 34 days whereas the number of replications is equal to 200. For all scenarios the warm-up period is equal to 30 days. All results are presented along with error bars corresponding to a 95% confidence interval. Note that the number of replications is high for scenarios C because the crisis length is short (4 days in our tests).

4.3 Key Performance Indicators

The following key performance indicators have been selected to evaluate the performance of the model:

1. Length of stay for every care pathway in the emergency unit (including waiting time for a hospital bed).
2. Duration of care activities for each care pathway.
3. Average number of patients present in the emergency unit at any time.
4. Human resources occupancy rate.

Scenarios are evaluated based on these performance indicators in the next Section. For validation of the model, length of stay and unit occupancy are preferred to be compared with history values from the hospital information system.

4.4 Discussion

The main indicator (length of stay) is presented in Figure 5. For scenario group A, as expected, the ideal model is the best scenario and provides a lower bound for that KPI. For scenario group B, the best decisions to improve the LOS are (B-6) (psychiatric patients routed to another unit) and (B-1) (Reducing waiting time for a hospital bed). Reducing other waiting time for paraclinical exams provide also good results. For scenario group C, the best improvement is obtained by action (C-6), when all paraclinical exams waiting times are reduced, although (C-3) has the highest impact (Reducing waiting time for a hospital bed). Figure 5 shows that care activities are longer in the case of UF, which is also expected since patients are less urgent and care process might be longer. Figure 6 shows the average number of patients in the emergency unit: here again, psychiatric patients as well as waiting duration for a hospital bed have the highest impact on that KPI. Also doctor occupancy is presented in Figure 6: we see that the occupancy rate is not significantly different across all scenarios (except for A-1 and C-1), which means that the increasing the number of human resources in the system might not improve the performances. The same trend has been observed for other human resources occupancy rate.

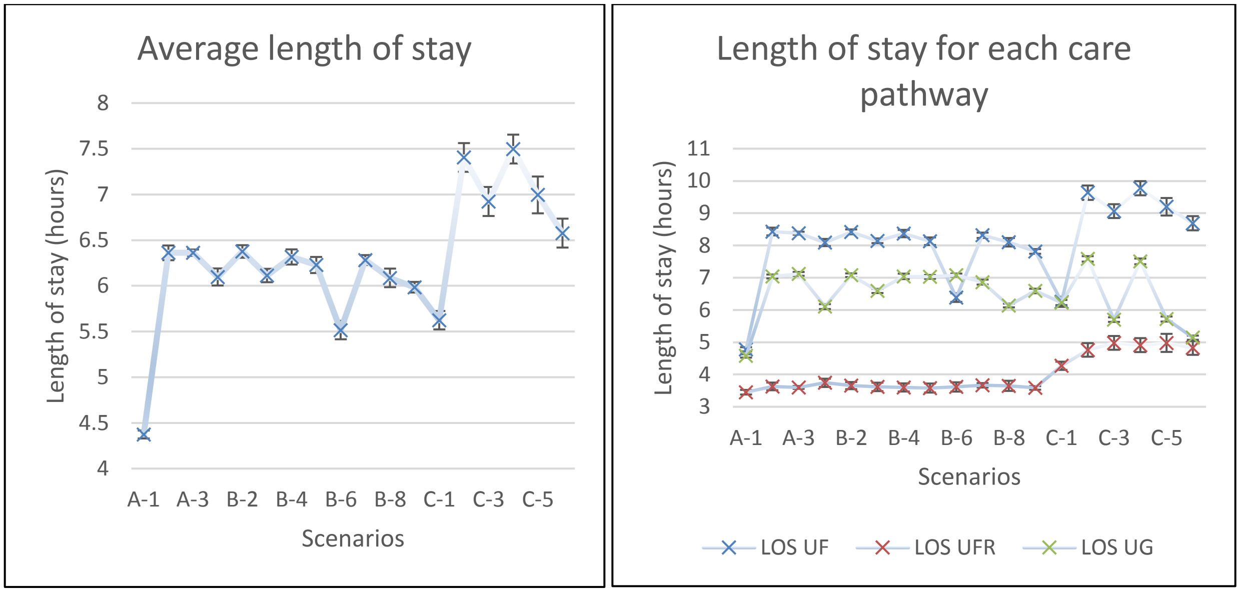

Figure 5 : Average length of stay in the emergency unit.

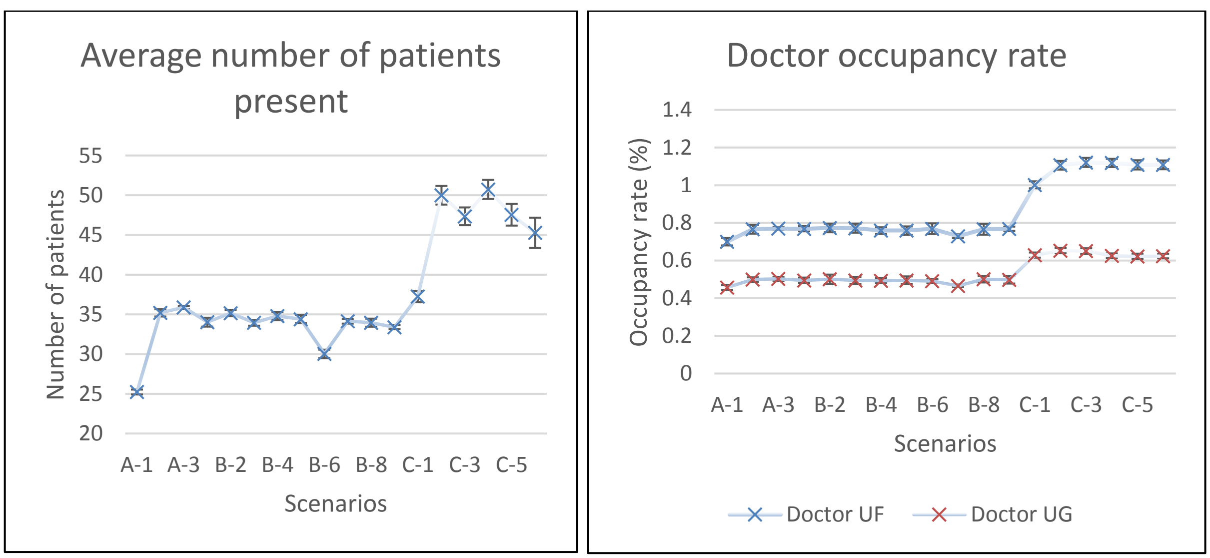

Figure 6: Average number of patients in the emergency unit and doctor occupancy rate.

5 CONCLUSIONS AND PERSPECTIVES

In this paper we provide a framework for the modelling and simulation in order to monitor and control the emergency units in the event of a major crisis. The proposed framework includes the following innovative features: (i) modular models which are centered on patient care pathway and health-care professionals activities through the use of a special class of UML state charts: such approach allow a high reusability of the framework across different hospitals; (ii) a dynamic connection to the hospital information system, in order to import automatically initial settings for the simulation; (iii) a wide range of arrival models in order to mimic the arrival scheme depending on the scenario under study and on the usual variations during the day. Finally the provided tool is intended to be used in the emergency unit by health-care practitioner as decision aid for the management of the service and the activation if required of exceptional measures in the event of crisis. Examples of results have been presented to show the diversity of the experiments that can be conducted with the tool.

For future works we intend to include a predictive algorithm in the model in order to propose precise arrival forecast using data history. Such feature would allow health-care practitioners to use the tool as a short notice decision aid. Robust optimization is another lead to study intelligent control of emergency units along with our simulation model. Also the framework needs to be tested in more hospital emergency units to assess its flexibility and robustness.

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