A customizable Agent-Based Simulation Framework for Emergency Departments

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Abstract. Emergency Departments (EDs) face increasing complexity due to rising patient demand, resource constraints, and the need for efficient service coordination. Traditional simulation models, while useful, cannot be easily adapted to a different hospital environments, making it difficult to transfer and scale solutions. Based on previous work, with a simulator working in a hospital, this work describes a modular Agent-Based Modeling and Simulation (ABMS) approach for increasing flexibility adaptation and reuse in ED simulations. The proposed technique, which deconstructs existing models into individual components, will allow hospitals with different workflows and operational constraints to construct customized simulations. To validate this methodology, we develop a structured, modular framework using NetLogo and Python. The suggested metasystem enables adaptive simulation-based decision assistance for emergency departments, which improves resource allocation and operational planning.

Keywords: Agent Based Modeling · Emergency Departments · Modular Simulation Framework · Resource Optimization · Adaptive Healthcare Modeling.

1 Introduction

Emergency Departments (EDs) face challenges such as growing patient demand and complexity of service, which requires careful coordination of staff and resources [11,6]. Simulation helps analyze complex systems under predictable and unpredictable conditions. This article presents the key principles and one experimental design of a basic ED using an Agent-Based Modeling and Simulation (ABMS) framework. Unlike the previous works, which obtain a tool that have

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been designed to be applied in a specific ED, and it is difficult to adapt for being applied in others, the proposal is based on a modular system, which improves the design and allows reuse of the different elements, enabling the computational models can be applied in multiple EDs that have different operation.

Simulation becomes a useful Decision Support System that allows the analysis of different types of situation and also obtains data that are difficult to obtain in reality, answering 'what if' questions to predict real-life system outcomes [8]. There are several techniques to model and simulate a system, but when we talk about ED, in the literature, we find references mainly of two of them, Discrete Event Simulation (DES) and ABMS. For system flow analysis, DES is the most commonly used method, while ABMS offers a more dynamic and detailed perspective by modeling the behavior and interactions between multiple individual agents, such as patients, doctors, nurses, and their environment. One of the important characteristics of ABMS is the "emergent properties", in other words, "the higher-level system properties emerge from the interactions of lower-level subsystems (Agents)", making it the ideal choice according to various studies [9,14]. This adaptability makes it possible to create environments that are customized to the requirements of the system under study.

The variability in ED operations results in differences in regulatory systems and certifications, e.g., in the field of phlebotomy, we observe a regulatory divergence between the United States and Spain [10,4]. When considering the implementation of simulation techniques to improve EDs, these structural and regulatory variations must be taken into account to the specific characteristics of each emergency system. Once a simulator is operational and validated in a hospital, different studies show that its adaptability is adequate for hospitals with similar operations. However, it becomes more challenging for hospitals with different regulations or operational approaches due to the monolithic nature of current models [1,5]. A monolithic system is one in which different components of the software are strongly integrated and can complicate its adaptation to new contexts. Taking into account this situation, two initial solutions are presented: modify the existing monolithic model to adapt it to new needs, despite the difficulties this may entail, or develop a new simulator from scratch.

This article presents an alternative approach inspired by the modularity and versatility of Lego® blocks, allowing us to transform the monolithic approach. Before starting, it is necessary to define the methodology to prevent it from becoming a monolithic structure again. Using a validated simulator of an ED, the objective is to identify and extract some agents to encapsulate them into a reusable agent box.

The remainder of this article is structured as follows: Section 2 provides an overview of the concepts and limitations of the existing simulation models to understand the objective of the article; Section 3 analyzes a validated ED simulator by the HPC4EAS group to identify and decompose the monolithic system; Section 4 explains the design of the experimental validation, the structure needed for make the 'agent box' and the results of the experiments, and Section 5 describes the conclusions and future plans for the research work.

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2 Theoretical Framework

Simulation approaches are essential tools for explore complicated systems in EDs and ABMS allows for a deeper and more complete understanding of how a system works, making it the ideal choice according to various studies [9,14]. The HPC4EAS group, a research group of the Universitat Autònoma de Barcelona (UAB), collaborating with the ED staff of Sabadell Hospital (Corporació Sanitària Parc Taulí), a reference center in the Catalan health System, has developed a conceptual model and a computational model for ED that utilize the ABMS technique, distinguishing between active and passive agents. Active agents are capable of making decisions, and passive agents do not take initiative on their own, but are essential to execute predetermined processes and enable interactions. The interaction between these agents and the modeled environment allows replication of the particularities of a real ED [12].

The research begins with the development of a conceptual model derived from a meticulous analysis of the elements of the ED, including the triage system that classifies urgency into five severity levels, specifically the Manchester Triage System [15] with level I being the most critical and level V the least [16].

After establishing the conceptual model and understanding the mechanisms of the ED operation, the next step was the creation of the computational model. The actual model becomes a sophisticated tool to predict the behavior of the ED, implemented with NetLogo. Regarding the software, although other alternatives such as Mesa, Repast, or AnyLogic have been studied [13], the choice of NetLogo powered by Python, combines the familiarity of the group and the ease of prototyping of NetLogo with the advanced analytical capabilities of the Python ecosystem, offering a pragmatic and tailored hybrid solution.

The group's validated simulator has been previously applied to various studies, including resource optimization [3], analysis of rare scenarios [2], and modeling disease transmission like MRSA within the ED [7].

After different studies in the same hospital with good results, it is extremely difficult to adapt to other ED with many different behaviors. It can be seen that the models and simulators developed to date by the HPC4EAS research group and other researchers operate in a monolithic manner, creating certain limitations in terms of adaptability, and some of them propose some alternative [1,5]. ABMS provides a modular structure in which individual agents interact on the basis of straightforward rules. This makes it an excellent solution for tackling this issue and easing adaptation to various scenarios. First, it is necessary to define how to get the definitions for an ED in a standard way for the conceptual model and how to transform it reusing the components of the computational model.

As can be seen in Figure 1, after generating the conceptual model with the data collected from the experts, the objective is to be able to define a modular system, which we will call a metasystem, which already has the basic components based on the work previously carried out and the specifications of different hospitals.

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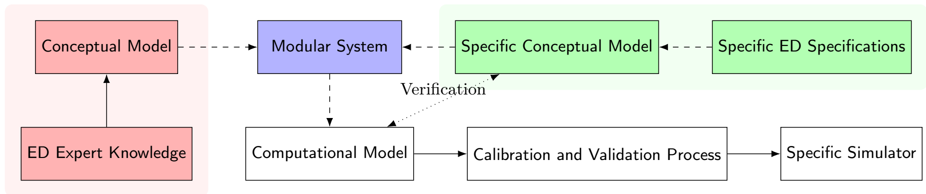

Fig. 1. Diagram of the design process of a simulator using a modular system for a specific ED.

The need for a metasystem makes sense, and in order to have it, it is first necessary to analyze what we currently have and break down those agents into a modular system. In the following section, analyze the current structure of the computational model from the HPC4EAS group to see which parts of the conceptual model can be easily linked and perform an experimental validation with short requirements to see how it can be possible.

3 Breaking Down the Current Simulator

In the ED simulator of the Hospital of Sabadell we find several fundamental agents. In this section, the different elements of the system are broken down, and each of the properties that they have in the current version is analyzed to understand the design of the metasystem. On the one hand, within the active elements of our system, we can discern between active agents and locations that act as active agents.

Currently, different agents are clearly identified in the actual ED Simulator: Admissions staff, Triage Nurses, Patients, Doctors (in Area A), Doctors (in Area B), Nurses (in Area A), Nurses (in Area B), Auxiliary Staff, the Information System, Careboxes, Test Rooms, Waiting Rooms, Ambulances, and Hospitals. The first eight agents listed have exclusively human roles. The last six agents are physical spaces (e.g., triage rooms, Area A/B) and should instead be modeled as passive environmental entities with properties like; Capacity limits, resource availability (e.g., beds, equipment) and spatial coordinates for agent navigation. This distinction ensures that agents interact with their environment rather than treating locations as autonomous actors, preserving the focus of ABMS on agent-environment interaction.

The system allows to measure different information like waiting times, workflow, and manage interactions which help to create a system that is organized. Nevertheless, some of the agents have inadequate simplification of the model, for example, admission agents has an incoming-queue attribute inside the agent, which specifies a fixed list of agents awaiting service. In real-world scenarios, admissions staff typically do not operate with a static queue; agents (like patients) assess their environment, organize themselves by observing the behavior of others, or sometimes ask questions to determine their turn.

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This approach introduces a direct dependency between agents that is not consistent with the principles of the ABMS, where interactions should be mediated by decentralized rules or emergent features of the system. In some cases, a ticketing system is used to establish the order of service, but this mechanism should be explicitly modeled as a separate environment entity or rule. Details such as these can affect the usefulness of the model, as an overly simplified representation may not capture the real dynamics of the system. If we want to see a truly decentralized system in action, it requires a bit of rethink in how we build these agents, especially regarding how they sense and react to their environment. Doing so will allow us to tap into more realistic and surprising emergent behaviors, which is really the essence of ABMS.

4 Experimental Validation

This section covers the experiment conducted to validate this initial approach to a new fully agent-based methodology that will allow us to create our metasystem. The proposed case study presents a simplified version of Sabadell's current hospital concept, designed to verify that the methodology can be implemented as proposed. The work is early, so it requires this simplification for analyze each individual part.

In the simplified version, ED is organized into two main zones and a triage area that serves as an entry point to manage medical care according to urgency. Zone A is dedicated to critical care, serving patients with priority levels I to III (the most urgent). On the other hand, Zone B focuses on non-critical care (levels IV and V) with a waiting area to manage patient flow. The system involves various agents with different roles. Patients enter through the triage area, where the triage nurse assesses their urgency depending on the priority level, and care nurses provide essential care in CareBoxes or treatment rooms while updating the patient's status. The computer system tracks patient data, supports decision-making processes, and monitors resource use. The workflow is: patients enter → triage → routing (Zone A/B) → care (CareBox/treatment) → discharge.

An experimental design has been proposed to analyze the methodology to have our metasystem basis predefined. In this experimental design, NetLogo was used and combined with the Python programming language to allow the creation of a structure for each of the agents independently in independent boxes. This has been a significant challenge, as NetLogo does not have a way to organize modules into different files or structures, making it a tedious task to have a highly complex system since everything is intertwined.

To manage modularity, we organized the NetLogo project hierarchically. Directories separate UI elements, agent definitions (subdivided per agent type with files for setup, loop, actions, etc.), global variables, and environment setup. A specific file naming convention aids clarity. The complication is that NetLogo does not accept this structure by default, taking advantage of the integration it has with Python a script in this language is added for processing and sorting this structure into a format that NetLogo can understand.

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By organizing the project, each component of the system is managed in isolation. This means that the definitions, behaviors, and configurations of each agent are located in individual files, easy to identify. Thanks to this, it is easier to update or modify an agent without affecting others, which facilitates the maintenance of the model over time. To validate its operation, a simplified conceptual and computational model was performed.

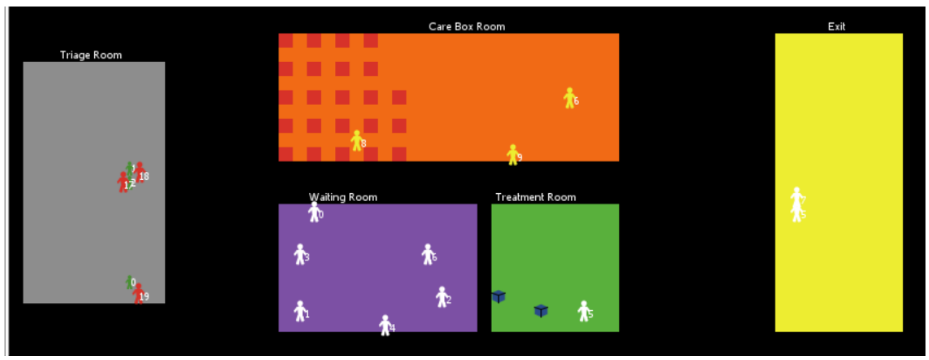

Fig. 2. Basic example for ED created with the modular structure.

Figure 2 shows the experimental work using our methodology. It consists of a Triage Room on the left, a care box for the most urgent patients at the top, waiting and treatment rooms for less urgent patients, and, on the right, the agents who have already completed all the steps. In addition, the integration of the files into a single executable file (main) is automated. Using a Python script, all the code needed for NetLogo has been prepared with the modular parts, which has allowed them to be synchronized and made to work during the simulation. Having tested this part, we now need to adapt the current monolithic model to improve its adaptability to validate our metasystem.

5 Conclusions

The use of simulation in ED is becoming increasingly important, given the increasing level of saturation they face. Through simulation, various challenging situations can be examined, allowing emergency services to adequately prepare and respond to adverse circumstances, especially in critical contexts. Simulation plays a crucial role in the strategic planning of these services. After analyzing the advantages of ABMs and seeing the performance of current simulation systems with rigid and poorly modular behaviors, a solution has been proposed that allows separating the behavior of the agents and allowing new agile implementations by effectively reusing previous work.

The proposed structure allows the individual behavior of each agent to be analyzed in the most realistic way, avoiding excessive coupling and the complexity

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of monolithic models. Although the initial model incorporates severe simplifications (for example, in queue management and static behaviors of some agents), the proposed structure will allow future improvements aimed at incorporating dynamics previously implemented in a monolithic manner with mechanisms for decentralized coordination. This task required a combination of NetLogo and Python, as the project can be structured into independent modules, with each agent defined in separate files. This modular approach facilitates system updates based on the specific context of each ED. However, NetLogo has limitations that do not allow the inclusion of modules in this manner, which is improved by integrating Python to make the metasystem.

The experimental validation in Section 4 has been useful for verifying the methodology, but is insufficient for full integration. The next steps will need to focus on defining how ED information is collected and structured for connection with the metasystem modules. In addition, it will be necessary to finish decomposing the current simulator into completely independent modules, ensuring that each one can interact in a flexible and scalable manner within the new environment. Following the defined structure will improve the adaptability of the system to different hospital contexts and facilitate future updates, but real-world testing would be needed across different EDs to fully confirm it.

In conclusion, defining the structure of a metasystem to simulate ABMS in the ED will allow for improved management of multiple hospitals. By allowing each agent to be modeled independently at the computational level, we can focus on future changes and not on restructuring monolithic systems. This approach opens new possibilities for emergency departments to prepare for future challenges. The change to modular systems and the possibility of collaborative development of these modules can significantly improve simulation capabilities. This advancement will allow us to improve not only the ED, but also other systems that need to adapt to various environments. This concept can also be applied to the effective management of urban areas or public transportation networks, where reusing components and flexible adaptation are important to optimize functions.

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