Metasystem for Modeling Emergency Departments

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***Abstract*—Emergency Departments (EDs) are complex systems that require coordination of medical personnel and resources to manage situations effectively. This research addresses the basic principles for designing a modular system that allows the creation of computational models to improve service quality using available resources. Based on the accumulated knowledge of experts in the ED field, the modular system ensures that each component accurately reflects the particular features present in various health care emergency environments, thus ensuring its adaptability. By applying Agent-Based Modeling and Simulation (ABMS), an analysis of the agents involved, such as patients, doctors, resources and computer systems is considered. ABMS, known for its ability to adapt individually to each agent, allows the design of customized environments that meet the unique needs of various regions and healthcare structures. Inspired by the modularity and versatility of Lego® blocks, this ABMS system seeks to transform a monolithic approach into an adaptable tool that, through a description of the metasystem and an agent box, enables the construction of computational models to potentially improve the quality of emergency care, facilitating strategic decision-making in this critical service.**

***Keywords*-Emergency Department (ED); Agent-Based Modeling and Simulation (ABMS); Emergency Healthcare Systems; Modular Design; Decision Support Systems (DSS).**

I. Introduction

The Emergency Departments (EDs) currently face an increasingly complex landscape due to saturation experienced in recent years, a phenomenon that highlights both the growing demand for emergency medical care and the need to provide quick and efficient responses in a pressured environment [1].

Simulation stands out as a compelling tool in the context of EDs, allowing us to perform analyses of hypothetical scenarios through "what if" questions [2]. This technique enables anticipation and preparation against potential adverse situations, helping to improve response capacity to the increasing demands that these services may face, especially in critical situations like pandemics or flu outbreaks, which have recently tested their capacity [3]. For instance, through simulation, it is possible to assess the impact that an increase of the patients arrival at ED would have on waiting times and service quality, thus allowing us to devise effective strategies to reduce saturation and ensure adequate care.

In the realm of EDs, simulation techniques are crucial for the analysis of complex processes. Among these, Discrete Event Simulation (DES) and Agent-Based Modeling and Simulation (ABMS) stand out for their effectiveness. DES focuses on the analysis of discrete events over time, allowing evaluation of how each event impacts the flow and operation of the emergency system. It enables us to understand sequences and resource use but might not capture all human interactions. In contrast, ABMS offers a more dynamic and detailed perspective by modeling the behavior and interactions between multiple individual agents, such as patients, doctors, and nurses, as well as 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 [4][5].

The variability in the operation of EDs is clearly manifested in the differences in regulatory systems and certifications, e.g., in the field of phlebotomy, we observe a regulatory divergence between the United States and Spain [6]. In the former, certification is a mandatory requirement, while in the latter, it is not required. When considering the implementation of simulation techniques to improve EDs, these structural and regulatory variations must be taken into account. Therefore, it is necessary to adapt simulation solutions to the specific characteristics of each emergency system.

Models and simulators developed up to date by the Research Group of the Universitat Autonoma de Barcelona (UAB) "High Performance Computing For Efficient Applications and Simulation" (HPC4EAS) and other researchers operate in a monolithic manner, which creates certain limitations in terms of adaptability. A monolithic system, by definition, is one in which different components of the software are tightly integrated or unified into a single program developed for an specific case, which can complicate its adaptation to new contexts. Faced with 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.

Given the application of the ABMS concept in these systems and inspired by the modularity and versatility of Lego® blocks, a third proposal emerges: to disaggregate those monolithic simulators to create an "agent box." This box would contain all the agents that could be involved in the ED, including medical personnel, patients, administrative staff, and physical resources. This strategy allows the simulator to be fluidly adapted to different ED environments and also to expand the agents and their interactions within the system, a solution that will enable handling the complexity of these environments.

The remainder of this article is structured as follows: Section II provides a concise summary of the previous works by the HPC4EAS group; Section III examines the fundamental properties of the proposed metasystem; Section IV reviews similar research, Section V presents an example of operation, and Section VI describes future plans for the research work.

II. Previous Work

This section presents the results of projects carried out by HPC4EAS, research group from the Department of Computer Architecture and Operating Systems at the Universitat Autònoma de Barcelona (UAB). This project is conducted in collaboration with the staff of the ED at Sabadell Hospital (Corporació Sanitària Parc Taulí), a reference center in the Catalan health system. Additionally, various studies related to the topic are integrated.

The research group has developed both a conceptual model and a computational model (We can consider that the simulator is the implementation of the computational model) that utilizes the ABMS technique, distinguishing between active and passive agents. Active agents are capable of making decisions and acting autonomously, representing individuals, such as doctors, nurses, and patients, who interact and respond to the dynamics of the ED. On the other hand, passive agents do not take initiatives on their own but are essential for executing predetermined processes and enabling interactions, such as hospital information systems, communication networks, and laboratory services. These agents interact within a virtual environment that simulates the areas and processes of an ED, managing different levels of urgency and priority in patient treatment. The interaction between these agents and the modeled environment allows for the replication of the particularities of a real emergency service [7].

The project has evolved through several key phases, starting with the development of a conceptual model derived from a meticulous analysis of the elements of the ED, including the triage system that stratifies urgency into five levels of severity, specifically the Manchester Triage System [8], with level I being the most critical and level V the least. In addition, to mapping other operational aspects and examining the interactions among agents to reproduce the system behavior, the simulator also distributes patients in the ED into two zones, Zone A and Zone B, according to this severity classification, assigning patients with levels I to III to Zone A for priority care, while those with less severity, levels IV and V, are placed in Zone B, designed for less urgent situations. This segmentation is important for managing patient flow [9].

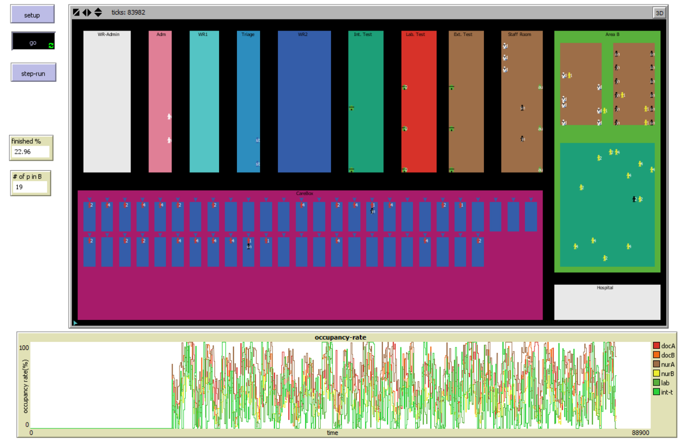

Figure 1. Simulator of the Sabadell Hospital ED, created with NetLogo.

After establishing the conceptual model and understanding the mechanisms of the ED operation, the next step was the creation of the computational model. This model translates the theory and observations of the conceptual model into algorithms and data structures that can be processed by computer systems. In this phase, the behaviors of both active and passive agents are programmed, and the interaction rules and operational procedures, such as the triage system, are encoded. The goal of the computational model is to faithfully reflect the dynamics of a real ED, allowing the simulation of different scenarios and their possible outcomes as can be seen in Figure 1. This model becomes a sophisticated tool for predicting the behavior of the ED at Sabadell Hospital. This scenario was represented using the NetLogo software [10], a modeling environment designed for ABMS, which provides the possibility to accurately design and simulate the operations of a hospital ED.

In the work conducted by various members of the research group, the simulator has been adapted and applied to analyze how to optimally use the limited resources available in the ED [11], to generate information about specific scenarios that, while possible, rarely occur in reality [12], and thus learn about the best way to manage them, or also to analyze, model, and simulate the transmission of the Methicillin-resistant Staphylococcus Aureus (MRSA) virus [13], and its effects on the operation of the ED, in order to explore the potential benefits of adopting preventive measures.

III. General Characteristics of the Metasystem: Lego System

Building on existing work and advancements in the simulation and modeling of EDs using ABMS techniques, we propose the creation of a metasystem, named the Lego® System. This system aims to manage the modularity of ABMS to develop an adaptable simulation environment.

The metasystem will originate from a conceptual model developed with the collaboration of ED specialists and the

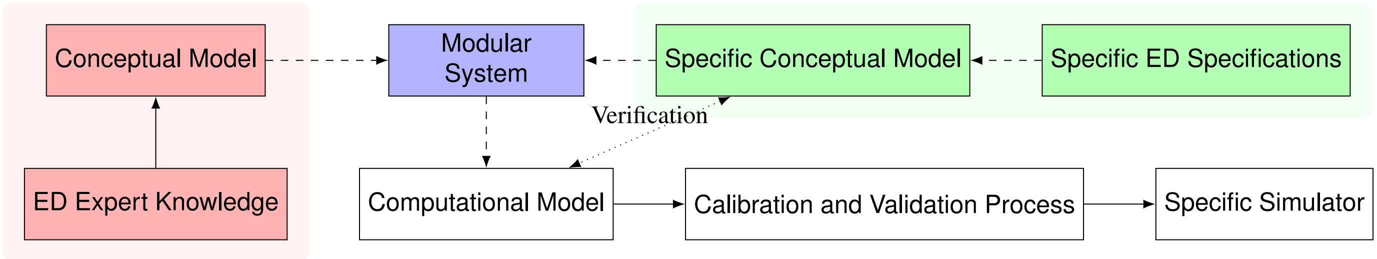

Figure 2. Diagram of the design process of a simulator using a modular system for a specific ED.

disaggregation of current simulators, which will facilitate the definition of standard modules that can be used in various health environments. This will allow for the efficient transition from a specific conceptual design to a computational configuration within the metasystem when it is necessary to develop a computational model for any ED. With the computational model ready, the necessary calibration and validation process must involve the use of specific data that the hospital can offer, and discussions should be held with them to determine the available data to guide this calibration to conclude with a specific simulator. This process is detailed in Figure 2. The section to be analyzed is highlighted in red, while the specific areas of an ED intended to be modeled with the metasystem are highlighted in green.

The goal is to develop a platform that facilitates the creation of computational models of EDs, through an intuitive interface based on "blocks". These blocks represent the various agents and processes involved in the operation of ED and are designed to be customizable. Flexibility is a key point; the system needs to allow for the combination of blocks in multiple ways, thus adapting to the operational particularities of various EDs. For example, it is possible to explore the impact of variations in staff roles, e.g., analyzing the consequences of assigning more or fewer responsibilities to a nurse or simulating scenarios where another team member assumes these tasks. With monolithic systems, such adaptations are costly.

To carry out the disaggregation of these components, it is important to analyze the state variables that will characterize the different agents, as well as define how transitions between these states will occur. In this context, three main categories are established: two corresponding to active agents and one to a passive agent, which will allow us to explore differences in their operation.

Among the active agents, we find common elements that all of them share, such as:

- **Identifier:** Each agent has a unique identifier that allows the system to recognize it in each temporal iteration.
- **Location:** Records the current location of the agent in the ED, which can vary from admission to the treatment area or specific tests.
- **Action:** Agent actions, such as waiting to be called, receiving instructions, or moving between different areas of the ED. These actions will vary by agent.

For the particular case of patients, there are complex state variables and transitions. We can distinguish three specific state variables; personal details, priority level, and communication level. Patients are recognized as one of the most crucial agents in the ED. Their **personal details**, such as age, gender, culture, and religion, are collected and considered to provide tailored treatment. The assignment of a **priority level** based on triage determines the urgency of medical attention, while the **communication level** between the patient and the ED staff is an indicator of the effectiveness of the interaction.

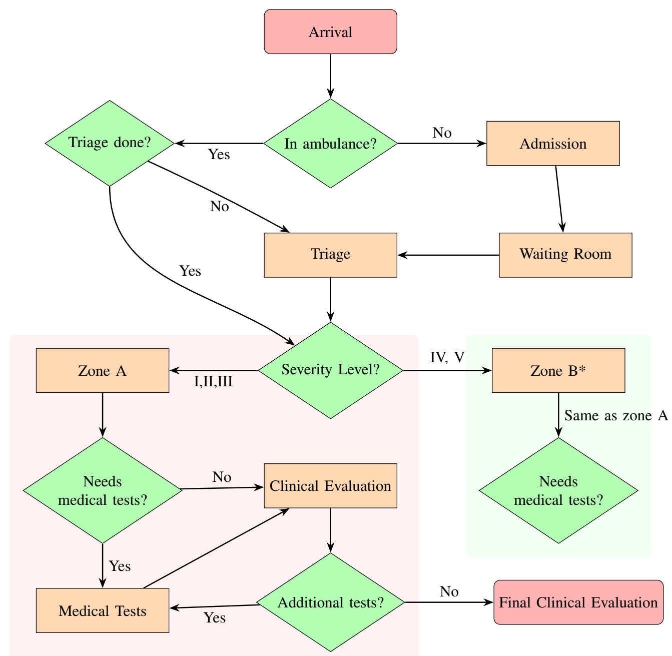

Figure 3. Diagram of the process patients go through in the ED.

The diagram showed in Figure 3 illustrates the process a patient undergoes upon arrival at an ED. It begins with their arrival, a critical point where their unique identifier is assigned, and their initial location or time of arrival is recorded. If they arrive in a medicalized ambulance, triage has already been conducted on-site; otherwise, if they arrive on their own or in a nonmedicalized ambulance, the process starts with their admission.

Priority level assignment occurs during triage, guiding the patient through the system to either to treatment areas, a separated zone (Zone B in the figure) with one specific waiting room and attention boxes for less severe cases (patients with priority level IV or V) or directly to a carebox (Zone A) for patients with more critical conditions (patients with priority level I, II or III).

The level of communication is important at each stage, from assessing whether medical tests are needed to making decisions about additional treatments. An evaluation cycle of treatment and possible re-evaluation continues until a resolution point is reached: the patient is discharged or further measures are taken based on their needs.

Each step of the process reflects the interaction between the patient's state variables and the actions of the ED system.

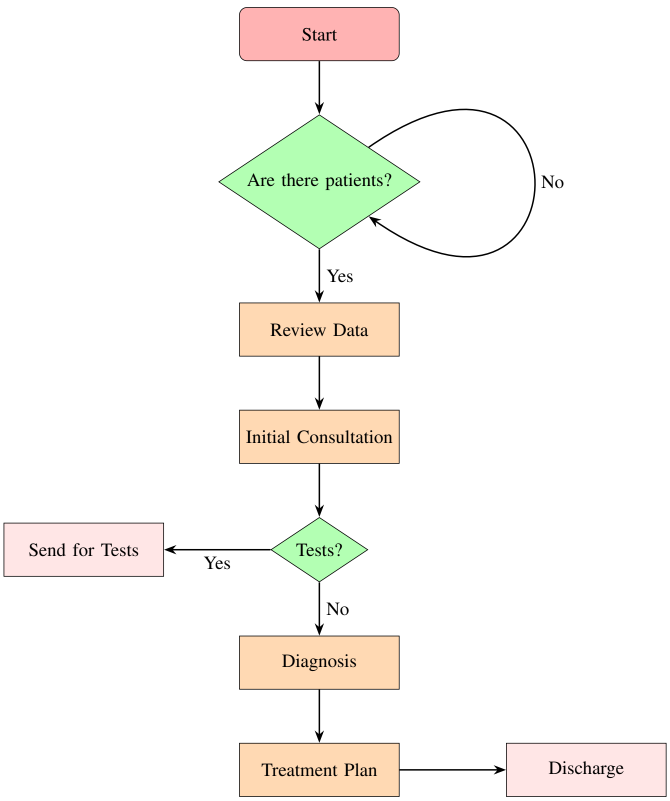

Figure 4. Diagram of the process that doctors undergo in an ED.

Continuing with the exploration of active agents within the ED, doctors are a central figure whose state variables reflect their role in the care environment. Unlike patients, the variables that define a doctor's actions are more straightforward, as they are related to defined tasks and a sequence of clinical steps.

Doctor's actions in the ED range from being inactive, which could mean waiting for the next patient, to more interactive actions, such as asking a patient to come forward, requesting detailed information, making a preliminary diagnosis, and ordering specific tests or treatments. A doctor may also be in an active waiting phase, awaiting the results of tests they have ordered, then making decisions based on those results, such as ordering the patient's discharge from the ED or making a final diagnosis to be entered into the Computer System, as evidenced in Figure 4.

The level of experience of the doctor, classified as low, medium, or high, influences their actions, and is a critical component that impacts the efficiency of work within the ED. A highly experienced doctor may be able to make quicker diagnoses or handle more complex cases in less time. For this reason, the metasystem incorporates a state variable to manage such issues. This is not reflected in the schema because the process remains the same; however, it depends on the state of each agent.

The operation of the Information System (IS) in an ED is essential for efficient and accurate care. It is part of an interactive process where the key decisions that the IS makes are in response to the received requests. Initially, the system checks for pending requests and, based on this, proceeds to obtain reports, register patients, and issue medical alerts. Decisions about whether patient data already exist lead to further actions, such as registering new data or adding them to the existing system. The workflow facilitates the processing of information and the continuous updating of medical records.

As a passive agent, the IS depends on interactions with active agents, such as the medical or administrative staff of the ED, to change state. The system's propensity for errors is classified into low, medium, and high levels, which can affect the operability of the ED.

The IS, as a passive agent within the ED, plays a significant role in coordinating between the different components of the healthcare system. The ability to process and issue information accurately is necessary to maintain a smooth workflow and to ensure that patients receive the necessary care at the appropriate time. It is a component that supports all the operations of the ED, from admission and triage to the patient being discharged.

The interaction between doctors and patients, mediated by the information system, is a delicate dance of consultations, diagnostics, and decisions that advance the patient through the care process, as reflected in the discussed figures.

IV. Related Work

The adaptability of simulation models to various health systems seeks to improve EDs. This flexibility will allow the implementation of the proposed modular metasystem, which can be adjusted to the specifics of different emergency care environments.

There are initiatives by research groups that have used simulation to enhance the effectiveness of EDs. The 3S Research Group and the Shelford team in England have conducted simulations at the University Hospital of Dublin [14] and in specific cases of the ED in London [15] respectively, offering valuable reference models for our proposal.

Moreover, it is important to analyze health systems in their social and economic context, as factors such as funding and access to health services, vary significantly between countries [16].

TABLE I. COMPARISON OF HEALTHCARE MODELS

Model	Funding	Control and Management	Coverage and Features
Beveridge	Income taxes	Government	Universal, public
Bismarck	Social insurance	State regulates	Employment-dependent, copayments
National Insurance	Taxes and insurances	Mixed	Universal, greater choice of providers
Out-of-Pocket	Private	Individual	Limited access, no financial protection

Analyzing how health systems function provides a more global perspective. It's necessary to evaluate the different health models found in each country. According to the World Health Organization, there are four main models [17]. Each has its distinctive characteristics regarding funding, management, and coverage.

The Beveridge model, implemented in countries like Spain, Portugal, and Finland, is characterized by its funding through income taxes, with the government assuming total control of healthcare management and providing universal coverage. This approach contrasts with the Bismarck model, prevalent in Austria, Germany, and Switzerland, where funding comes from mandatory contributions to social insurance funds. Although the state regulates healthcare entities, coverage depends on the individual's employment status, and copayments are included for certain services.

On the other hand, the National Health Insurance Model, found in Japan, Canada, and South Korea, combines elements of both previous models offering universal and equitable coverage, regardless of employment affiliation [18]. This model allows a greater choice of healthcare providers. Lastly, the Out-of-Pocket model is distinguished by the absence of collective funding, leaving individuals to face healthcare costs without a financial safety net, which limits universal access to health.

Each model reflects a different philosophy regarding the role of government, individual responsibility, and the principles of social solidarity. While the Beveridge and National Health Insurance models focus on universal coverage guaranteed by the state, the Bismarck and Out-of-Pocket models present a more segmented or individualized approach to healthcare coverage, which causes different types of ED operations in each case. These differences are reflected in Table I.

These factors can lead to different roles and internal functioning aimed at optimizing available resources. For example, the approach to phlebotomy in the United States, where there is specific training for this skill, differs from other countries with different training approaches, such as in Spain, where nurses are responsible for this process. With the new modular "Lego®" system, the need to adapt the simulator to these variations is no longer a problem, as the modules can be customized and reconfigured to reflect any health system.

There are tools seeking something similar like VisualizER, a DES tool that exemplifies how simulation can be applied to optimize EDs [19]. Although it allows effective simulation of emergency operations, it does not offer the capability to model the individual behavior of agents, which is a crucial component for anticipating unforeseen events.

Our proposal for an ABMS-based metasystem advances beyond existing DES solutions by leveraging the advantages of ABMS for creating modules that allow the result to emerge from the individual interaction of agents. This feature enables understanding and managing the often unpredictable dynamics of EDs, thus providing an adaptable system for healthcare professionals.

V. OPERATION OF THE METASYSTEM

In the metasystem for modeling EDs, it is crucial to have an interface or set of tools that facilitate customization of the system to the specific needs of different hospital environments. This functionality allows users to manipulate and redefine the stages and agents involved in the process easily.

Each component of the health system, represented by an agent, can be selected, configured, and placed within a workflow. The proposal is to drag and drop components, thus modeling the flow of the care process according to the criteria of each ED. Through this interface, for example, a new triage procedure specifically designed to respond to pandemic emergencies could be integrated, adjusting the metasystem to reflect changes in protocols. To achieve this, it is necessary to establish a basic form of communication between agents through primitives that are easily interchangeable among them and capable of adaptation. Examples of such primitives include conversing and utilizing objects, which are essential for defining each agent's own internal mechanism.

There will always be a need for a series of forms or commands that allow specifying and modifying the properties and behaviors of each agent. This functionality is relevant when wanting to add a new agent, e.g., a 'pandemic triage agent.' Here, the person in charge has the opportunity to access a library of predefined agents and select the one that fits their needs. Subsequently, the functions of this agent can be customized by adjusting parameters and behaviors.

In the event that a necessary agent is not predefined, tools are provided for users to create one from scratch. This allows the system to be adaptable, enabling each healthcare center the ability to mold the metasystem to their operational reality.

Figure 5 shows the structure of an ED. At the bottom, the set of "agent box" can be observed, a collection of roles and functions from which one can choose to assign to the different phases of the care process. For example, during the admission phase, a distinction is made between a process for a public ED and a private one. In the triage phase, a nurse specialized

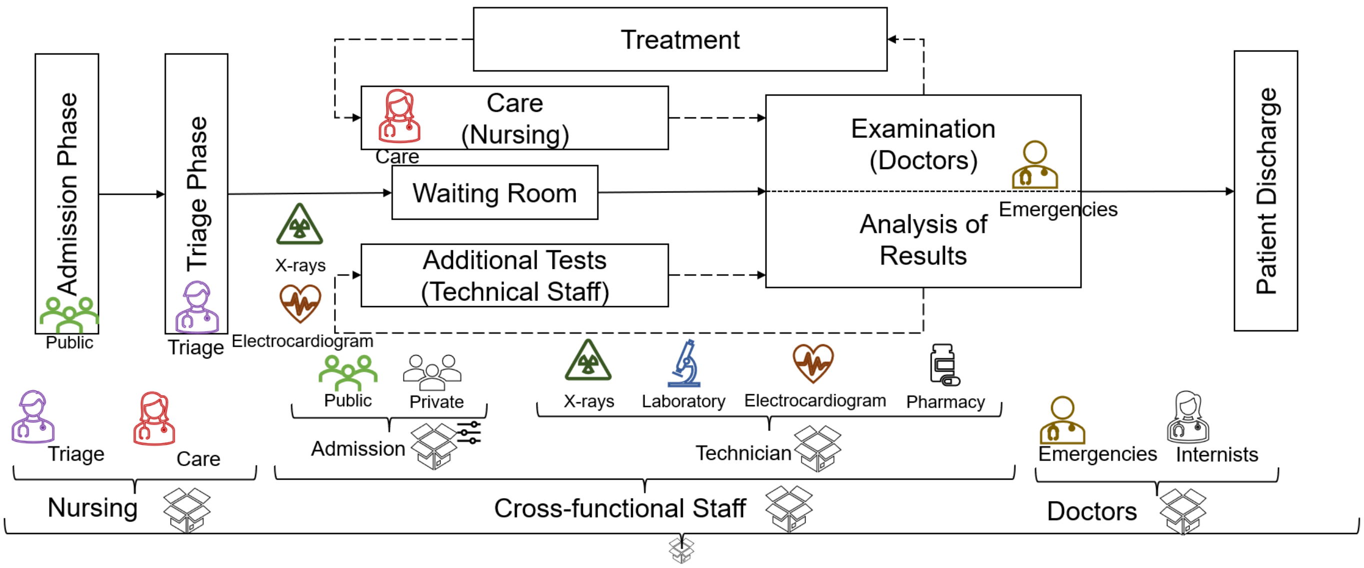

Figure 5. Example of Modules Utilized in a ED.

in this task is required. However, if the situation demands the incorporation of a triage nurse with greater experience due to an increase in the complexity of cases or the need to expedite the process, this new type of professional could be added. This process would be carried out by duplicating the configuration of the existing triage nurse and adjusting her parameters of behavior and performance according to the additional experience she brings to the process.

Consider the scenario where an ED in Spain is public, in such a case, this specific setting can be selected to work within the system. Similarly, settings for other stages, such as Triage, Waiting Room, and Performing Additional Tests can be customized to specify the capabilities and processes for each element of the system. This customization process allows the system to transition smoothly from the general agent-based configuration shown with the box to a more specific configuration that can be shown with the selected agent boxes in the diagram of the Figure 5.

This tailored approach ensures that each component of the ED could operates optimally according to the defined roles and requirements, enhancing both efficiency and patient care.

VI. Conclusion and Future Work

Simulation in EDs is greatly beneficial in addressing the increasing complexity and saturation these services currently experience. The ability to analyze problematic situations in advance through the simulation of hypothetical scenarios allows EDs to prepare and respond effectively to adverse situations, especially in critical contexts, such as pandemics or disease outbreaks. Simulation not only improves response capacity to growing demand but also contributes to the strategic planning of EDs.

ABMS stands out as the appropriate tool for simulating EDs, surpassing DES in terms of the ability to model the complexities of such systems. ABMS, with its "emergent properties", allows for a detailed representation of interactions among multiple agents, such as patients, doctors, and nurses, and their environment, capturing the essence of human processes.

The development of simulators using ABMS represents a significant advance, allowing models to be adapted to different EDs. The transition from monolithic models to a LEGO-type modular system, referred to as an "agent box," facilitates the adaptation and expansion of simulators to meet various configurations and needs of ED. This modularity allows for efficient customization and reconfiguration, reflecting any health system and its operational particularities.

This simulation proposal differs from other solutions, such as DES and tools like VisualizER, in its focus on agent adaptation and modeling. Through the "emergent properties" of ABMS, it is possible to model individual behavior and interactions between agents, a crucial component for managing the often unpredictable dynamics of EDs. This provides an adaptable system for healthcare professionals, enabling more effective management of EDs.

However, there are limitations and potential future directions for the expansion of this technology. One is the number of predefined modules in the "agent box," which could be addressed by creating a common repository where modules adapted to new needs and contexts are shared and updated. Moreover, expanding the use of modular systems in EDs to other healthcare and geographic contexts could provide valuable insights and enhance the efficiency of EDs globally.

In conclusion, the proposal of an ABMS-based metasystem for the simulation of EDs contributes to a better understanding and management of these services. Through the ability to model the complexity of human interactions, this technology opens new possibilities for preparing EDs for current and future challenges. The evolution towards modular systems and collaboration in the development of modules can further enhance simulation capabilities, offering continuous improvement of EDs.

In the future, the Delphi method, a process used to arrive at a group opinion or decision by surveying a panel of experts [20], will be necessary to build a comprehensive conceptual model and develop the meta-model. This analysis will involve multidisciplinary collaboration with clinical expertise and the use of ABMS.

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