# Methicillin resistant *Staphylococcus aureus* transmission reduction using Agent-Based Discrete Event Simulation

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## Abstract

Methicillin resistant Staphylococcus aureus (MRSA) is a significant problem arising in healthcare, most commonly in large, tertiary-care hospitals, and its spread among patients causes many downstream effects, such as longer lengths of stay for patients, higher costs for hospitals and insurance companies, and in many cases, more fatalities. An agent based discrete event simulation model is developed to investigate the dynamics of MRSA transmission in the University of Maryland Medical Center (UMMC). The simulation model is used to examine the effectiveness of infection control procedures to reduce the spread of infection within the medical center. Specifically, experiments are performed to examine the efficacy of hand hygiene compliance, patient cohorting, patient isolation, patient screening, and decolonization on the incidence of MRSA transmission.

## Introduction

In large hospitals, there are a large number of patients as well as health care workers (HCWs) that come into contact with each other frequently throughout the course of a day. If one of those patients or HCWs becomes colonized with methicillin resistant *Staphylococcus aureus* (MRSA), the bacteria could spread by way of HCWs within the hospital. As a result, many patients fall victim to hospital-acquired, or nosocomial infection. It is estimated by the Committee to Reduce Infection Deaths (RID) that infections acquired in hospitals lead to over 100,000 deaths per year and an additional $30.5B in hospital costs[1]. More specifically, close to 300,000 (out of 2 million) infection cases involved MRSA, with close to 20,000 of those cases resulting in fatalities.

Many experts agree that nosocomial infections (NIs) are mostly preventable[2], given a sanitation-conscious healthcare institution. These infection control policies consist of improving hand hygiene compliance, screening patients for MRSA, isolating patients testing positive for MRSA, decolonizing patients, and dividing patients into nurse-specific groups, a method known as patient cohorting. However, studies have shown that such measures have proven difficult to implement and enforce, due to both HCW non-compliance and cost considerations.

This study seeks to identify the most effective infection control measure or measures that could reduce the incidence of MRSA transmission without becoming cost prohibitive. To accomplish this goal, an agent-based discrete event simulation package will be designed and developed to model MRSA transmission dynamics and the impact of infection control measures (ICMs) in the University of Maryland Medical Center (UMMC).

## Methodology

Agent-based modeling (ABM) is a powerful technique that seeks to generate emergent characteristics from simple, rule-based individual behavior. In other words, the goal of ABM is to determine whether or not macroscopic trends can be generated from endogenous characteristics. This technique will be used to define agents in a hospital, specifically patients, nurses, physicians, and visitors, that will interact with each other throughout the simulation period. The interactions between agents serve as the source of transmission dynamics within the hospital. Discrete event simulation (DES) will be used to propagate the interactions between the agents and serve as an interface to collect data for various configurations of hospital operations, such as the implementation of specific ICMs. The simulation will be stochastic, implying there will be a number of events that are determined through the use of pseudo-random number generation. The stochastic nature of the simulation requires multiple replications of each scenario to be executed, and thus Monte Carlo methods will also be incorporated into the design of the software.

In order to implement the agent-based model, each agent will be defined in terms of its characteristics and behavior. This type of modeling is supported best by object-oriented programming (OOP), in which object classes are defined with inherent characteristics and methods. Patient agents will have fixed locations within the hospital and will be visited by all of the other agent-types in the model. They will also have a level of risk representative of their illness, which will affect the likelihood of whether or not they will become colonized with MRSA as well as whether or not they will contaminate an HCW. HCW agents will be modeled as resources that can be requested by their assigned patient agents. HCW agents will be further divided into nurse and physician agents, who have different hygiene behavior and different patient assignments. Nurses will be modeled with better hygiene compliance, smaller patient assignments, and more frequent visits than physicians. Patient cohorting is only implemented through the assignment of patients to nurse agents. Visitor agents will be assigned a specific patient within the hospital, and will remain with the patient for the duration of their stay.

The transmission of MRSA will be modeled on the basis of whether or not a newly admitted patient transmits the bacteria to a HCW, a colonized HCW transmits the bacteria to a patient, or a colonized visitor transmits the bacteria to a patient. The transmission itself is determined stochastically, based on the risk level of the patient and the behavior of the HCWs that visit. These transmission probabilities will be calibrated with data directly from UMMC. Once colonized, a patient remains colonized until the patient has become infected or decolonized. A patient can become infected based on the risk level of its condition, at which point the HCW can detect the condition of the patient and begin treatment and infection control. The patient can only begin the decolonization or treatment process once the state of the patient has been identified by an HCW. A colonized HCW can become decolonized upon the occurrence of its next hand hygiene activity. The probability of a HCW washing its hands is based on its own hand hygiene compliance, factoring the risk level and isolation status of the patient.

DES typically consists of three design methodologies: time stepped DES, event oriented DES, and process oriented DES. Time stepped DES propagates time using a fixed time step until the simulation time of a scheduled event has been reached, at which point the event is processed and time is advanced further. A significant disadvantage of time stepped DES is that if the events are distant in time, the simulation could propagate a long time without processing any events, which is an inefficient use of computational time. Event oriented DES jumps directly to discrete simulation times at which an event is scheduled to occur, processes the scheduled event, and then proceeds to the next scheduled event time. This methodology leads to a serial processing of events, which is simpler to implement, but still inefficient. Process oriented DES operates in a slightly different way, where each simulation component is modeled as a process that executes through a series of active and passive states until the simulation has reached a terminating condition. Process oriented DES also jumps to discrete simulation event times, but the execution of the simulation occurs as a series of parallel processes.

The process oriented DES methodology is becoming the most common technique used in simulation currently, and thus is the method of choice for this software project. All of the agents in the simulation will be represented as processes, each requesting the availability of one or more of the other types of agents. The only allowable interactions are between patients and HCWs, and patients and their visitors. Interactions between HCWs are not modeled. The patients will request the services of both types of HCWs, namely nurses and physicians. The patients will also request the services of visitors. For each patient that requires service, a list of appropriate resources must be defined to represent the nurses and physicians assigned to that patient.

Due to the relatively small likelihood of MRSA transmission to a patient on any given interaction, the simulation will be executed over a long period of time, on the order of one year. This simulation length will allow for a transient period, during which the startup dynamics can be discarded. The number of replications will be determined based on the runtime of an individual simulation run and an examination of the sensitivity of the model.

## Implementation

The simulation package will be developed entirely in Python, a dynamic object-oriented programming language. Other languages were considered, but Python has proven to be the most flexible of the candidates, and also contains a number of packaged modules that will reduce architecture development and still execute relatively quickly.  Python does not require dynamic memory allocation or type declarations as in C and C++ and runs much faster than MATLAB, which is a crucial advantage due to the planned length of each simulation run.

In addition to basic Python, NumPy, SciPy, and SimPy will all be useful resources for building the software package.  NumPy is a multi-dimensional array-based module that contains a large number of operations for arrays which will be helpful for event list management and metric tracking.  SciPy is a module used for scientific computation tasks, including optimization and genetic algorithm capabilities.  SimPy consists of process oriented DES classes and methods which will be used to develop the simulation architecture for the software.  The advantage of SimPy over implementing the process oriented DES in C or C++ using POSIX Threads (pthreads) is that the passive and active states of all processes are completely deterministic, and therefore it is not necessary to account for the unpredictable behavior of pthreads.

The software development consists of six major stages.  The first stage is the definition and design of object classes, data, and methods for each of the agent types.  This object class definition is implemented as a Python module, which can be imported by other software components.  Implementing the object classes and methods in this manner incorporates modularity into the software, because the classes and methods defined in the module can be updated at any time without affecting the integrity of the software package.  The second stage consists of the simulation architecture necessary to propagate the interaction between agents, which can be implemented in a similar modular manner. The third stage will introduce the capability to perform Monte Carlo simulation, which will be implemented as part of the simulation architecture module.  The fourth stage consists of parameter definitions that will be used to drive the simulation.  The variation of these parameters will be defined during validation and used to generate data.  The fifth stage of software development consists of creating the specific model of the hospital, using the object classes and simulation architecture developed in the previous stages. More specifically, the model will specify the dynamic environment in which the agents interact for a specified period of time.  The sixth and final stage will introduce metric tracking into the simulation, which will be implemented into the specific model itself. This stage will allow statistics to be generated and analyzed during the validation and testing period.

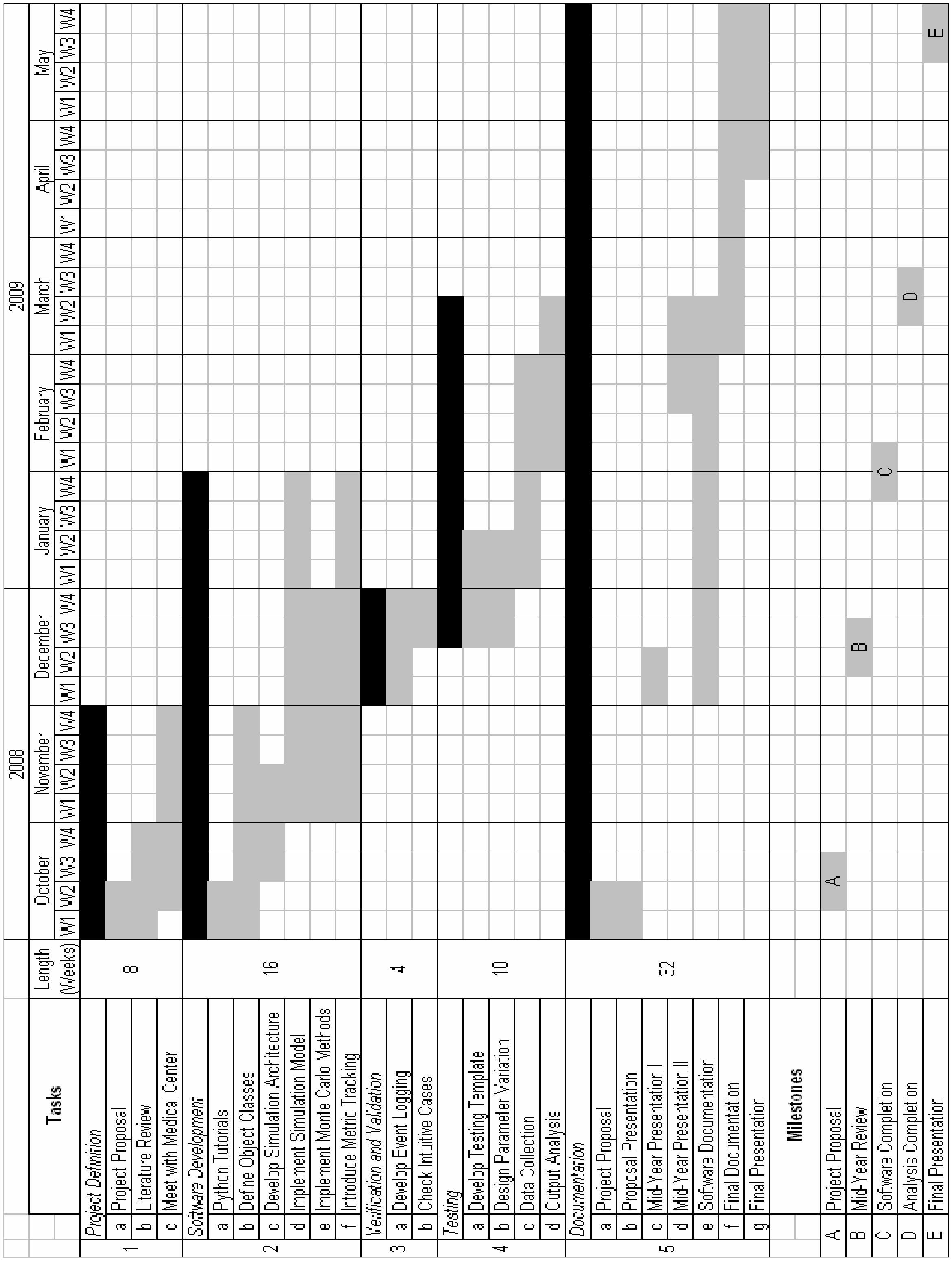
## Validation and Testing

On completion of the software package, a series of test cases will be performed to validate the model against those of References 3 through 6.  The successful model will first generate similar trends in the transmission of MRSA for a baseline case, without any ICMs in effect.  After this stage of validation, the model will be tested in order to examine the effectiveness of hand hygiene compliance, patient screening, patient isolation, and patient cohorting to identify the most effective ICMs.  Specifically, the goal is to verify or refute the following trends:

- Increasing hand hygiene compliance reduces the incidence of NI, but with the effect of diminishing marginal returns
- Decreasing hand hygiene compliance past a threshold value drastically increases the incidence of NI
- Only screening all or almost all of incoming patients significantly reduces the incidence of NI
- As the HCW/patient ratio nears unity, the incidence of NI vanishes
- Isolating colonized patients reduces the incidence of NI

In order to expedite the validation and testing of the model, a template will be designed that will allow batches of simulation cases to be run with a single request.  A processing script will also be developed to perform output analysis on the collected data.

# Project Schedule and Milestones



## Deliverables

At the conclusion of this project, the goal is to be able to produce a flexible software package in Python accompanied by full documentation that could be used for additional hospital studies in the future. Another goal is to be able to quickly run additional infection studies in the future. In order to accomplish this goal, a template is required where all of the input variables are specified via spreadsheet. The spreadsheet is then exported as a delimited text file which can be loaded by the software package using some simple instructions. A script could also be developed to assemble the simulation data into a readable summary file. In addition, a final report will be compiled that explains the methods and implementations used as well as the data collection and analysis performed to provide recommendations on infection control. These results are to be presented to the course instructors and participants, as well as to the medical center.

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