Thesis Overview:

Modeling and Simulation for Healthcare Operations Management using High Performance Computing and Agent-Based Model

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Hospital based Emergency Departments (EDs) serve as the primary gateway to the acute healthcare system, are struggling to provide timely care to a steadily increasing number of unscheduled visits. It is a highly integrated service units that primarily handles the needs of the patients arriving without prior appointment, and with uncertain conditions. In this context, analysis and management of patient flows play a key role in developing policies and decision tools for overall performance improvement of the system. However, patient flows in EDs are considered to be very complex because of the different pathways patients may take and the inherent uncertainty and variability of healthcare processes. Due to the complexity and crucial role of an ED in the healthcare system, the ability to accurately represent, simulate and predict performance of ED is invaluable for decision makers to solve operations management problems. One way to realize this requirement is by modeling and simulation.

In this thesis, we build high fidelity simulation tools to identify system bottleneck, quantitatively predict the benefit and cost of a policy, and discovery knowledge for a better understanding of the complex ED system. The agent-based model and simulation technique provides a flexible way to study ED operations as it predicts the system-level behavior from micro-level interactions, so as to see the forest through the trees. In this way, policies such as staffing could be changed and the effect on parameters such as waiting times and throughput could be quantified. Here, we use agent-based model and simulation techniques to model the interaction of ED components (i.e, patient, nurse, doctor, equipment etc.). We then applied high performance computing techniques to execute the model and analyze simulation results (Fig. 1). In summary, armed with the ability to execute a compute-intensive model and analyze huge datasets, the overall goal of this study is to develop tools to better understand the complexity (explain), evaluate policy (predict) and improve efficiencies (optimize) of ED units. The two main contributions are:

An agent-based model for quantitatively predicting and analyzing the complex behavior of emergency departments. Prediction, explanation & optimization are challenging for a complex system like emergency department. While the bottom-up simulation techniques can help understand how different elements of healthcare system work together under different conditions. It is a crucial pre-requisite for improving the coordination and integration of healthcare, and increasing the efficiency of resource allocation. Thus, a precise ED simulator enables managers to make better decisions by letting them see the impact of changes before implementing them. The objective of this model is to grasp the non-linear association between macro-level features and micro-level behavior with the goal of better understanding the bottleneck of ED performance and provide ability to quantify such performance on defined condition. The model was built in collaboration with healthcare staff in a typical ED and has been implemented in a NetLogo modeling environment. In order to validate its adaptivity, the presented model has been calibrated to simulate a real ED in Spain, simulation results have proven the feasibility and ideality of using agent-based model & simulation techniques to simulate the ED system. More specifically, in this model, policies such as staffing, human factors such as sanitary staff behavior, new cases such as a flu outbreak could be set up and their effects on system performance such as waiting time and throughput could be quantified. Case studies are provided to present some capabilities of the simulator on quantitively analyzing the cost and effect of proposal changes to the ED in order to support decision making (e.g, Fig. 3). Because of the complexity of the system, high performance computing technology was used (Fig. 1) to increase the number of studied scenarios and reduce execution time [1-2].

A simulation and optimization based methodology for calibrating model parameters under data scarcity. To achieve high fidelity and credibility in conducting prediction and exploration of the actual system with simulation models, a rigorous calibration and validation procedure should firstly be applied. However, one of the key issues in calibration is the acquisition of valid source information from the target system. The aim of this contribution is to develop a systematic method to automatically calibrate a general emergency department model with incomplete data (Fig. 2). The proposed calibration method enables simulation users to calibrate the general model for simulating their system without the involvement of model developers. High performance computing techniques were used to efficiently search for the optimal set of parameters (Fig. 4). The case study indicates that the proposed method appears to be capable of properly calibrating and validating the simulation model with incomplete data. We believe that an automatic calibration tool released with a general ED model is promising for promoting the application of simulation in ED studies. In addition, the integration of the ED simulator and optimization techniques could be used for ED systematic performance optimization as well [3]. In addition, the integration of the ED simulator and optimization techniques originally developed for model parameters calibration (Fig. 4) could also be used for systematic performance optimization, i.e., by changing the objective function and variable constraints. For example, with constraints (budget, place or quality of service guarantees) and design parameters, the proposed simulation-based optimization workflow could be used to find the optimal (and suboptimal) design parameters to achieve best system performance.

In summary, starting from simulating the emergency departments, our efforts proved the feasibility and ideality of using agent-based model methods to study healthcare systems. The model could be used as a tool to quantitatively evaluate prospective planned changes to the healthcare system for decision making [2]. With the amount of adjustable parameters, the simulator is customizable to simulate a variety of scenarios. The presented simulator is currently working as a platform to study Methicillin-resistant Staphylococcus Aureus transmission in EDs and as an experimental platform of EDs to provide data under various scenarios for knowledge discovery.

Although this work was focused on the ED, the model methods and framework developed in this thesis can most likely be applied to many other healthcare entities, such as an intensive care unit, a comprehensive full service hospital, a managed care organization, or a vertically integrated system of primary care providers, and outpatient services. The framework developed in our work could be used to build a full model of integrated care system. A full model of integrated care system will be able to represent a comprehensive tool to quantitatively evaluate prospective planned changes to the integrated care system for decision making, and open a wide field of possible simulation scenarios for a better understanding of the integrated care complex system.

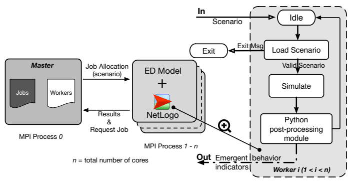

Fig. 1 The execution framework for the ED model on a cluster.

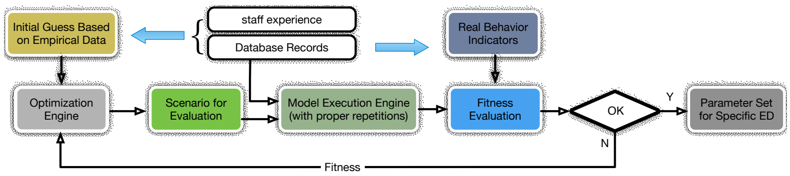

Fig. 2 A systematic model calibration and validation process.

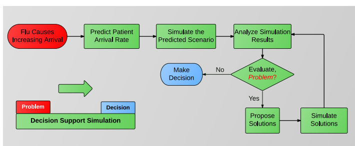

Fig. 3 A simulation supported decision making process.

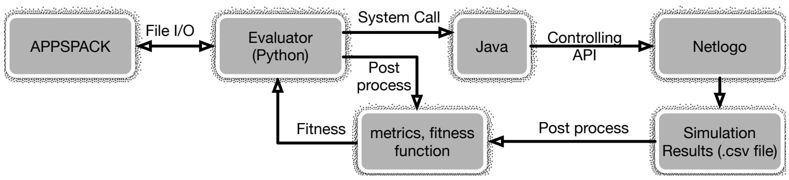

Fig. 4 Data flow in simulation-based optimization experiments.

References

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[2] Zhengchun Liu, Eduardo Cabrera, Manel Taboada, Francisco Epelde, Dolores Rexachs and Emilio Luque. Quantitative Evaluation of Decision Effects in the Management of Emergency Department Problems. Proceedings of 2015 International Conference on Computational Science, June, 2015, Pages 433-442.

[3] Zhengchun Liu, Dolores Rexachs, Francisco Epelde, Emilio Luque. A simulation and optimization based method for calibrating agent-based emergency department models under data scarcity. Computers & Industrial Engineering, Volume 103, January 2017, Pages 300-309, http://dx.doi.org/10.1016/j.cie.2016.11.036