IMPROVING PATIENTS EXPERIENCE IN AN EMERGENCY DEPARTMENT USING SYSTEMS ENGINEERING APPROACH

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ABSTRACT

Khazaei, Hosein. M.S.M.E., Purdue University, August 2019 . Improving Patients Experience in an Emergency Department Using Systems Engineering Approach. Major Professor: Hazim El-Mounayri Professor.

Healthcare industry in United States of America is facing a big paradox. Although US is a leader in the industry of medical devices, medical practices and medical researches, however there isnt enough satisfaction and quality in performance of US healthcare operations. Despite the big investments and budgets associated with US healthcare, there are big threats to US healthcare operational side, that reduces the quality of care. In this research study, a step by step Systems Engineering approach is applied to improve healthcare delivery process in an Emergency Department of a hospital located in Indianapolis, Indiana. In this study, different type of systems engineering tools and techniques are used to improve the quality of care and patients satisfaction in ED of Eskenazi hospital. Having a simulation model will help to have a better understanding of the ED process and learn more about the bottlenecks of the process. Simulation model is verified and validated using different techniques like applying extreme and moderate conditions and comparing model results with historical data. 4 different what if scenarios are proposed and tested to find out about possible LOS improvements. Additionally, those scenarios are tested in both regular and an increased patient arrival rate. The optimal selected what-if scenario can reduce the LOS by 37 minutes compared to current ED setting. Additionally, by increasing the patient arrival rate patients may stay in the ED up to 6 hours. However, with the proposed ED setting, patients will only spend an additional 106 minutes compared to the regular patient arrival rate.

1. INTRODUCTION

1.1 Emergency Department Problem Statement

Emergency Department overuse and overcrowding is increasingly becoming a worldwide crisis [1]. This might be due to different reasons such as increased demand for health care service, shortage of human resources and physical equipment, complex regulations and procedures of ED and increased number of people without health insurance, especially in US [2] [3]. In addition to that, difficulties in data storage process and medical errors, which are all due to complex and dynamic nature of ED will cause some other problems including rising unnecessary costs and patient longer lengths of stay [4]. A recent study has claimed that the number of patients served by EDs is increasing as 30 million patients per year in United States. Due to US health regulations and laws, EDs are supposed to provide service to everyone without any limitation; therefore, it will be the last option for uninsured people. In other hand, shortage of funding sources is a main reason of ED closures, which is being a main public health concern through all the world [5] [6]. It has been reported that more than 50% of patients visiting the emergency departments are not satisfied with their wait time and perceived care [7]. Emergency departments in hospitals are supposed to provide immediate care to patients 24 hours a day and 7 days of week, thus they are under a lot of pressure since nurses and physicians must always be ready for providing service to patients [8]. According to a recent study, 57% of Winter Simulation Conference (WSC) articles in healthcare systems modeling are coming from United States of America, which shows a great focus and concern over the healthcare system cost and efficiency. Additionally, only 9% of the papers were focused on resource utilization as the application of their analysis [3].

1.2 Systems Engineering, A Methodology to Improve Healthcare Delivery Process

This research study is inspired by two reports about improving healthcare delivery process, 1) Building a better delivery system; a new engineering/ healthcare partnership and 2) Applying Systems Engineering Principles in Improving Health Care Delivery. These two reports can be considered as two wings of a bird, thus considering both to apply systems engineering approach for healthcare field is necessary. According to the National Academy of Engineering and Institute of Medicine, there is a significant paradox with US healthcare system. United States of America acts as leader in medical science and technologies related to it, by utilizing the most recent techniques in clinical research, training and medical practices. Additionally, since there are lots of resources and attention for improving individual patient treatments, there has been lots of focus on doing researches in life and physical sciences in US. This has made US the biggest player in medical world to have the most advanced medical devices, equipment and drug manufacturer. Moreover, since theres a big market inside of US, this support has been even more, and leads US to become stronger and more rewarded to continue through this path, to be the world leader in medical sciences, but with a very high cost associated with it [9] [10] [11].

Despite mentioned positive sides of US healthcare industry, theres a dark side of the story, too. US healthcare policy makers and administrators are spending less resources and attention to improve operational healthcare performance and quality. It gets worse when focusing on high level healthcare systems such as hospitals and health networks. In other words, despite spending lots of money and resources for US healthcare improvements, there isnt enough quality, productivity and satisfaction in healthcare operations. Considering the1.6 trillion budget of US healthcare, there are so many threats to US healthcare safety, quality and access [12] [13] [14] [15] [16]. After discussions about problems of US healthcare, the report then suggests looking into the US healthcare world, as a big system which includes four nested levels. This is a very helpful step to apply systems engineering techniques, to transfer to a better healthcare system with better quality and performance. US healthcare system is divided into 4 different levels including: individual patient, care team, organization and environment.

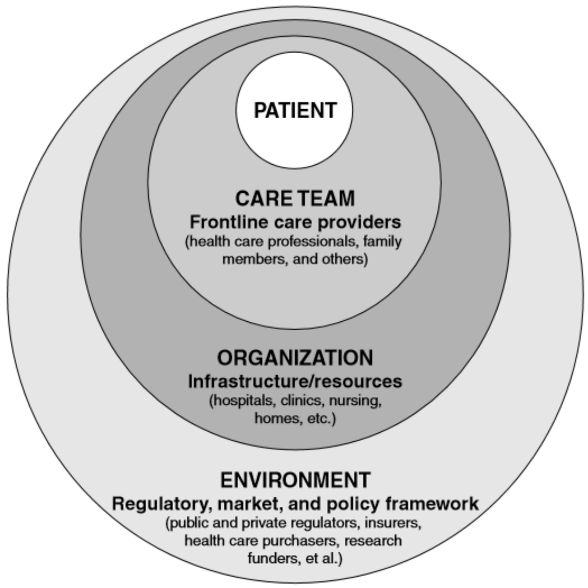


Fig. 1.1. Four Level Healthcare System [9]

As mentioned earlier, one of the most important factors of a good healthcare system is to be patient-centered. Individual patient is what the healthcare system is working for. Patients are expecting to receive right type of treatment. The process that they go through must be safe, efficient and timely. The other level of the healthcare system is the care team. Second level of healthcare includes physicians, healthcare professionals and family members of the patient and all these groups efforts will affect on the result and the quality of the care that the individual patient is receiving. Next level of the healthcare system is organization. This level includes hospital, clinics and even homes. This is where the resources and equipment are provided for individual patients and care team to go over the treatment process. Finally, the last level of healthcare system is the environment. It includes all policy makers, financial managers, healthcare market, etc. Any decisions and changes made by these groups will affect the other three levels and moreover, big changes and transitions to better healthcare systems are started by fourth level people and organizations [9] [17] [18].

Now that all four levels off a healthcare system have been defined and grouped together, one of the earliest steps to run systems engineering study is to name all the stakeholders of the desired system, which in our case is healthcare system, since they all have different set of requirements and needs. There are 7 major stakeholders considered in healthcare [19] [20]:

Group 1: Consumers, patients, caregivers and patient advocacy organizations

Group 2: Clinicians and their professional associations

Group 3: Healthcare institutions such as hospital systems and medical clinics, and their associations

Group 4: Purchaser and Payers, such as employers and public and private insurers

Group 5: Healthcare industry and industry associations

Group 6: Healthcare policymakers at the federal, state, and local levels

Group 7: Healthcare researchers and research institutions

These different stakeholders can all be included in four nested levels of the healthcare system, as mentioned earlier:

Level 1: Individual Patients which includes Group 1

Level 2: Care Team which includes Group 2

Level 3: Organization which includes Group 3

Level 4: Environment which includes Groups 4, 5, 6, 7

This grouping methodology helps researchers to understand and reduce the complexity of the healthcare system.

According to the second motivator of this research, systems engineering tools and techniques are highly used and implemented to improve quality and performance of complex healthcare systems. According to the author, there are 6 major steps to apply systems engineering approach to model and improve and existing healthcare system [21]:

1. Define system purpose and scope, specify required functions and resource types, and develop relevant performance measures along with desired performance thresholds.

2. Specify, collect, and develop required data through data collection methods.

3. Design, validate, and verify appropriate system models. This involves selecting the right modeling tools, building and validating the model.

4. Use the model to learn about system behavior to find the best design alternative. The engineer often develops appropriate experiments for the studying the model and analyzing the results.

5. Use the results of step 4 to determine how to configure the system for best performance. This involves specifying equipment requirements, staffing levels and patterns, scheduling procedures, workflows, and so forth. Sensitivity analysis is also important to determine how system performance will be affected by perturbations to nominal conditions.

6. Develop implementation and evaluation plans and coordinate their performance.

1.3 Emergency Department at Eskenazi Hospital

In this study, a very big and major healthcare facility located at Downton, Indianapolis has been selected for the SE approach implementation. Eskenazi Hospital is one of the main healthcare providers of Indianapolis and surrounding areas and treats more than 100,000 patients yearly. Emergency department at Eskenazi is almost the main component of the hospital, since 80% of the admitted patient first are seen by care team of ED. This makes the ED a very interesting place for systems engineers to investigate. As reported by Eskenazi, the median time for patients to get board is around 7 hours. Additionally, almost 25% of the patients will stay more than 6 hours in the ED to get treated and discharged. ED at Eskenazi has different treatment areas, which are designed to response different type of emergency needs and requirements. It includes: intake unit, low acuity unit, high acuity unit, shock unit and CDU as different treatment areas. In total, ED at Eskenazi has capacity of 90 beds, 30 physicians and more than 90 nurses [22].

1.4 Thesis Objectives and Outlines

The main objective of this research study is to apply step by step SE approach to improve patient satisfaction and quality of care at Emergency Department of Eskenazi Hospital. SE approach is a great guide to drive this research project, since from the earliest phases of project, including system and scope definition, to data collection, model development, model improvement and even implementation, there are lots of tools and techniques that can be used to reach the main objective of this study. Objectives and aims of this research project can be summarized as follows:

The main problem that is going to be addressed in this report is to minimize LOS of patients at emergency department at Eskenazi hospital to be closer to the Nationwides average of US emergency departments. Currently, average LOS of patients in US emergency departments is 2 hours and 15 minutes, however patients spend 3 hours and 54 minutes averagely at ED of Eskenazi hospital [23].

The first objective of this research is to apply 6 steps of SE approach to improve patients experience by minimizing LOS of patients at ED of Eskenazi hospital.

The second objective of this project is to have organized data observation plans, analyze them and make good use of collected data in the mathematical model to have a good model which is as close as possible to ED process and system.

The third objective of this research study is to develop a DES model of ED process which is verified and validated with different techniques and using historical data from ED data base.

The fourth objective of this research project is to propose different what-if scenarios and test them to see different impacts on the LOS of patients at Eskenazi ED.

The fifth objective of this research project is to define 2 overcrowding conditions and test two better what-if scenarios with the new patient arrival rates and find the best solution to the overcrowding issue at ED of Eskenazi Hospital.

Second chapter of this report is a literature review chapter. It starts with ED simulation overview and explanation, followed by defining systems engineering approach as a method to solve complex engineering problems. Additionally, different tools of SE have been mentioned that are used in healthcare improvement studies.

Third chapter of this report is about the methodology of the research project. 6 steps of SE approach are explained and implemented in detail. First, the system and model scope are explained. Then different data collection phases and sources are being mentioned. Next step is to mention, simulation method and modeling tool. Additionally, different inputs of the model are explained, and the model development process has been discussed. Also, model verification and validation plans are discussed in detail. Once the modeling process is done, different what-if scenarios and the methodology to pick the optimal solution to overcrowding condition has been discussed.

Fourth chapter summarizes results from verification, validation, impacts of the what-if scenarios on the LOS of patients and finally the best scenario in case of overcrowding conditions is selected.

Last chapter (Chapter 5) summarizes the conclusion and future work ideas are proposed.

1.5 Thesis Contribution

- Getting advantage of systems engineering approach to run the DES model for the Emergency department at Eskenazi Hospital

- Use of different SE tools and techniques including: diagraming, data collection methods, interview, modeling, etc.
- Modeling the ED system, using Arena Simulation to better understand and analyze the ED performance by defining relevant KPIs (patient throughput, LOS).
- Implementing different set of observations from ED, used to create a detailed and multi aspect DES model, as a prediction tool for ED managers
- Implementing statistical analysis for collected data to derive probability distributions and ED performance investigation
- Defining and classification of Nurses different responsibilities to have a better resource modeling tool
- Proposing and testing 5 different what-if scenarios to reduce LOS of patients
- Testing 2 overcrowding conditions and selecting a solution from proposed what-if scenarios to minimize LOS of patients in case of emergency situations

2. LITERATURE REVIEW

This chapter gives an overview of the emergency department simulation and major challenges to ED process improvements. Then systems engineering approach will be proposed as a methodology to solve engineering complex problems. Finally, different tools and techniques of SE for healthcare delivery area and its improvements are mentioned and examined.

2.1 Emergency Department Simulation

Emergency Department (ED) is a vital component of each hospital, since its supposed to provide healthcare needs to patients at any moment (24/7). If the capacity and patient flow design of the ED is not defined based on the number of arrived patients, ED would be a very crowded and busy place in hospitals. Having a high number of patients in ED causes long waiting times for patients to be seen and treated. It can also make hallways very crowded, too. Moreover, it has some other negative effects on emergency departments staff (nurses, physicians, etc.). Facing a high volume of work and emergency cases can make them less productive and having less efficient communications between themselves [1] [24] [25].

There are some other major problems followed by overcrowding that not only affects ED staff, but patients, too. Overcrowding might make physicians and nurses to have more stress level and therefore act violently. This can be very dangerous to patients, since it would increase medical errors and mortality rates. Thus, considering emergency department overcrowding issue is being a very important and high priority task for all healthcare managers [26] [27].

ED process simulation and analysis has been a very important topic for the researchers to conduct their studies based on, since 1960 and still there are lots of improvements that can be applied to it. Researchers have designed different type of simulation methods to model ED process behavior, for a better understanding, which makes it easier to study and analyze. There are lots of benefits in creating simulation models of ED including: having a better understanding of the ED as a big system, finding the bottlenecks of the patient flow, reducing the time that patient spend in ED, using the simulation model as a cost-effective method to test different possible changes in ED, etc [1] [28] [29].

2.2 Systems Engineering, A Method to Solve Complex Engineering Problems

Systems Engineering (SE) is an engineering approach that helps better understand complex systems and solve engineering issues by looking into definition, design and control of the system based on the requirements, systems functionalities and objectives. In other words, its an interdisciplinary approach that brings successful systems into reality based on needs and functional requirements associated with that systems. This could be very helpful and efficient in terms of cost and resources usage, since it considers all required factors of a successful system before it even exists [19] [21].

SE approach has been used for more than 50 years for development of complex systems. Its being used in different engineering filed like production of ships, automobiles, aircrafts, software engineering, military, etc. SE experts have proved that use of systems engineering can increase the quality of the products and helps improving complex systems by reducing project schedule, while it only includes15-20% of project efforts [30].

SE approach is defined very well in an organized and doable manner that can help most engineering problems. As a summary, to follow the SE approach, first the system that is going to be studied or designed has to be defined with specific goals and requirements. Then, systems engineers will work with other engineering fields experts to come up with possible design options and alternatives and after trade-off analysis they decide about the best design option. Once, the design is finalized, its time to do verification and validation of the selected design option. Thats where engineers have to make sure that the system is designed and made in the most proper way and its satisfying its requirements and goals. Based on the INCOSE definition, the last step to go with SE approach is to implement assessment analysis to see how the system works. There are lots of benefits and advantages associated with the SE approach including, increased product complexity, reducing product development cycle time, increased safety, taking advantage of re-use of components, better resource management, etc [19].

Although Systems Engineering practices have been used in a wide variety of applications and fields related to different sciences and has been proved that they can bring more efficiency, quality and a lot of other advantages, theres been some resistance to use it in healthcare area. There has been a lot of valuable returns in use of systems engineering methods to improve healthcare quality wherever it was used, however healthcare field has been very slow to embrace this change [31] [32] [33] [34].

As discussed earlier, healthcare organizations show resistance to apply systems engineering practices to improve their performance. However, there are lots of great experiences and examples in other different categories, like use of SE approach to reduce cost of production in a big manufacturing company (BOEING), that can be very helpful to be investigated and work as a lesson for healthcare administrators. Although there isnt significant technical effort and costs associated with use of systems engineering itself, there are lots of obstacles and difficulties found in organizational, multi- organizational and environmental levels to systematically apply SE approach as a continuous improvement method in healthcare filed. There are lots of regulations and policies defined for managers in healthcare delivery process. These regulations, along with lack of support for researchers and novel studies to improve healthcare delivery process, are all the reasons that SE approach is having less impact on healthcare sector compare to other applications. To get the most possible advantages of SE approach in healthcare field, all the stakeholders must be committed, to use SE, and well equipped with the analytic system thinking techniques. As a result, all healthcare professionals, healthcare managers, engineering groups, employers and state and federal governors should consider use of SE as a very helpful tool to improve quality of healthcare [9].

2.3 Systems Engineering, Healthcare Simulation and Limitations

Systems Engineering and simulation arent new to healthcare delivery world. These two tools have been used for more than 50 years and from 1950s have been used to better understand healthcare delivery process and make improvements to existing healthcare. However, with the new changes to current healthcare operations and with the new definitions to a successful healthcare system, perspectives have been updated for simulation intentions. New healthcare systems are patient-centered systems, means the focus of the system is to bring the best quality of care to patients. For example, one of the important considerations that shows the quality of care for patients is Length of Stay (LOS) of patients in emergency department. Although there are thousands of papers published in healthcare field, there are still emergency departments that are having average LOS of patients more than the national average. By using systems engineering approach and having patients satisfaction as one of the early requirements defined for the system, researchers would know whats going to be the outcome of the study and make plans for it ahead of time for model development and data collection methods [9] [24] [35].

As mentioned earlier, although there are lots of simulation studies in the history of this research, there still lots of limitations and gaps in this area. One of the biggest challenges in this area, is that healthcare delivery systems are very complex systems and capturing all the complexity and details of these systems is very difficult. There are so many human and physical resources, and IT related factors associated with those systems that capturing all of them is very difficult. Therefore, when enough details and factors of the healthcare systems arent captured, scope of the study and accuracy of the results are questionable. On the other hand, data availability limitations are one of the other important considerations. When enough data arent available for researchers and model developers, there will be less accurate and reliable results coming from models which reduces the value of the study. Moreover, verification and validation techniques arent considered in the early phases of the study. This causes problems later in the model development process. By having SE approach implemented, patients flow and research goals will be in the same directions and also collected data and patients flow will be validated in the early stages along with statistical methods at the end of the study. This could save a lot of time and effort and could make more reliable models and results [36].

2.4 Systems Engineering Tools Used for Healthcare Applications

Systems Engineering approach provides a lot of helpful tools and techniques for the healthcare application, that can be used in all 6 steps of the process. One of the fundamental tools of SE, which is used in almost all engineering applications, is "Vee" process model.

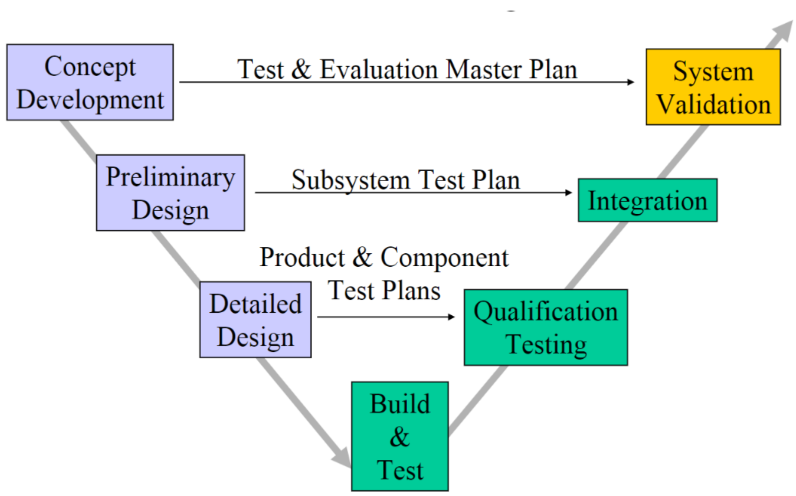


Fig. 2.1. Vee Diagram [35]

Following this diagram, on the upper left side every systems design process must get started with concept development of the system, where the users needs and requirements and what the system should be at the end will be defined, and ends on the upper right side, with a user validate system. As it can be seen from the diagram, Vee diagram has two different set of activities. On the left side of the diagram, creating the detailed design of the system is the outcome of the process and it gets achieved by decomposition and definition of system architecture design. Moreover, the right site of the Vee diagram includes activities associated with integration and validation of the subsystems to make the final system design and goal. Its important to know that verification and validation process starts from the earliest steps of the Vee diagram, conceptual development, to the end, where the whole system must get approved [35].

When creating a mathematical representation of a healthcare system, one of the major concerns and consideration of the modeler should be about having a good data. A model must be feed with enough and right data to be able to provide a good prediction of the systems quantitative performance. This even get more serious, when the system that is going to be modeled, is a healthcare system. Healthcare operations are very stochastic, and every individual component of the system can make a great impact on the systems performance patients satisfaction level. There are several ways that correct data can be used by researchers in healthcare simulation studies. Electronic Health Records, or historical data, observations and scheduling interviews are just a few examples of how data can be collected and used. On the other hand, once enough amount of data is collected, there has to be some statistical analysis applied on gathered data, otherwise those data will be meaningless and useless [9] [20].

One of the other SE tools that can be helpful in healthcare area are systems-analysis tools. Systems-analysis tools can be a very helpful way of understanding the complexity of healthcare system and to find out how the system is operating and see if it is satisfying the requirements of a healthcare system with good performance. Analyzing patient flow in a hospital or finding out about allocation of the resources in an emergency department are just some examples of the applications of these tools. Use of these tools are mostly applicable for existing healthcare systems, where by doing some analysis and testing some possible changes to current system, systems engineers can achieve improvements in performance of the healthcare system. Two important components of systems-analysis tools are models and simulation. Models are the mathematical representation of the system, and by using models, different sections of the healthcare system can be described as specific subsystems that can affect each other and making changes to any of the subsystems can result a difference in the overall performance of the system. This can save a lot of money and time, since just by modeling a system, researchers are able to test different possible changes to an existing healthcare system and find out about overall systems outcome without on-site implementation of the changes [9].

Discrete Event Simulation (DES) is an example of systems-analysis tools that is widely been used to simulate and improve healthcare operations. It can be used in different healthcare fields like operation rooms, emergency departments and other healthcare provider settings [37]. MM Gunal and M Pidd did a review study about use of DES in healthcare (2010). They were able to group use of DES based on different objectives and different level of details [38]. In 2014, Karim Ghanes and his colleagues, conducted a DES study to not only understand the complex behavior on ED, but also reducing Length of Stay (LOS) of patients. Their approach was to optimize LOS based on a budget constrain, and that cost was a result of different staff scheduling [39].

One of the big advantages of using DES models is reducing the time and efforts of rework. It means by having a general representation of the healthcare operations, it can be used in different setting. In 2010, Paola Facchin et al, created a general and flexible ED representation that could get used in all emergency departments of three large town in Italy. There was no need to change model structure to model different emergency departments. [40].

DES has many other different applications and can be used in different healthcare setting. For example, Michael D. Seminelli et al (2016) used a DES study to improve healthcare operations at an Optometry clinic. The main objective of the study was to investigate patients throughput and they were able to optimize staffing schedules and increase number of daily treated patients by 8 [39]. DES models arent only used to reduce LOS or increase patients throughput of the ED. One of the other applications of DES is to improve resources utilization. Hamad and Arisha (2013) created a DES model of an emergency department in North Dublin, which was made to increase productivity and utilization rate of the healthcare providers [42].

One of the other important tools of systems engineering, and probably the newest one, in Model Based Systems Engineering (MBSE). MBSE is a novel method of modeling, in a documented paradigm that supports SE approach in different steps including system definition (requirement analysis, design, analysis, verification and validation. In other words, MBSE supports the development of the system from the earliest phases (conceptual design), to the later life cycle states. Its been proved that use of MBSE can bring important advantages to the system development process including: enhanced communications between all stakeholders of the system, increasing quality and productivity, reducing risks associated with the development activities, increased knowledge transfer between team members. MBSE could be considered as a new way of applying SE approach in different applications, including healthcare. In the traditional SE approach, documents are the core platform and framework of the study, however in the MBSE, models are considered as framework of the development process [22] [43] [44].

MBSE uses the advantage of models and to develop models, there must be a modeling language used for it. One of the popular systems modeling languages in the MBSE world, is SysML, Systems Modeling Language. Its an extension of the UML, Unified Modeling Language. UML is an object-oriented software development language and is developed by Object Management Group (OMG). SysML language was developed by OMG to be a handful tool available to engineers for modeling complex systems like healthcare systems. SysML cover four different views of system (structure, behavior, requirements and analytic) and these views are defined by 7 different type of diagrams available for use. These diagrams are: Activity Diagram, State Machine Diagram, Sequence Diagram, Use case Diagram, Block Definition Diagram, Internal Block Diagram and Parametric Diagram [22] [45].

3. METHODOLOGY

This chapter explains 6 steps of the Systems Engineering approach that is designed to improve healthcare delivery systems, implemented for ED of Eskenazi Hospital. Each step is explained and implemented in detail.

As mentioned earlier in the introduction, the methodology proposed for this study is to apply systems engineering approach to improve healthcare delivery process in ED of Eskenazi hospital. There are 6 defined steps to follow SE approach for this purpose and in each one of the steps, several SE tools and techniques have been used. The following pages will be all based on those 6 steps:

3.1 Define system purpose and scope, specify required functions and resource types, and develop relevant performance measures along with desired performance thresholds

This step can be considered as the conceptual design and development phase of the Vee diagram. Here we define all the characteristics of the System of Interest (SOI). To get advantage of different SE tools, MBSE diagraming framework will be used along with traditional SE method, which is documentation, to define system characteristics and different parameters related to it. As mentioned earlier in, SysML is one of the languages that can be used in MBSE approach and it consists of 3 different type of diagrams: Behavior diagram, Requirement Diagram and Structure diagram. Activity, Sequence, State Machine and Use Case diagrams are sub diagrams of the Behavior diagram. Block Definition, Internal Block, Parametric and Package diagrams are sub diagrams of the structure diagram. Finally, Requirement diagram doesnt have any sub diagram and is the only diagram used in Requirement type diagram. Below is the definition and usage of different diagrams in SysML:

Requirement Diagram: As the name explains, this diagram is used to show different requirements of a system in a text-based environment. Additionally, it can show the relationship between different requirements and design elements. One of the biggest advantages of this diagram is that it can be used in requirements traceability activities.

Activity Diagram: This diagram is a behavior diagram that is used to show the actions in orders based on inputs, control and outputs. In other words, this is used to show how the system actions are done to transform inputs to outputs.

Sequence Diagram: Its a behavior diagram and is supposed to show messages that is exchanged between parts of a system.

State Machine Diagram: Based on SE definition, each system will have a state that are triggered by set of events. State machine diagram is used to show the transition of an entity in the system between these states.

Use Case Diagram: Each system is supposed to achieve set of goals. Different functions of a system and how different actors of a system work together to achieve systems goals are shown in Use case diagram.

Block Definition Diagram: Its one of the structure diagrams of SysML and is used to show the decomposition and classification of system elements in terms of Blocks.

Internal Block Diagram: Like the system that have different set of elements and theyre classified in block definition diagrams; each element might consist different parts and their interconnection is shown in Internal Block Diagram.

Parametric Diagram: Its used as an engineering analysis tool in SysML, where different property values of parts will be shown. It can be used different engineering formulas or other properties related to a part in system.

Packaging Diagram: Its a high-level structure diagram that includes all model elements in terms of packages.

Emergency Department at Eskenazi Hospital and Care Process:

Eskenazi hospital is located at Indianapolis downtown and is one of the most important healthcare providers in the area. Emergency Department of Eskenazi supports treatment process of around 100,000 patients per year. Patients are treated based on the first in, first out pattern, means they will be placed in the appropriate treatment area based on the availability of rooms. To define the patient flow, the pathway which patients go through to get appropriate treatment and leave the ED, there were a couple of observations and discussion with ED staff and physicians. Figure 3.1 shows the final and validated patient flow of ED.

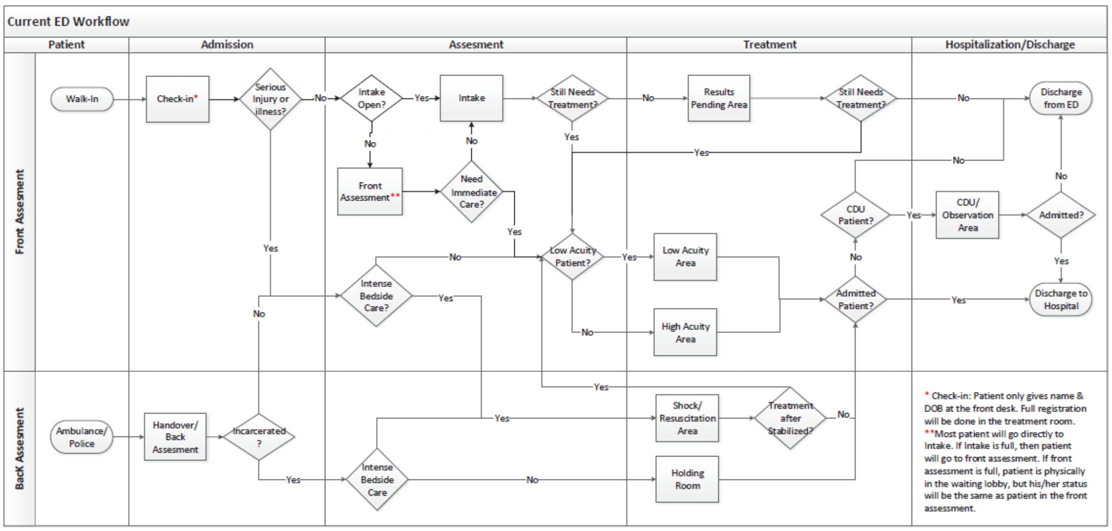


Fig. 3.1. Patient Flow Diagram

This is the generic pathway of the ED treatment process that has been defined to represent the actual process. As it can be seen in the patient flow, journey of a patient starts with one of the two arrival methods, Walk-in and Ambulance/ Police. These two arrival points are considered as front (Walk-in) and back (Ambulance/ Police) arrivals. The first interaction point of the patients and ED staff is where they get registered in front and back assessment decision points. As it is defined by ED process at Eskenazi hospital, patients will be quickly registered first when theyre arrived and will be assigned to the appropriate treatment area, based on the acuity level and their initial condition. Its worth to mention that most of the patients coming to the back assessment will get assigned to the high acuity area. Complete registration of patients, getting their full identity and insurance information, is done by ED staff when theyre stabled and getting treatment in the assigned rooms, which is called bed-side registration. Now that patients have been assigned to their treatment area, lets look at those areas. There are 5 different treatments area based on the acuity level, including intake, low-acuity, high-acuity, shock and holding area.

3.1.1 Intake Area

Based on the available data from historical sources and actual observations, which will be explained later, majority of ED patients will be board to intake area. Additionally, more than 70% of patients coming to the intake will leave the ED without going to any other places. Therefore, intake is the most crowded area in the ED at Eskenazi. There 7 pods in intake and each pod has 3 rooms, with one assigned nurse all the time. One of the pods of intake is called SWAT, which is a fast track treatment unit for patients with minor issues. Theres some possibility that patients of intake go to Low Acuity area, if more treatment is needed, but as mentioned earlier most intake patients will leave ED directly.

3.1.2 Low-acuity Area

Low-acuity or LA area, is designated to patients coming to ED, who require staying there for a longer time, even more than a day, to get stabled. It consists of two different sections, LA psychology and LA medical. Patients will usually leave LA after enough and appropriate treatment is received, however based on the collected data, a small percentage of LA patients will go to High-acuity or Shock area. LA area includes 24 rooms and usually there are 4 nurses available to provide appropriate care.

3.1.3 High-acuity Area

As mentioned earlier, mostly patients coming from the back side are going to High-acuity or HA area. As the name of this area explains itself, its designated for patients with high-acuity illnesses. Due to different nature of issues with patients of this area, 50% of HA patients will get admitted to the hospital for more treatment and to continue healing process. Additionally, based on the collected data, they stay around 6 hours in HA to receive appropriate treatment. Based on the time of the day, theres always 3 to 4 nurses available in HA, and there are also 16 rooms there.

3.1.4 Shock Area

Shock are is one of the crucial areas in ED at Eskenazi. Thats designed for patients coming to ED with a very severe situation, who need immediate attention and care. Due to severe condition of those patients, after they get stabilized, they will be transferred to other ED areas for more treatment. There are 5 rooms designated for Shock area and 2 to 3 nurses available all the times.

3.1.5 Holding Area

Since only 3% of patients coming to ED go to this area, it doesnt have much effect on the ED simulation study. Those patients, who are incarcerated and must be hold, while theyre treated will be kept in Holding area.

3.1.6 ED Resources

One of the other necessary steps of step 1 in SE approach is defining required resources used in the system to bring the successful result or product. One of the required resources of ED are rooms. Rooms are where patients will be kept until they diagnosis and treatment process are done. As described earlier, there are different number of rooms for each treatment area. Another crucial type of resource working in ED to help system getting work done, are human resources. Registrations staff, registered nurses (RNs), care technicians (CTs), physicians, students, security staff, housekeeping staff are all examples of human resources at ED. In this study, the focus is on CTs, RNs and physicians. Each one of these care providers are responsible for some tasks related to treatment process and their availability is based on the treatment area they work at. Later, when data collection step is explained, there will be detailed information about their schedule and availability.

3.1.7 Performance Measures

For every system, whether an existing one or some new system developing through SE approach, there should be some qualitative and quantitative measurements considered for system successful implementation evaluation. In other words, from SE perspective, there must be statistical analysis implemented on systems performance measurements to assess system based on what it was defined as the functional requirements of the system in the conceptual design phase. In our case, there are some TPMs (Technical Performance Measures) including: Length of Stay (LOS), Patients throughput (number of patients visited ED through specific duration), Resources utilization rate (including physical and human resources), etc [35].

3.2 Specify, collect, and develop required data through data collection methods

Second step of the SE approach is probably the most important step through improvement of healthcare delivery system of ED at Eskenazi hospital, since without having right and enough information about the existing system, there wont be a good understanding of current system performance. This would lead systems engineers into a big trap, and that is not having enough knowledge and understanding of a complex system like the healthcare system. This might cause waste of resources, since it will affect the decisions that are being concluded from current state of the system. Additionally, data collection step is one the biggest challenges in healthcare improvement studies, since historical data might not be usable and effective as it should be [37]. Thats where systems engineering tools will be used to propose different methods of data collection. In this study, data have been collected through different sources including: historical and electronic data from ED database, data sheets of ED staff schedules, interviews with ED staff (RN, CTs and physicians), direct observations by SE research team members and direct observations by interns working in Eskenazi Hospital.

Different set of interviews were conducted in different times. Some of them happened in presence of an ED physician, who dedicated a lot of her time for the project. The other interviews conducted by SE team members and interns, when they were doing their observation and data collection in ED and by talking to ED care technicians and nurses. The information that were collected through these interviews leaded to the development of patient flow diagram, ED process understanding, development of observation plans for data collection and nurses daily tasks definitions, which will be explained in detail later. Another source of data for this research was use of historical and electronic data. Those data were extracted with the help of a data analyst from ED of Eskenazi for arrival data, Length of Stay (LOS) of patients, number of patients treated in a defined duration of time (patient throughput) and probability that a patient goes to which treatment area first, and these data were used in the model development and verification and validation of the model (step 3).

Moreover, there are some scheduling data for the availability of human resources to provide treatment for patients and some other documents for the number of available rooms in each treatment area. All these available data will be shown in the following pages.

Observations were a very helpful tool in the data collection process. One of the biggest advantages of having someone follow the ED process and ED staff to understand and collect tasks times is that the data collected through this process cannot be extracted from any other sources. For example, there isnt any time collected about how much time a nurse spends with some specific patient, or there isnt much data about patients transfer route to other treatment areas, when theyre done in their first treatment process. There were 3 rounds of data observation in this study. First, observations conducted by SE team member. By help of a former masters student of the SE team and the writer of this report, data were collected about how much time patients spend in the registration area and the plan of other observations were decided by observing the ED process and talking to ED staff. Another round of ED observation was conducted by a medical school intern and the focus of this observation round was to collect overall time that each one of the ED staff (CTs, RNs and Physicians) spend in patients room and to collect total time a patient spends in any of the treatment areas. Additionally, the area that patients transferred after their treatment is done was observed and documented, too.

Final round of observations for data collection was collected by a student of Mathematical sciences. The focus of this observation was to focus on the nurses to break down their daily tasks into different type of responsibilities they have as ED RN. These tasks were grouped in different workflows that were defined by the help of ED physician, who was mentioned earlier. These workflows and detailed data associated with their time will be explained in the following section.

3.2.1 Extracted Data and Analysis

Arrival Data

Based on the defined patient flow, there are two type of arrival in the system, front assessment and back assessment. There are historical data based on the day of the week and per 1/6 hour for 24 hours of a day for both front and back arrival patients. As an assumption for the model, there will be only one arrival node in the system and this arrival will be the sum of both front and back arrivals. Following figure is the excel file that was extracted for patients arrival data.

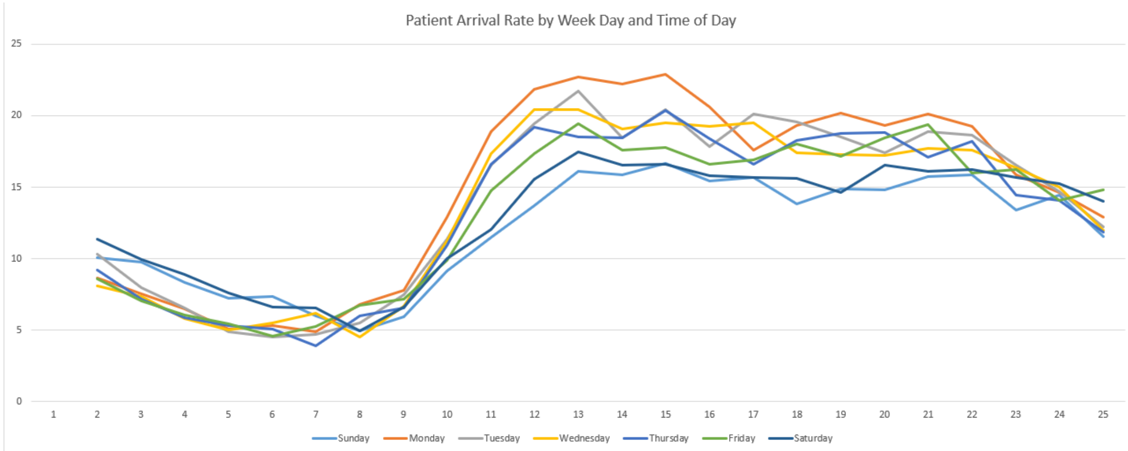


Fig. 3.2. Patient Arrival Rate by Day of Week and Hour of Day

Registration

As mentioned earlier, there were # of patients observed in registration area and since based on the observations and recommendations of ED staff there isnt much waiting and waste of time in this process, no more data was needed for that.

Room Assignments

Based on the historical data, patients will be assigned to their first treatment area based on the probability percentages. Additionally, after first treatment process, some patients might need more treatment and must be transferred to other areas. This was collected through in person observations.

Human Resources Schedules

Following tables shows the human resource schedules and their availability, extracted from ED data sheets:

Table 3.1.
CT Schedule

Treatment Unit	7a-11a	11a-3p	3p-7p	7p-11p	11p-3a	3a-7a
Intake	1	2	2	2	1	1
LA	0	1	1	1	1	0
HA	1	2	2	2	1	1
Shock	0	0	0	0	0	0

3.2.2 Nurse Workflows Definition

As it was described earlier, last phase of data collection process was with a focus on RNs to understand how they spend their day and to see what type of responsibilities they have as a nurse. Data collector was shadowing different nurses and talking to nurses about their tasks grouping method. Additionally, there were couple of meetings with the writer of the report and the ED physician working with the SE team and finally nurses workflows were defined as follow:

Workflow: A clinically meaningful goal accomplished by a set of tasks performed by an RN

Check: RN engages in a routine review of the overall ED clinical condition to determine what tasks are outstanding.

Care: RN engages in a routine provision of patient care independent of a specific medical order

Intake: RN facilitates patient's entry into the RN's care area of the ED

Discharge: RN facilitates patient's departure from the RN's care area of the ED to another ED care area, an inpatient bed, another medical unit, home, or police custody

Medications: RN facilitates medication delivery to patient

Orders: RN facilitates provision of medically ordered care

Table 3.2.
Nurse Schedules (Monday to Friday)

Treatment Unit	7a-9a	9a-11a	11a-3p	3p-7p	7p-11p	11p-3a	3a-7a
Intake Pod 1	1	1	1	1	1	1	1
Intake Pod 2	1	1	1	1	1	1	1
Intake Pod 3	1	1	1	1	1	1	0
Intake Pod 4	0	1	1	1	1	1	0
Intake Pod 5	0	1	1	1	1	0	0
Intake Pod 6	0	0	1	1	1	0	0
Intake Pod 7	0	0	1	1	1	0	0
LA Pod 1	1	1	1	1	1	1	1
LA Pod 2	1	1	1	1	1	1	1
LA Pod 3	1	1	1	1	1	1	1
LA Pod 4	1	1	1	1	1	1	1
HA Pod 1	1	1	1	1	1	1	1
HA Pod 2	1	1	1	1	1	1	1
HA Pod 3	1	1	1	1	1	1	1
HA Pod 4	0	0	1	1	1	1	1
Shock Pod 1	1	1	1	1	1	1	1
Shock Pod 2	1	1	1	1	1	1	1
Shock Pod 3	0	0	0	1	1	0	0

Table 3.3.
Nurse Schedules (Saturday and Sunday)

Treatment Unit	7a-9a	9a-11a	11a-3p	3p-7p	7p-11p	11p-3a	3a-7a
Intake Pod 1	1	1	1	1	1	1	1
Intake Pod 2	1	1	1	1	1	1	1
Intake Pod 3	1	1	1	1	1	1	0
Intake Pod 4	0	1	1	1	1	0	0
Intake Pod 5	0	0	1	1	1	0	0
Intake Pod 6	0	0	0	1	1	0	0
Intake Pod 7	0	0	0	0	0	0	0
LA Pod 1	1	1	1	1	1	1	1
LA Pod 2	1	1	1	1	1	1	1
LA Pod 3	1	1	1	1	1	1	1
LA Pod 4	1	1	1	1	1	1	1
HA Pod 1	1	1	1	1	1	1	1
HA Pod 2	1	1	1	1	1	1	1
HA Pod 3	1	1	1	1	1	1	1
HA Pod 4	0	0	1	1	1	1	1
Shock Pod 1	1	1	1	1	1	1	1
Shock Pod 2	1	1	1	1	1	1	1
Shock Pod 3	0	0	0	1	1	0	0

Table 3.4.
Physician Schedule

Treatment Unit	7a-3a	9a-6p	3p-11p	5p-2a	11p-7a
HA/Shock	1	0	1	0	1
Intake/LA	1	1	1	1	1
Intake (SWAT)	0	1(till 5p)	0	1(till 11p)	0

Interruptions: RN is interrupted from current workflow by an urgently necessary clinical task of higher priority

Downtime: RN is not performing medically relevant activities

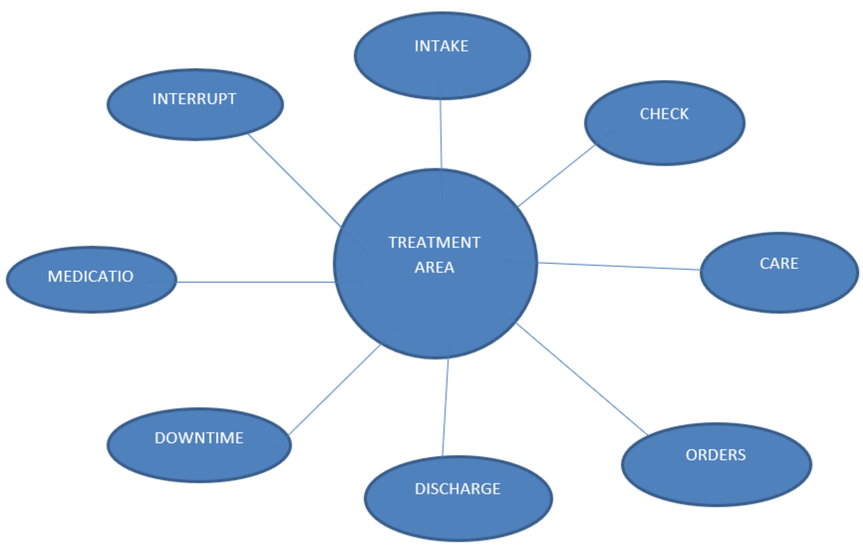


Fig. 3.3. Nurses Workflows

Additionally, the following table shows different type of tasks getting done by RNs, in any of the defined workflows:

Table 3.5.
Nurses Workflows Categorize

Workflow	Tasks
Check	Check for orders, results, etc.
Care	Routine patient care activities
Intake	Take report, clean patient, clean room, data entry and observation, patient discussion, blood draw, line placement, EKG
Discharge	Printing discharge paperwork, data entry and observation, patient discussion, give report, clean room
Medications	Medication unpackaging, medical administration, data entry, patient discussion, pharmacy discussion
Orders	Blood draw, EKG, take patient to radiology, etc.
Interruptions	Patient request, clinical discussions
Downtime	No task undertaken

3.3 Design, validate, and verify appropriate system models. This involves selecting the right modeling tools, building and validating the model

As the title of this step explains, this is where based on data acquired in step 2, and the system scope and definition, a mathematical model will be designed to show system overall performance. First, a modeling approach and the appropriate tool for it will be explained. Then, the model will be designed and created based on the designed workflow and analyzed data from step 2. Finally, a verification, validation approach will be designed to make sure the model is working well and is exactly representing the ED at Eskenazi hospital.

3.3.1 Discrete Event Simulation Theory

Discrete Event Simulation or DES is one of the simulation paradigms, that is being used by a lot of computer simulation tools to model different type of systems. This simulation is created based on what is called, State. A state of a system is set of data that includes different characteristics and system behavior measurements that can get changed and evolved by time, when system is moving forward to achieve its final goal. Different variables in program are where the state of the system is being stored. State of a system can be considered in different ways that can be showing different characteristics of the modeled system. For example, in ED simulation, a state can be number of patients waiting to enter the Intake treatment area, or number of treated patients in Low-acuity area. Variables of a system will change over time based on the function S(t), which works as a step function. It means that systems state gets changed with discrete events over time and in each moment of the simulation time, system is having a specific state with its corresponding occurrence time. One of the other elements of DES is clock, which makes a list of different events in line and the time that theyre supposed to happen in the model evolution.
As a summary, a DES tool works based on a very simple loop and by repeating the same loop until the time is up for the simulation. The modeler first sets the clock to 0 and then executes initial events and create a list based on their time of occurrence. Then it completes all the events available in the list until theyre all done. Then it looks to see if there are more events in the schedule list. If theres more, it will execute it, otherwise it terminates the simulation run [46].

3.3.2 Arena Simulation Software

Arena Simulation Software is a DES tool from Rockwell Automation which is widely used in different applications such as manufacturing companies, service engineering area, healthcare, etc. Arena gives the users the option of a comprehensive simulation environment, that have different tools and features to support the simulation study in all the steps. Modeling in Arena is based on objects called modules, which are the building blocks used for model creation. Arena can be a good tool to support simulation studies in terms of logic, data, statistical analysis, etc. Arena is based on the SIMAN simulation language and with providing flexibility and great modeling power, can be used in complicated problem and modeling studies [47].

3.3.3 Data Analysis and Probability Distributions

One of the tools used in Arena software is Input Analyzer that is used in the software to help modeler to put raw data in the software and get the probability distribution of different processes in the model, that can be used in Arena [47].

In this research, several probability distributions are used, and they are, Beta (BETA), Lognormal (LOGN), Gamma (GAMM), Weibull (WEIB), and Triangular (TRI). All probability distributions have been extracted from Arena Input Analyzer tool and they have passed at least one of the statistical tests (Kolmogorov test or Chi-square test). The following section will summarize some of the features of each one of these distributions [48].

Beta Distribution: It is defined as Beta (β, α): BETA (Beta, Alpha) where beta and alpha are shape parameters and are positive real numbers.

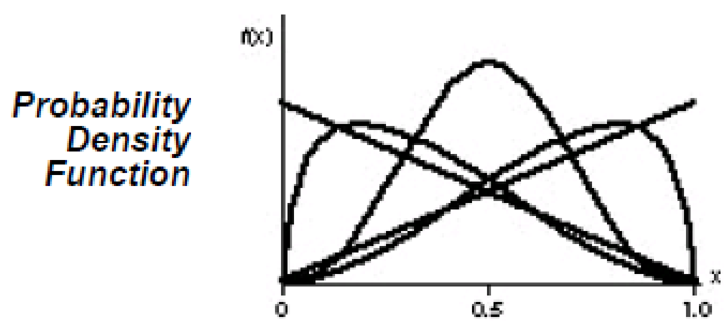


Fig. 3.4. Beta Distribution [48]

Lognormal: That is defined as Lognormal (μ, σ): LOGNORMAL (LogMean, LogStd) and both μ and σ are positive numbers.

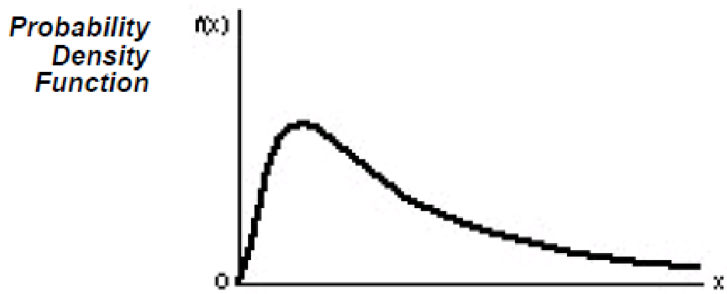


Fig. 3.5. Lognormal Distribution [48]

Gamma: It is defined as Gamma (β, α): GAMMM (Beta, Alpha) where beta and alpha are shape parameters and are positive real numbers.

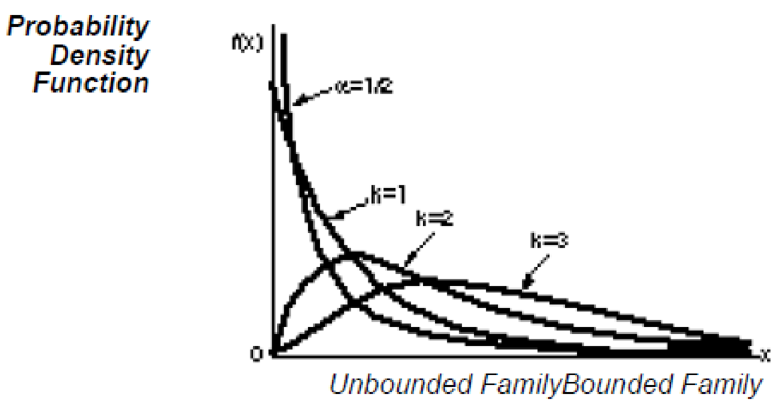


Fig. 3.6. Gamma Distribution [48]

Weibull: That is defined as WEIBULL (β, α): WEIB (Beta, Alpha) where beta and alpha are shape parameters and are positive real numbers.

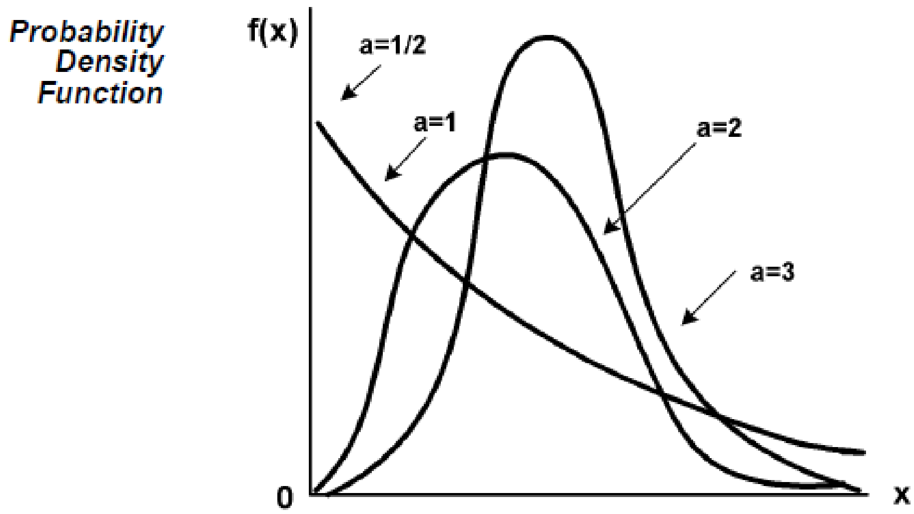


Fig. 3.7. Weibull Distribution [48]

Triangular: It is defined as Triangular (a, m, b): TRIANGULAR (Min, Mode, Max) where $a < m < b$ [48].

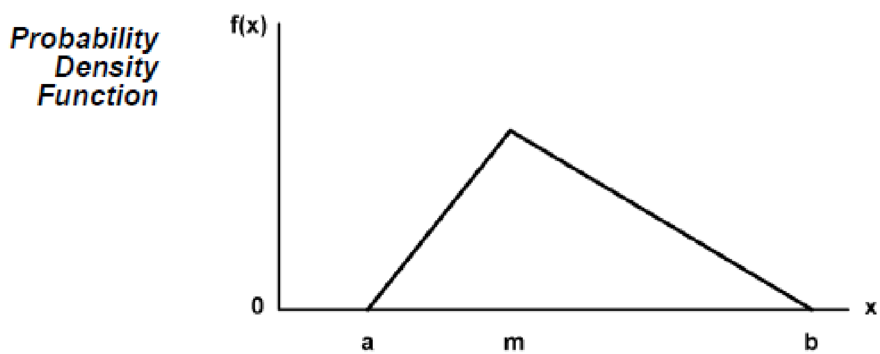


Fig. 3.8. Triangular Distribution [48]

The following section summarizes the probability distributions for all treatment process and for each treatment area, one example of a data fit histogram is shown. All the data are extracted from the observations data.

SWAT Probability Distributions: For SWAT treatment area BETA, LOGN and GAMM distributions are used, and the following table shows distribution parameters used in the model.

Table 3.6.
SWAT Probability Distributions

Treatment Process	Probability Distribution
Nurse Intake Process	$0.5 + 10 * \text{BETA}(0.844, 4.13)$
Nurse Check Process	$0.5 + 7 * \text{BETA}(0.531, 2.32)$
Nurse Interrupt Process	$0.5 + \text{LOGN}(0.822, 0.508)$
Nurse Care Process	$0.5 + 6 * \text{BETA}(0.53, 1.4)$
Nurse Orders Process	$0.5 + \text{GAMM}(1.19, 1.46)$
Nurse Medications Process	$0.5 + 4 * \text{BETA}(0.973, 2.42)$
Physician Process	$-0.5 + 12 * \text{BETA}(1.84, 2.31)$
Nurse Discharge Process	$0.5 + \text{LOGN}(1.24, 1.08)$

Below is the nurse discharge process of SWAT area as an example:

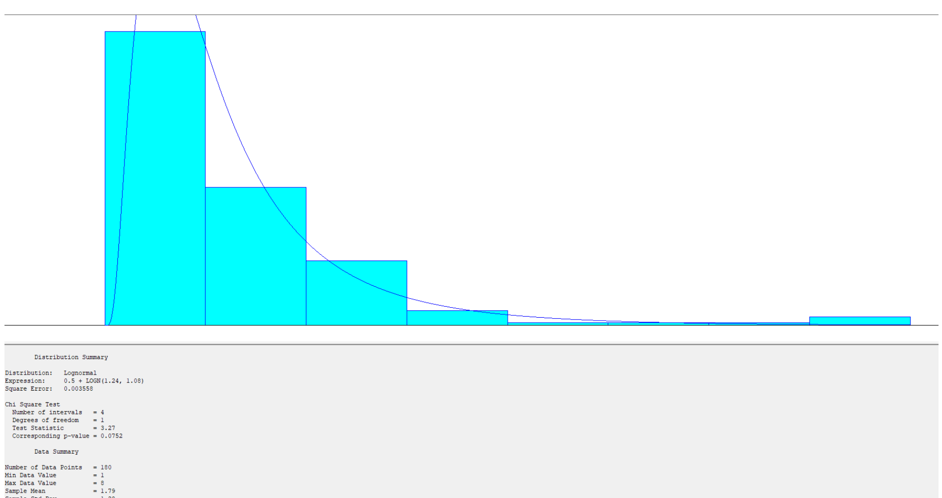


Fig. 3.9. SWATS Nurse Discharge Process Data Fitting Histogram

Intake Probability Distribution: For intake treatment processes, mostly GAMM is used for distribution and CT process is the only BETA distribution.

Table 3.7.
Intake Probability Distributions

Treatment Process	Probability Distribution
CT Process	$60 + 360 * \text{BETA}(1.21, 1.21)$ in Seconds
Nurse Intake Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.2446$
Nurse Check Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.0285$
Nurse Interrupt Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.0442$
Nurse Care Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.0403$
Nurse Orders Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.1974$
Nurse Medications Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.0982$
Physician Process	$-0.5 + \text{GAMM}(2.83, 3.07)$
Nurse Discharge Process	$(1.5 + \text{GAMM}(4.63, 1.57)) * 0.1385$

Physician data fist histogram as an example:

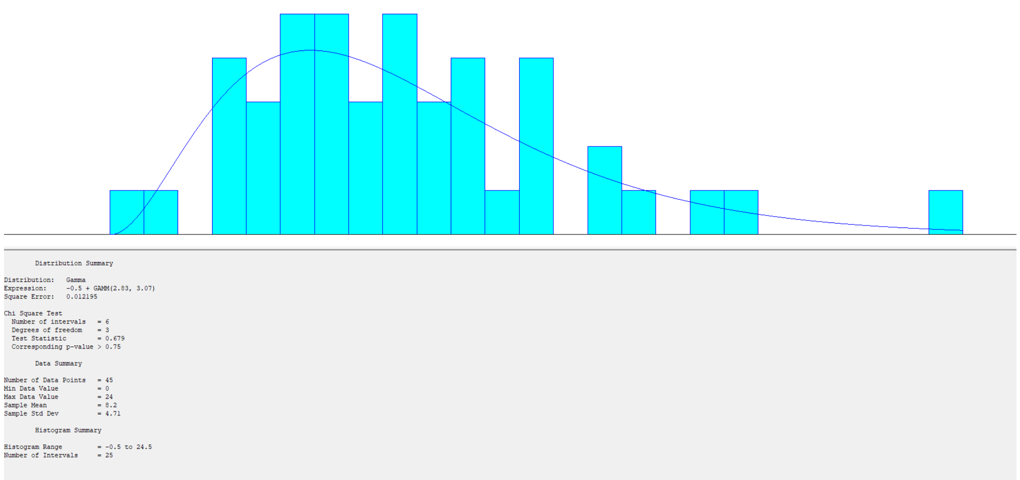


Fig. 3.10. Intake Physicians Process Data Fitting Histogram

LA Probability Distribution: For LA treatment area, LOGN, GAMM and BETA distributions are used.

Table 3.8.
SWAT Probability Distributions

Treatment Process	Probability Distribution
CT Process	$0.5 + \text{LOGN}(1.5, 1.46)$
Nurse Intake Process	$0.5 + \text{GAMM}(0.893, 1.69)$
Nurse Check Process	$0.5 + 6 * \text{BETA}(0.6, 3.38)$
Nurse Interrupt Process	$0.5 + 25 * \text{BETA}(0.173, 3.74)$
Nurse Care Process	$0.5 + 15 * \text{BETA}(0.536, 5.29)$
Nurse Orders Process	$0.5 + \text{LOGN}(1.94, 2.38)$
Nurse Medications Process	$0.5 + \text{LOGN}(1.12, 0.929)$
Physician Process	$-0.5 + \text{GAMM}(6.7, 1.34)$
Nurse Discharge Process	$0.5 + 11 * \text{BETA}(0.581, 4.09)$

Nurse orders treatment process data fitting histogram is like:

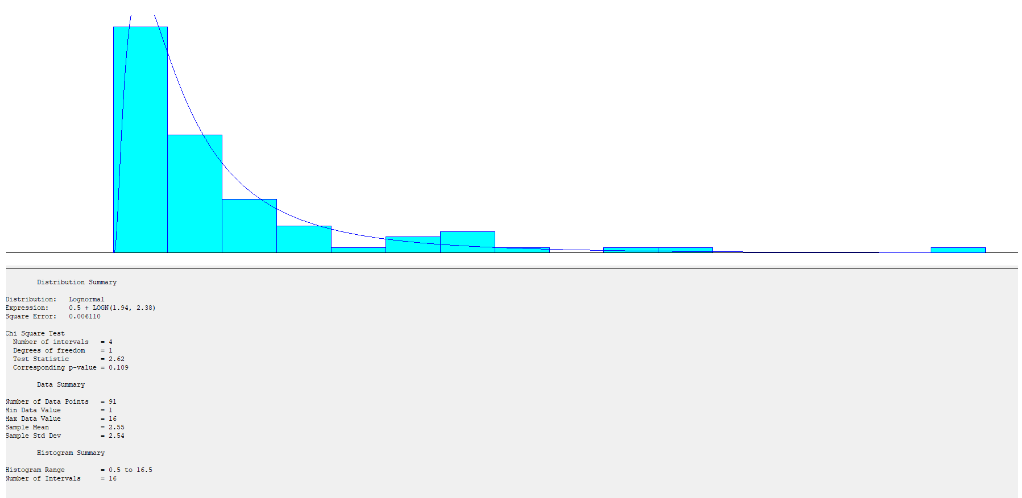


Fig. 3.11. LA Nurses Orders Process Data Fitting Histogram

HA Probability Distribution: For HA TRIA, LOGN, BETA, WEIB and GAMM data distributions are used.

Table 3.9.
HA Probability Distributions

Treatment Process	Probability Distribution
CT Process	TRIA $(3.5, 5.5, 7.5)$
Nurse Intake Process	$0.5 + \text{LOGN}(1.24, 1.08)$
Nurse Check Process	$0.5 + 6 * \text{BETA}(0.523, 2.2)$
Nurse Interrupt Process	$0.5 + 13 * \text{BETA}(0.436, 3.28)$
Nurse Care Process	$0.5 + 7 * \text{BETA}(0.83, 3.36)$
Nurse Orders Process	$0.5 + \text{WEIB}(3.16, 1.1)$
Nurse Medications Process	$0.5 + \text{LOGN}(1.41, 1.19)$
Physician Process	$-0.5 + \text{GAMM}(11, 0.996)$
Nurse Discharge Process	$0.5 + 20 * \text{BETA}(0.396, 3.55)$

Nurse orders process data fitting is as follow:

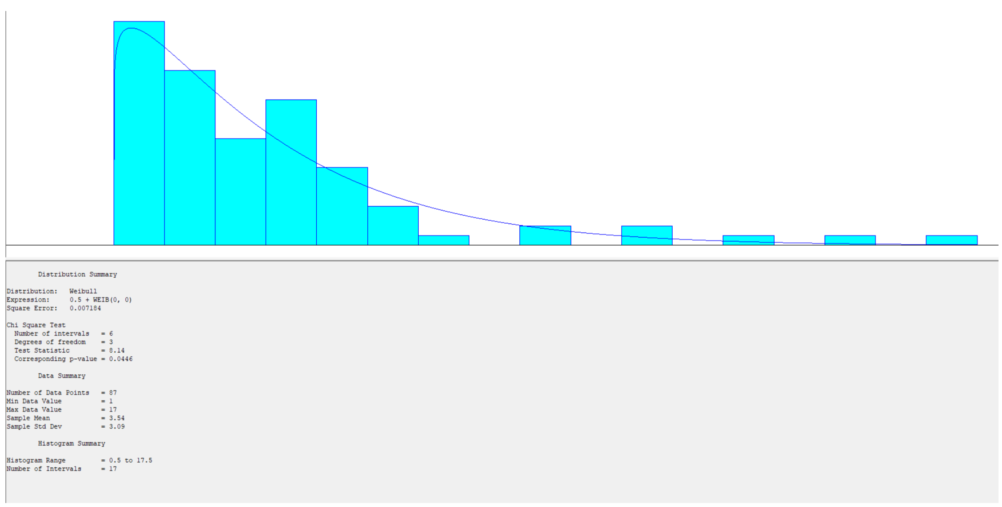


Fig. 3.12. HAs Nurses Orders Process Data Fitting Histogram

Table 3.10.
Shock Probability Distributions

Treatment Process	Probability Distribution
Nurse Process	2 + GAMM (56, 0.737)
Physician Process	4.5 + GAMM (31.5, 0.864)

Shock Probability Distribution: For Shock treatment processes GAMM distribution is used.

Shock nurse process data fitting histogram is as follow:

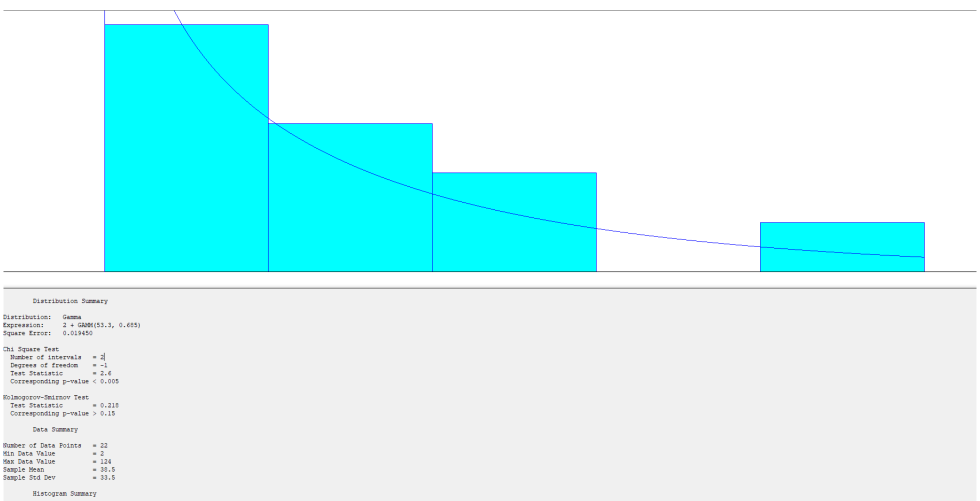


Fig. 3.13. Shocks Nurses Process Data Fitting

As mentioned earlier, one of the considerations of this model development process is to break down nurses tasks into detailed workflows and based on the collected date:

Above table shows how a nurse spends his/her time of the day for every single task. For example, an Intake nurse, spends 9.82% of his/her time to work on the medication related tasks.

The following section summarizes model assumptions.

Table 3.11.
Nurses Time Distributions by Workflows

Treatment Area	Intake	Check	Care	Orders	Medication	Discharge	Interruption	Others
Intake	24.46%	2.85%	4.03 %	19.74%	9.82%	13.85 %	4.42 %	20.83 %
SWAT	21.79 %	8.21 %	2.24 %	7.99%	8.73 %	24.03%	3.66%	23.36%
LA	7.49 %	4.61%	16.79%	8.56%	6.35%	8.82%	7.71%	39.67 %
HA	9.27%	5.37%	12.81%	12.53%	7.40%	9.07%	9.56%	34.00%

Model Assumptions

1) There is one arrival node for patients to get in to the ED, which is the combination of both front and back door arrivals.

2) Patients Left Without Being Seen (LWBS) arent considered in the model.

3) Due to very slight impact on the model outputs and lack of data, Holding area isnt included into the model.

4) 3 main human resources including: Nurses, Care Technicians and Physicians and bedrooms are considered as resources of the ED.

5) Patients are being seen based on their arrival time and with the First-In, First-Out (FIFO) methodology.

6) For each treatment area, except Shock area which only consists of Nurses and Physician resources, patients are 1st seen by Care Technicians. Then a Nurse will go through different treatment and responsibilities with patients and finally a Physician will check patients treatment progress and then a Nurse discharges the patient from treatment area.

7) None of the labs, including Radiology, X-Ray, etc. arent included in the model.

Model Development and Simulation in Arena Simulation Software:

In this model, two type of modules of Arena software, including Basic and Advance Processes have been used.

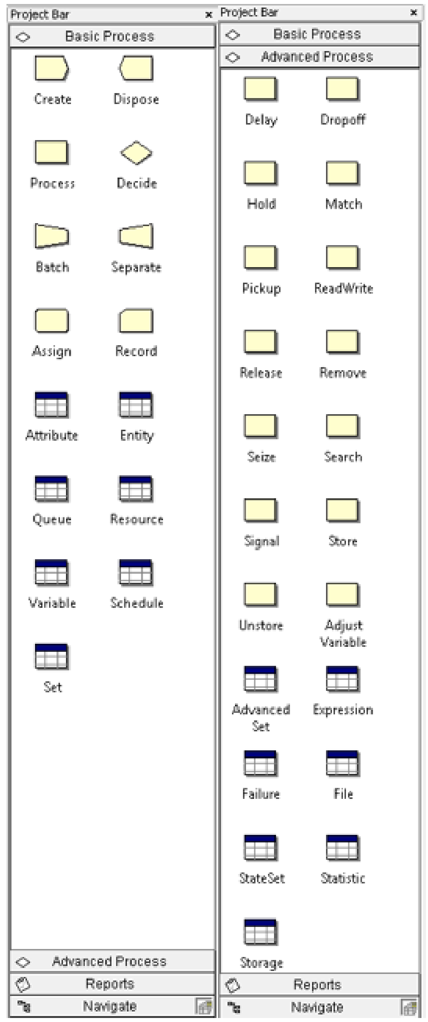


Fig. 3.14. Arena Used Modules

By having patient flow, data distributions selected for treatment processes, resource schedules and historical data, model will be created in the Arena.

Arrival method: Following picture shows how patients as the entities of the model will get created and will be assigned to different treatment areas based on the historical data.

Also, patients will be created in the model using Create module and their schedule will be entered based on the historical data and number of patients arrived in every hour based on the day of the week.

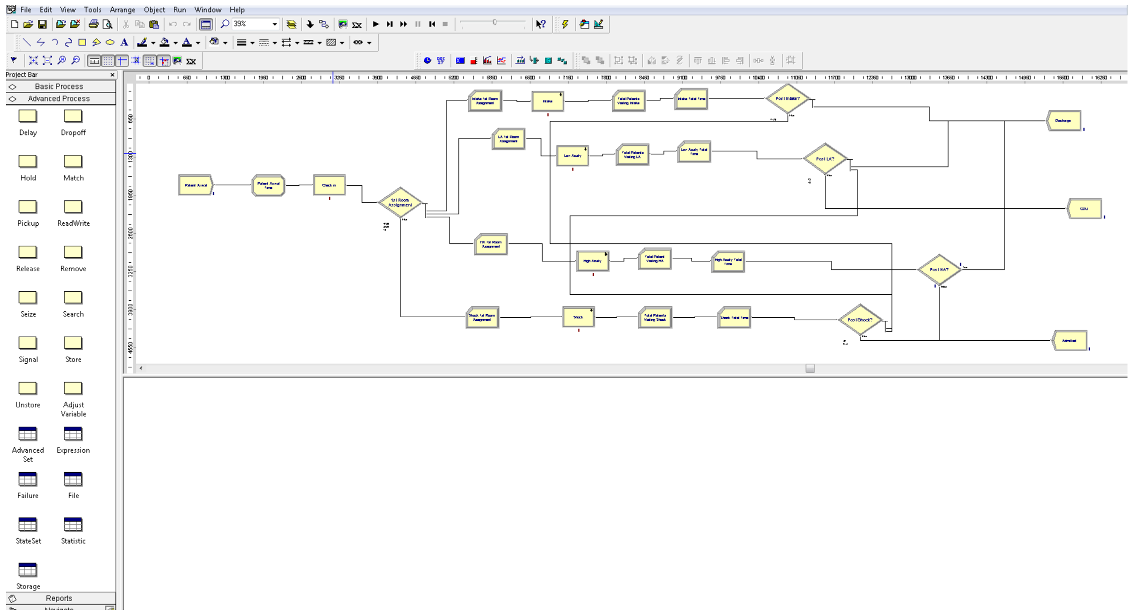


Fig. 3.15. Arenas Model

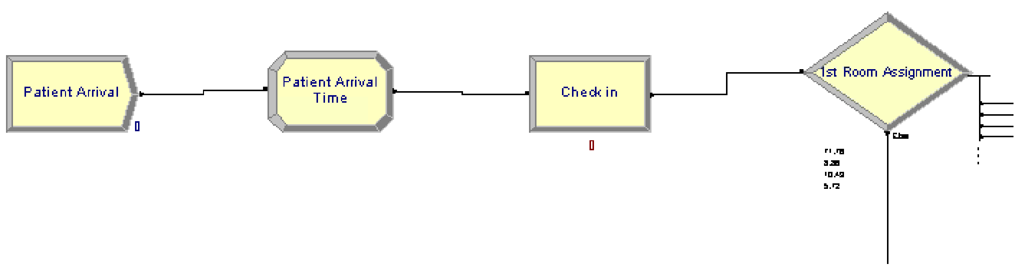


Fig. 3.16. Arrival in Arenas Model

Following picture shows a zoomed view of the general scheme of Intake, LA.

Also, this picture is HA and Shock treatment areas.

Treatment Areas Sub models:

SWAT Sub model:

Intake Sub model:

LA Sub model:

Create - Basic Process

	Name	Entity Type	Type	Schedule Name	Entities per Arrival	Max Arrivals
1	Patient Arrival	Entity 1	Schedule	Patient Arrival Schedule	1	Infinite

Fig. 3.17. Patient Creation in Arena

Durations

	Value	Duration
1	8.62	1
2	7.53	1
3	6.48	1
4	5.09	1
5	5.33	1
6	4.85	1
7	6.81	1
8	7.76	1
9	12.91	1
10	18.91	1
11	21.83	1
12	22.7	1
13	22.2	1
14	22.90	1
15	20.62	1
16	17.62	1
17	19.34	1
18	20.18	1
19	19.34	1
20	20.10	1
21	19.29	1
22	15.86	1
23	14.65	1
24	12.87	1
25	10.33	1
26	7.99	1
27	6.56	1
28	4.86	1
29	4.48	1
30	4.67	1
31	5.47	1
32	7.47	1
33	11.34	1
34	16.52	1
35	19.47	1
36	21.72	1
37	18.49	1
38	20.42	1
39	17.86	1
40	20.14	1
41	19.57	1
42	18.53	1
43	17.38	1
44	18.87	1
45	18.62	1
46	16.53	1
47	14.72	1
48	12.25	1
49	8.09	1

Fig. 3.18. Patient Arrival Schedule Creation in Arena

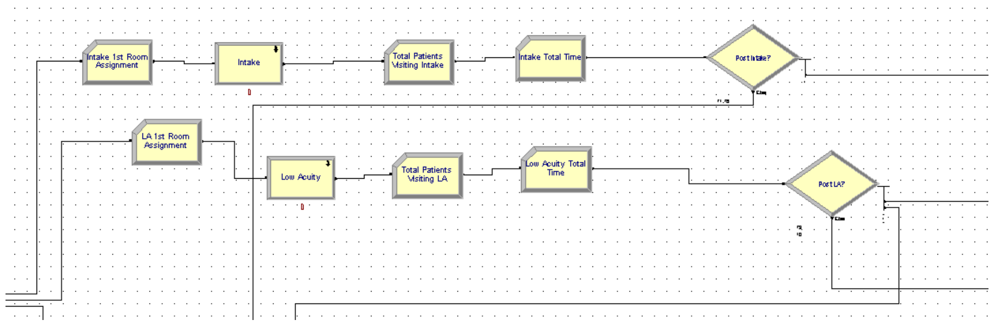


Fig. 3.19. Intake and LA in Arenas Model

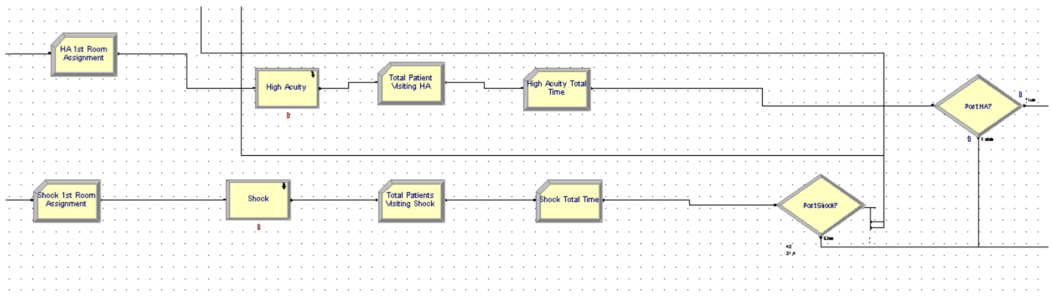


Fig. 3.20. HA and Shock in Arenas Model

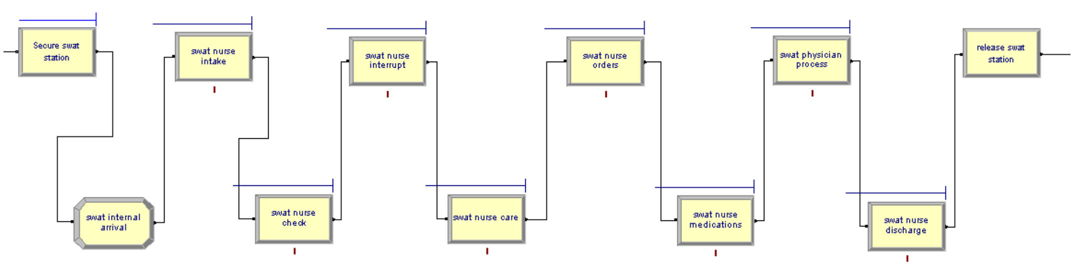


Fig. 3.21. SWAT Sub-Model

HA Sub model:

Shock Sub model:

All physical and human resources (beds and care providers) will be defined in sets and each set will include different resources associated with the set.

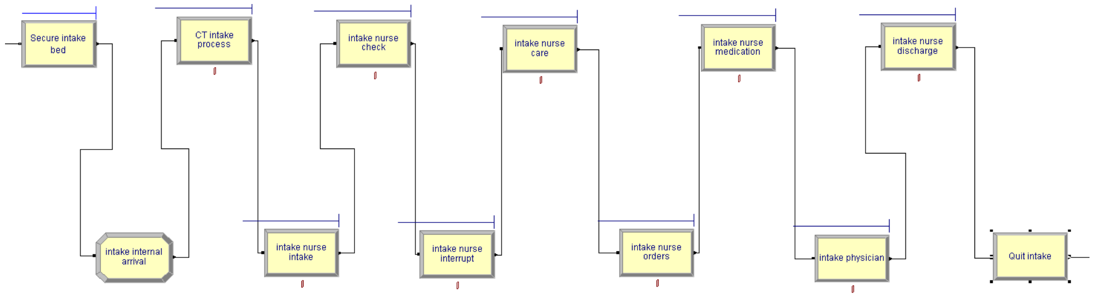


Fig. 3.22. Intake Sub-Model

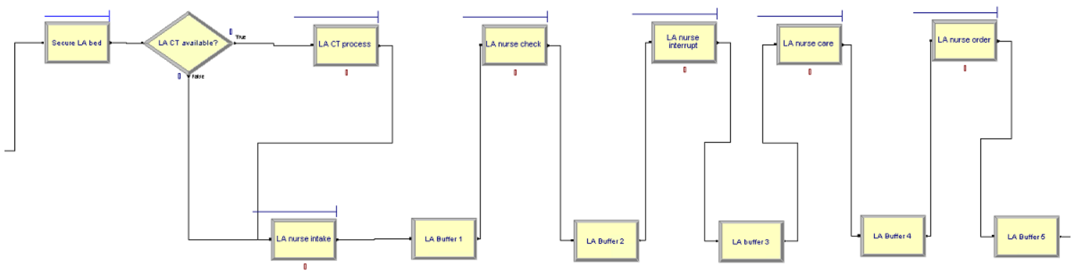


Fig. 3.23. LA Sub-Model (1)

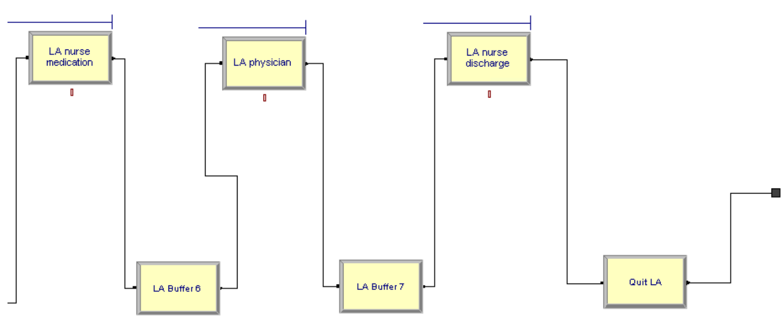


Fig. 3.24. LA Sub-Model (2)

Additionally, Arena provides an option to have fixed number of available resources or have them based on schedule.

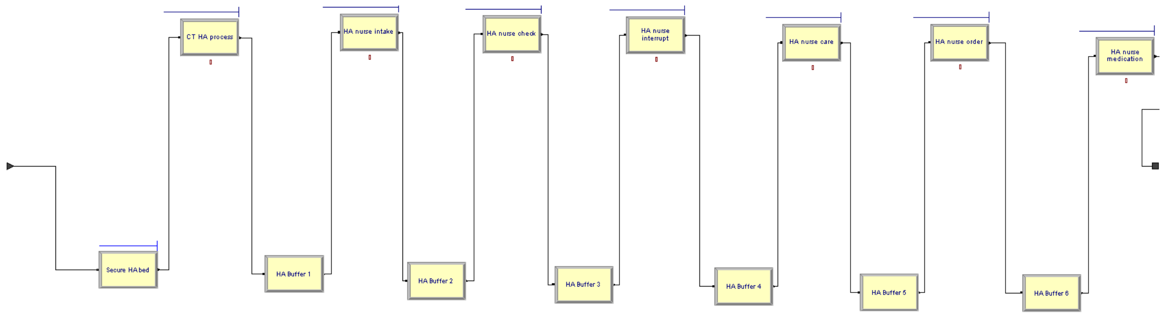


Fig. 3.25. HA Sub-Model (1)

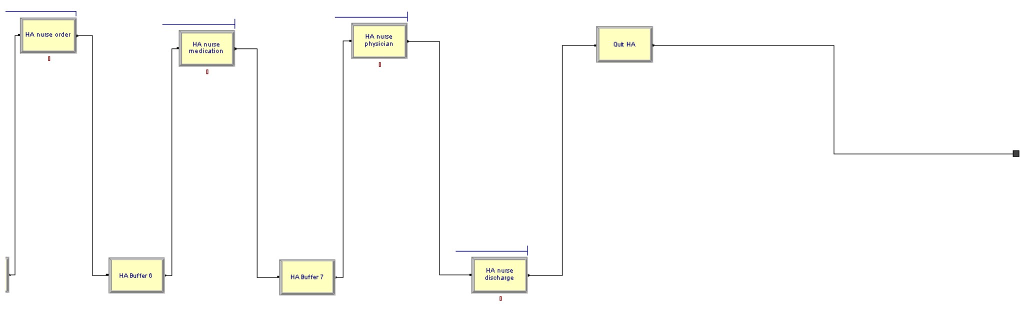


Fig. 3.26. HA Sub-Model (2)

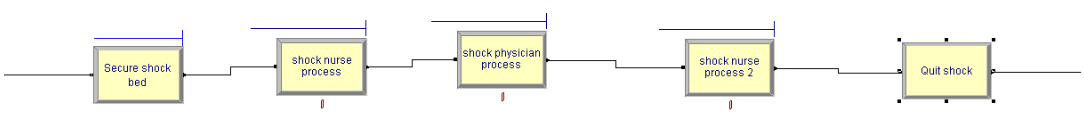
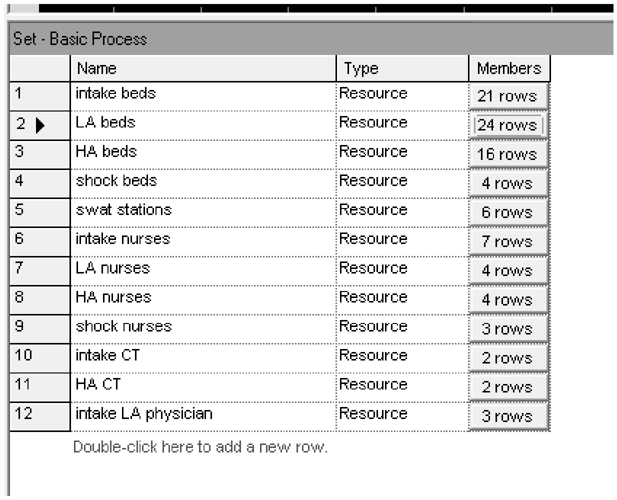


Fig. 3.27. Shock Sub-Model

Also, each one of the treatment processes are considered as a process in the model. The following figures show an example of how a process is defined in Arena model and the other processes defined in the model.

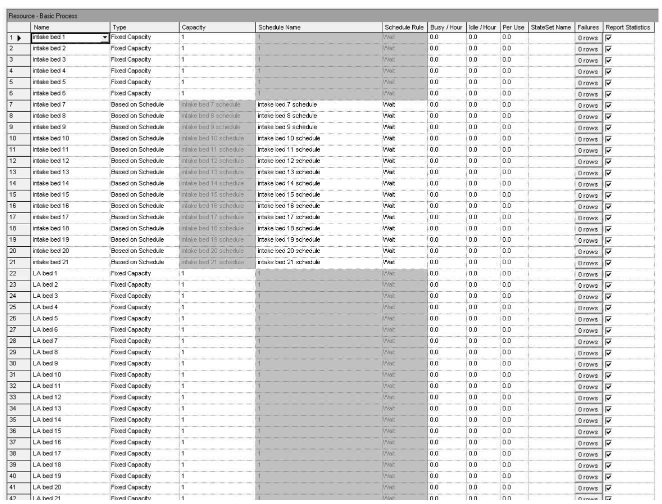


Set - Basic Process

	Name	Type	Members
1	intake beds	Resource	21 rows
2	LA beds	Resource	24 rows
3	HA beds	Resource	16 rows
4	shock beds	Resource	4 rows
5	swat stations	Resource	6 rows
6	intake nurses	Resource	7 rows
7	LA nurses	Resource	4 rows
8	HA nurses	Resource	4 rows
9	shock nurses	Resource	3 rows
10	intake CT	Resource	2 rows
11	HA CT	Resource	2 rows
12	intake LA physician	Resource	3 rows

Double-click here to add a new row.

Fig. 3.28. Resources Creation in Arena



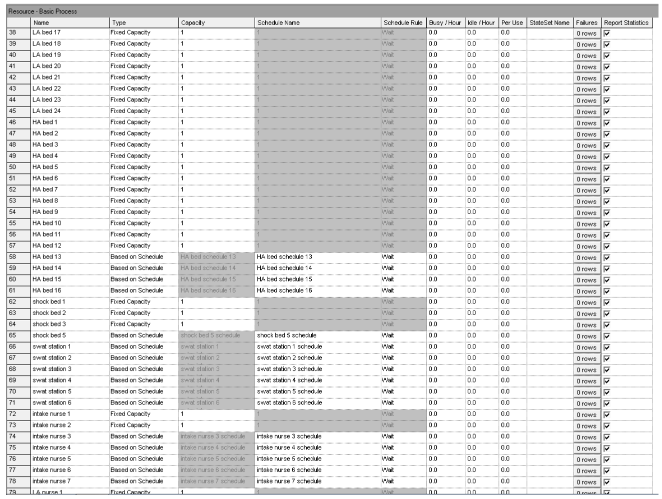
Resource - Basic Process

	Name	Type	Capacity	Schedule Name	Schedule Rule	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	intake bed 1	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
2	intake bed 2	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
3	intake bed 3	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
4	intake bed 4	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
5	intake bed 5	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
6	intake bed 6	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
7	intake bed 7	Based on Schedule	intake bed 7 schedule	intake bed 7 schedule	Wait	0.0	0.0	0.0		0 rows	☑
8	intake bed 8	Based on Schedule	intake bed 8 schedule	intake bed 8 schedule	Wait	0.0	0.0	0.0		0 rows	☑
9	intake bed 9	Based on Schedule	intake bed 9 schedule	intake bed 9 schedule	Wait	0.0	0.0	0.0		0 rows	☑
10	intake bed 10	Based on Schedule	intake bed 10 schedule	intake bed 10 schedule	Wait	0.0	0.0	0.0		0 rows	☑
11	intake bed 11	Based on Schedule	intake bed 11 schedule	intake bed 11 schedule	Wait	0.0	0.0	0.0		0 rows	☑
12	intake bed 12	Based on Schedule	intake bed 12 schedule	intake bed 12 schedule	Wait	0.0	0.0	0.0		0 rows	☑
13	intake bed 13	Based on Schedule	intake bed 13 schedule	intake bed 13 schedule	Wait	0.0	0.0	0.0		0 rows	☑
14	intake bed 14	Based on Schedule	intake bed 14 schedule	intake bed 14 schedule	Wait	0.0	0.0	0.0		0 rows	☑
15	intake bed 15	Based on Schedule	intake bed 15 schedule	intake bed 15 schedule	Wait	0.0	0.0	0.0		0 rows	☑
16	intake bed 16	Based on Schedule	intake bed 16 schedule	intake bed 16 schedule	Wait	0.0	0.0	0.0		0 rows	☑
17	intake bed 17	Based on Schedule	intake bed 17 schedule	intake bed 17 schedule	Wait	0.0	0.0	0.0		0 rows	☑
18	intake bed 18	Based on Schedule	intake bed 18 schedule	intake bed 18 schedule	Wait	0.0	0.0	0.0		0 rows	☑
19	intake bed 19	Based on Schedule	intake bed 19 schedule	intake bed 19 schedule	Wait	0.0	0.0	0.0		0 rows	☑
20	intake bed 20	Based on Schedule	intake bed 20 schedule	intake bed 20 schedule	Wait	0.0	0.0	0.0		0 rows	☑
21	intake bed 21	Based on Schedule	intake bed 21 schedule	intake bed 21 schedule	Wait	0.0	0.0	0.0		0 rows	☑
22	LA bed 1	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
23	LA bed 2	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
24	LA bed 3	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
25	LA bed 4	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
26	LA bed 5	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
27	LA bed 6	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
28	LA bed 7	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
29	LA bed 8	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
30	LA bed 9	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
31	LA bed 10	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
32	LA bed 11	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
33	LA bed 12	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
34	LA bed 13	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
35	LA bed 14	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
36	LA bed 15	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
37	LA bed 16	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
38	LA bed 17	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
39	LA bed 18	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
40	LA bed 19	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
41	LA bed 20	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
42	LA bed 21	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑

Fig. 3.29. All Defined Resources in Arena (1)

3.3.4 Model Verification

One of the important considerations of step 3 implementation through SE approach is to verify the model. This is a process that helps modeler to make sure that the model is created based on the intended assumptions, data and designated



Resource - Basic Process

	Name	Type	Capacity	Schedule Name	Schedule Rule	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
38	LA bed 17	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
39	LA bed 18	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
40	LA bed 19	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
41	LA bed 20	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
42	LA bed 21	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
43	LA bed 22	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
44	LA bed 23	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
45	LA bed 24	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
46	HA bed 1	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
47	HA bed 2	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
48	HA bed 3	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
49	HA bed 4	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
50	HA bed 5	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
51	HA bed 6	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
52	HA bed 7	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
53	HA bed 8	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
54	HA bed 9	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
55	HA bed 10	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
56	HA bed 11	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
57	HA bed 12	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
58	HA bed 13	Based on Schedule	HA bed schedule 13	HA bed schedule 13	Wait	0.0	0.0	0.0		0 rows	☑
59	HA bed 14	Based on Schedule	HA bed schedule 14	HA bed schedule 14	Wait	0.0	0.0	0.0		0 rows	☑
60	HA bed 15	Based on Schedule	HA bed schedule 15	HA bed schedule 15	Wait	0.0	0.0	0.0		0 rows	☑
61	HA bed 16	Based on Schedule	HA bed schedule 16	HA bed schedule 16	Wait	0.0	0.0	0.0		0 rows	☑
62	shock bed 1	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
63	shock bed 2	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
64	shock bed 3	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
65	shock bed 5	Based on Schedule	shock bed 5 schedule	shock bed 5 schedule	Wait	0.0	0.0	0.0		0 rows	☑
66	swat station 1	Based on Schedule	swat station 1	swat station 1 schedule	Wait	0.0	0.0	0.0		0 rows	☑
67	swat station 2	Based on Schedule	swat station 2	swat station 2 schedule	Wait	0.0	0.0	0.0		0 rows	☑
68	swat station 3	Based on Schedule	swat station 3	swat station 3 schedule	Wait	0.0	0.0	0.0		0 rows	☑
69	swat station 4	Based on Schedule	swat station 4	swat station 4 schedule	Wait	0.0	0.0	0.0		0 rows	☑
70	swat station 5	Based on Schedule	swat station 5	swat station 5 schedule	Wait	0.0	0.0	0.0		0 rows	☑
71	swat station 6	Based on Schedule	swat station 6	swat station 6 schedule	Wait	0.0	0.0	0.0		0 rows	☑
72	intake nurse 1	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
73	intake nurse 2	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑
74	intake nurse 3	Based on Schedule	intake nurse 3 schedule	intake nurse 3 schedule	Wait	0.0	0.0	0.0		0 rows	☑
75	intake nurse 4	Based on Schedule	intake nurse 4 schedule	intake nurse 4 schedule	Wait	0.0	0.0	0.0		0 rows	☑
76	intake nurse 5	Based on Schedule	intake nurse 5 schedule	intake nurse 5 schedule	Wait	0.0	0.0	0.0		0 rows	☑
77	intake nurse 6	Based on Schedule	intake nurse 6 schedule	intake nurse 6 schedule	Wait	0.0	0.0	0.0		0 rows	☑
78	intake nurse 7	Based on Schedule	intake nurse 7 schedule	intake nurse 7 schedule	Wait	0.0	0.0	0.0		0 rows	☑
79	LA nurse 1	Fixed Capacity	1	1	Wait	0.0	0.0	0.0		0 rows	☑

Fig. 3.30. All Defined Resources in Arena (2)

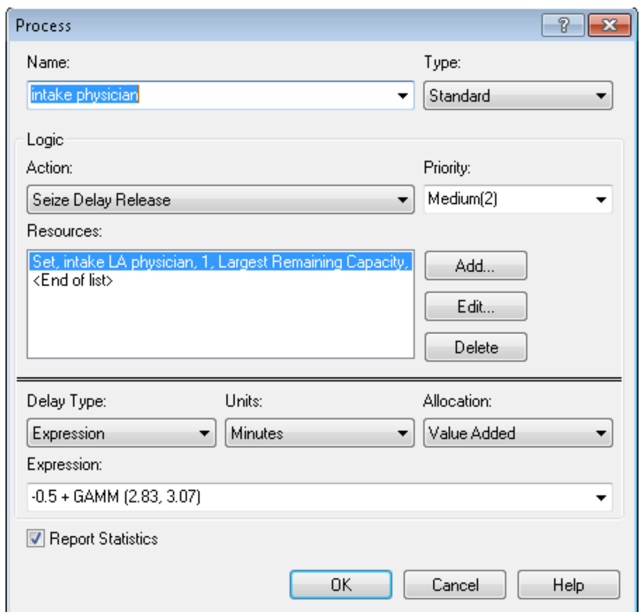


Fig. 3.31. Intake Physician Process Creation in Arena

flowchart. There are different types of model verification methods and here in this study. different verification methods were applied:

Process - Basic Process

	Name	Type	Action	Priority	Resources	Delay Type	Units	Allocation	Expression	Report Statistics
1	intake nurse interrupt	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.0442	☑
2	intake nurse care	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.0403	☑
3	intake nurse discharge	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.1385	☑
4	intake physician	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	-0.5 + GAMM (2.83, 3.07)	☑
5	intake nurse medication	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.0982	☑
6	intake nurse orders	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.1974	☑
7	CT intake process	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Seconds	Value Added	60 + 360 * BETA (1.21, 1.21)	☑
8	intake nurse check	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.0285	☑
9	intake nurse intake	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	(1.5 + GAMM (4.63, 1.57))*0.2446	☑
10	swat nurse intake	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + 10 * BETA(0.844, 4.13)	☑
11	swat nurse check	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + 7 * BETA(0.531, 2.32)	☑
12	swat nurse interrupt	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + LOGN(0.822, 0.508)	☑
13	swat nurse care	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + 6 * BETA(0.53, 1.4)	☑
14	swat nurse orders	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + GAMM(1.19, 1.46)	☑
15	swat nurse medications	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + 4 * BETA(0.973, 2.42)	☑
16	swat physician process	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	-0.5 + 12 * BETA (1.84, 2.31)	☑
17	swat nurse discharge	Standard	Seize Delay Release	Medium(2)	1 rows	Expression	Minutes	Value Added	0.5 + LOGN(1.24, 1.08)	☑

Fig. 3.32. Processes Creation in Arena

1. As there is a defined patient flow chart designed for the Eskenazi emergency department, entities, which are patients, should exactly follow the defined path. Therefore, model ran with slow speed and entities were visually seen to go through different possible paths. An important consideration for this method is to make sure that none of the entities are blocked in any process modules. Patients should start the process with Patient Arrival module and leave the system with any of Admitted, Discharged or CDU. Between these nodes they go through step by step diagnosis and treatment processes and its being seen by the modeler.

2. The other method of verification used in this study is to define different extreme and moderate conditions compared to the actual model. There are different factors that affect patient length of stay and patient throughput including physical and human resources like number of bedrooms in each treatment area, nurses, physicians and care technicians. Additionally, one of the other factors of ED system are entities, which in this case are patients, that will affect the whole system. As a matter of fact, having more resources should lead to less patients length of stay or adding more entities will cause more patients in each queue and then more patients waiting time. Therefore, by changing these factors

there should be some reasonable changes to the model outputs. Having said that, following options will be considered for the model verification purpose:

a. 1^{st} extreme condition: Doubling the number of arrived patients

b. 2^{nd} extreme condition: Removing one of the LA/Intake physicians, and one intake nurse, one LA nurse and one HA nurse.

c. 3^{rd} extreme condition: Combination of 1^{st} and 2^{nd} model options

d. 4^{th} extreme condition: Doubling number of arrived patients from 9am to 5 pm

e. Moderate condition: Adding one more LA/Intake physician, one more HA/Shock physician and one more LA nurse and HA nurse.

3.3.5 Model Validation

Validation and Verification are two necessary wings of modeling process and without them, models dont have enough value to study and test design alternatives. Validation is a process which proves the created model or abstraction is behaving like the actual model. In this study, since the approach is SE and one of the important factors of systems engineering approach is the early verification of the model, verification has been considered from the earliest stages of the process. Patient flow, which the Arena model is built on, was designed and verified with the effort of systems engineering team and a physician from Eskenazi hospital. This is very important because the model is made based on the designed patient flow and by having a valid flow, chances of having a good and valid model will increase.

The other method of validation used in this study, is using the historical data from Eskenazi hospital to compare them with model results. Patients length of stay and throughput will be considered as model results that are used in this step.

3.4 Use the model to learn about system behavior to find the best design alternative. The engineer often develops appropriate experiments for the studying the model and analyzing the results

Now that theres a verified and validated model, its time to investigate current existing model and look for the ways that how the performance of the model and patients satisfaction (quality of care) could be improved. As mentioned in the introduction, the main stakeholder of new healthcare systems are patients. In other words, best healthcare systems are patient based systems, means that patients satisfaction rate is one of the biggest concerns of the hospitals administration. Along with the treatment received by the patients, the time they spent in the ED, LOS, is an important factor to be considered. The main purpose of this step in this study, is to propose different changes to the system that can improve patients satisfaction by reducing LOS of the patient in ED. Theres another factor being considered, and thats keeping the cost of resources usage to the least possible amount. Consequently, proposed scenarios arent making much differences in the resources usage and by using current amount of resources some changes will be tested. The following section summarizes the constraints that what-if scenarios have been defined based on them.

Looking at ED at Eskenazi and because a big percentage of patients go to intake and more LOS of patients are associated with LA and HA, the following changes have been proposed to see possible impacts on the system.

3.4.1 Constraints Provided by ED Expert

1) Cost constrain is one of the main concerns of the ED administrators is that proposed changes arent adding any more costs associated with the ED treatment process or hiring budgets. This means that no additional human resources like physician or nurses and physical resources, like bedrooms should be added to model as proposed changes to improve the LOS.

2) The other constrain defined by ED administrators was the affordability of making the changes to ED. Emergency Department has a very fixed physical building set up and due to high volume of patients visiting the ED, changes and construction operations are almost impossible for the ED building. Therefore, if theres any possible changes to the ED setting, it shouldnt block ED current operation, even for a short period of time.

3) There is another requirement defined from ED expert and that is having some what if scenarios applied to the model to understand the impacts of Nurses and Physicians schedule and availability changes to the LOS of patients of ED.

1^{st} Scenario: In the 1^{st} scenario, one pod from LA will be removed and one pod will be added to the Intake, means 6 rooms will be removed from LA and 3 of them will be designated to the Intake. Additionally, since theres one nurse per pod in LA, associated nurse will be in charge of the added pod to intake.

2^{nd} Scenario: In the second scenario, one pod from LA will be removed and all 6 rooms of that pod will be added to Intake. However, instead of having LA nurse in charge of those rooms, that nurse will not be working anymore. Instead of that, one physician will be working in both LA and Intake from 9am to 5pm, which based on the historical data is the busy time of the day.

3^{rd} Scenario: In the 3^{rd} proposed scenario, one pod of LA will be removed, and one pod will be added to HA. It means that 6 rooms will be removed from LA and 4 of them will be designated to HA area. Additionally, One LA nurse will work in that added pod to HA.

4^{th} Scenario: This scenario is same as the previous one, however there will be no nurse working from LA in HA. That nurse will be removed from the ED and instead of that, on physician will work from 9am to 5pm in both LA and HA areas.

3.5 Use the results of step 4 to determine how to configure the system for best performance

This step is almost the final step of SE approach that will be done in this research study. Based on the outputs and changes resulted from 4 different scenarios, best possible scenario will be selected as the proposed method of change. Additionally, there will be another consideration in the next chapter that can help us to find the best propsed scenario to improve quality of care at ED of Eskenazi Hospital.

3.6 Develop implementation and evaluation plans and coordinate their performance

This step of SE approach is beyond the scope if this research study, since it must get done by ED at Eskenazi hospital. At the end of this report, one final scenario will be proposed to ED and it can be tested and evaluated by actual implementation at Eskenazi hospital.

4. RESULTS AND DISCUSSIONS

In this chapter results of each SE steps are presented. This includes MBSE diagrams, some of the data collected and analysis of data, verification and validation results. Additionally, results from what-if scenarios will be presented and one extreme condition will be tested to show difference between two of the scenarios and one of them will be picked as the better solution.

4.1 MBSE Diagrams

As mentioned in methodology chapter, MBSE is being used as one of the SE tools to define system context and boundaries and research process. 3 different diagrams have been created and each one of them gives the readers a good understanding of this study, scope and ED context of Eskenazi hospital.

The first diagram created for this study, is a block definition diagram (bdd) which is being used to define different factors of the ED at Eskenazi hospital and different inputs that has been used in this research. The first block of this diagram is Clinicians block, which includes different staff of ED considered in the model and they are nurses, care technicians and physicians. The other block is Data block. Two different categories are used as data types for the modeling purpose, historical data from ED and observation data. Additionally, Interface departments which are working with ED are shown and they are Critical Decision Unit (CDU) and Inpatient department. Also, different treatment areas, including Intake, SWAT, LA, HA and shock, which are considered in the modeling are shown in the other block. Last block of this diagram is Treatment Cost, which is another factor in finding the best of what-if scenarios.

Next diagram from MBSE, is and activity diagram (act). This diagram is the

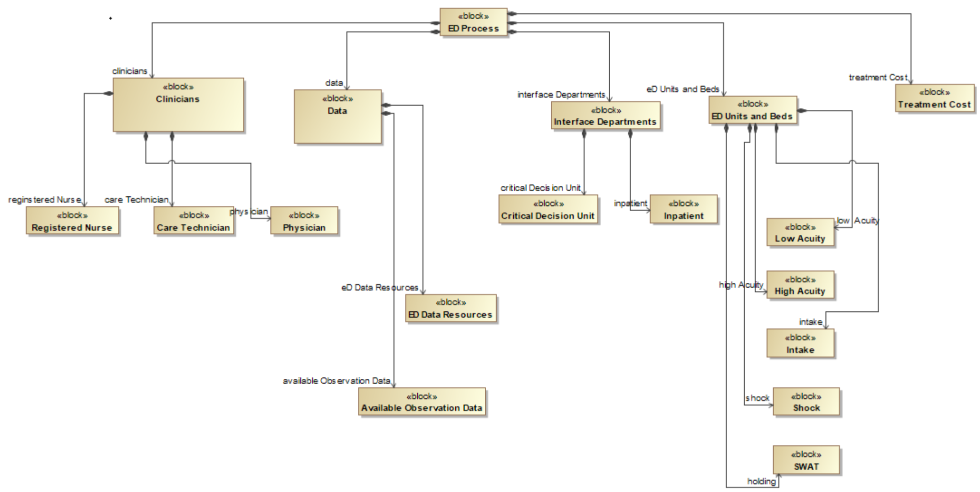


Fig. 4.1. bdd of ED

modeling process diagram and shows the modeling inputs, modeling method and tool and model outputs. In this study, model inputs are arrival data, data from historical sources and observations, staffing schedules and probability distributions used for treatment processes. As mentioned in methodology, Discrete Event Simulation is the modeling method and Arena Simulation is the tool used for it. Finally, model outputs are LOS, patients throughput, results from what-if scenarios and the extreme condition.

The other diagram created for this research is a use case diagram. This use case diagram explains different actors and their functions in this system and study. There are 3 main actors, patient, clinicians and model developer. Additionally, each one of these actors are having some functions in the system. For example, clinicians which are nurses, care technicians and physicians are working in ED and affecting treatment process flow. Also, model developer is responsible for ED model development and finding the best case from proposed what-if scenarios for ED model improve-

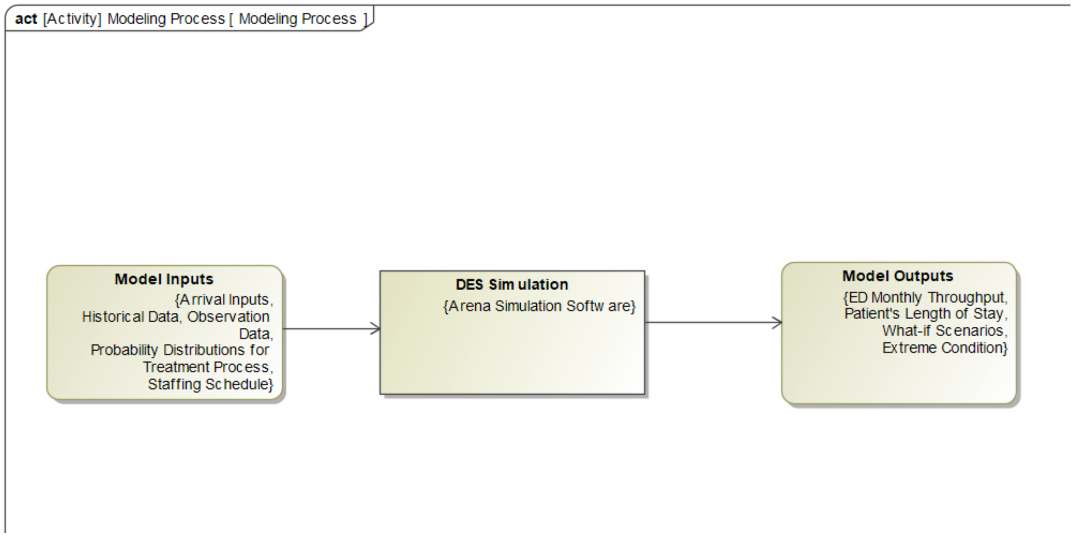


Fig. 4.2. act of Modeling Process

ments. Patients are the entities entering the system, therefore they are one of the main characters affecting the system. Also, by defining one extreme condition (crowding condition) patients will be entering the system with a higher rate compared to the current condition and this is another considerable factor for the model.

4.2 Data Analysis

There are two different phases of data collection in this research. Each one of them were conducted with specific purposes. First round of observation was done with a focus on patient. It was conducted to collect data related to the times patient spends with each one of ED staff and patients arrival and departure times. The following table is a summary of the collected data. Nurse Percentage and Physician Percentage are the amount of time that a patient spends with clinicians when they are at ED. Additionally, Others specifies times that patients are waiting in rooms, getting transferred to x-ray, radiology having food, etc.

Second round of observations were conducted with a focus on the nurse responsibilities. Data collector was shadowing different nurses to find out about their responsi-

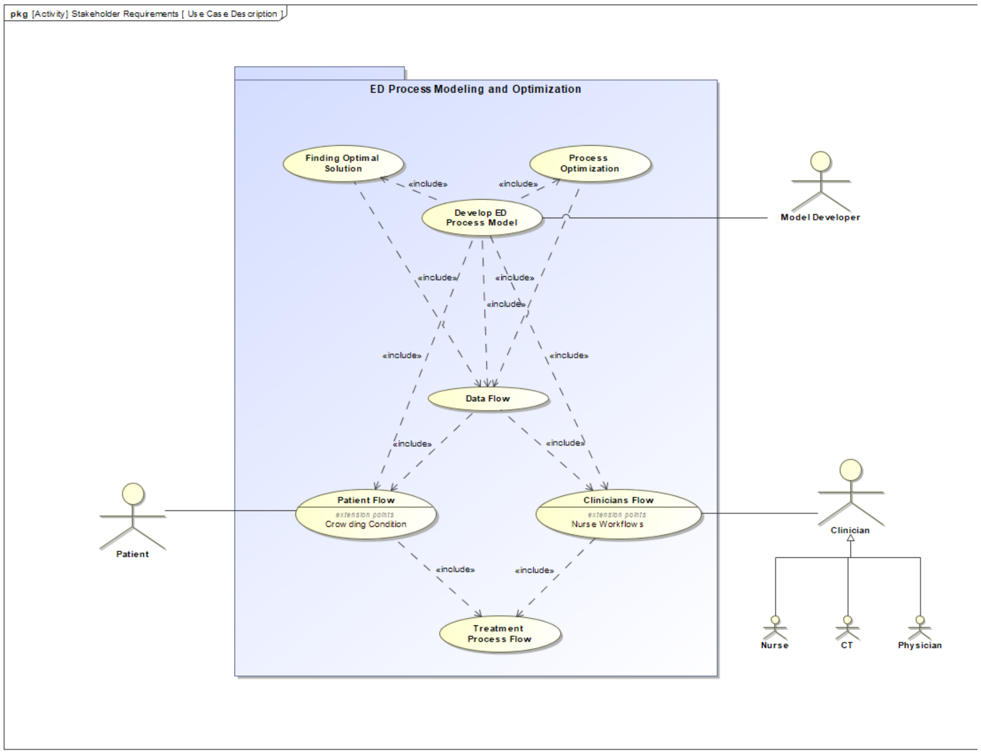


Fig. 4.3. uc of ED

Table 4.1.
Data Analysis of 1^{st} Phase Observation

Treatment Area	Nurse Percentage	Physician Percentage	Others
SWAT	24.49%	11.52%	63.99%
Intake	9.64%	5.70%	84.15%
Low Acuity	9.82%	4.54%	85.29%
High Acuity	12.47%	8.06%	78.48%
Shock	60.12%	45.33%	23.00%

bilities and how they spend their day. The following table shows how nurses spend their time doing different tasks. Others specifies the times that nurses are on their break, waiting for new patients to arrive, etc.

Table 4.2.
Data Analysis of 2nd Phase Observation

Treatment Area	Intake	Check	Care	Orders	Medication	Discharge	Interruption	Others
Intake	24.46%	2.85%	4.03%	19.74%	9.82%	13.85%	4.42%	20.83%
SWAT	21.79%	8.21%	2.24%	7.99%	8.73%	24.03%	3.66%	23.36%
LA	7.49%	4.61%	16.79%	8.56%	6.35%	8.82%	7.71%	39.67%
HA	9.27%	5.37%	12.81%	12.53%	7.40%	9.07%	9.56%	34.00%

4.3 Model Verifications

In this section, verification results are being shown. 4 different cases will be tested to see if the model reacts to new scenarios in a reasonable way. Following tables show results of these verification scenarios.

a. 1^{ST} extreme condition: Doubling the number of arrived patients.

Table 4.3.
1st Extreme Conditions Results for Verification

Treatment Area	Regular Condition LOS	1^{ST} Extreme Condition LOS
Intake	145.21	5993.10
LA	289.42	11869.66
HA	336.80	10650.35
Shock	250.59	3099.10
Total Average	250.06	9147.27

b. 2^{nd} extreme condition: Removing one of the LA/Intake physicians, and one intake nurse, one LA nurse and one HA nurse.

c. 3^{rd} extreme condition: Combination of 1^{st} and 2^{nd} model option

d. 4^{th} extreme condition: Doubling number of arrived patients from 9am to 5 pm

Table 4.4.
2nd Extreme Conditions Results for Verification

Treatment Area	Regular Condition LOS	2^{nd} Extreme Condition LOS
Intake	145.21	2376.59
LA	289.42	8886.35
HA	336.80	1585.90
Shock	250.59	227.84
Total Average	250.06	4405.78

Table 4.5.
3rd Extreme Conditions Results for Verification

Treatment Area	Regular Condition LOS	3^{rd} Extreme Condition LOS
Intake	145.21	14462.11
LA	289.42	16989.73
HA	336.80	10218.72
Shock	250.59	3980.91
Total Average	250.06	13792.39

e. Moderate condition: Adding one more LA/Intake physician, one more HA/Shock physician and one more LA nurse and HA nurse.

For extreme conditions, the reason that a long LOS is being seen is that the system gets saturated by the number of arrived patients after a while, then there will be long queues for each process and then a shortage of resources will occur in the system, therefore patients will experience a very long waiting times and therefore the average LOS of patients will increase drastically. To better understand this, lets compare the 1^{st} extreme condition with 4^{th} extreme condition. For the 1^{st} one, number of arrived

Table 4.6.
4th Extreme Conditions Results for Verification

Treatment Area	Regular Condition LOS	4^{th} Extreme Condition LOS
Intake	145.21	2868.90
LA	289.42	6330.98
HA	336.80	4270.81
Shock	250.59	497.62
Total Average	250.06	4523.70

Table 4.7.
Moderate Conditions Results for Verification

Treatment Area	Regular Condition LOS	Moderate Condition LOS
Intake	145.21	69
LA	289.42	163
HA	336.80	216
Shock	250.59	177
Total Average	250.06	143

patients got doubled for the whole time of simulation and for the 4^{th} condition, only number of arrived patients between 9am to 5 pm has been increased. Results show a drop in average LOS of patients in 4^{th} condition compared to the 1^{st} condition and the reason is, after getting saturated between 9am to 5pm, system will get back to the regular condition of arrival rate, therefore the average LOS in 4^{th} condition is less then the 1st condition.

For a right model, changing number of entered patients and having different resources should impact patients length of stay in ED. Obviously, by having more patients entering the system there will be more patients waiting to enter each treatment area and being seen by clinicians. Additionally, removing resources will cause less available resources and more patients in queue. On the other hand, having more resources must make patients to be placed in bedrooms and get treatment earlier and therefore leave ED earlier as well. Verification results are showing that developed model is reacting reasonably to model changes and is being built right with correct modeling methodology.

4.4 Validation Results

In this section validation results are discussed. The main purpose of validation is to make sure that developed computer model is representing the actual system. For this purpose, results of the model are compared with historical data extracted from Epic data base of Eskenazi hospital and results for patients LOS and monthly throughput are shown in the following tables.

Table 4.8.
LOS Validation Results

Treatment Area	Epic Results	Model Results	% Error
Intake	160.2	140.24	12.45 %
LA	319.8	282.62	11.62 %
HA	360	331.25	7.98 %
Shock	264.6	244.81	8.45 %
Total Average	234	244.08	4.30 %

Comparison between the model results and historical data shows some error in the length of stay of patients in different treatment areas. However, the total average of LOS is just showing 4.30% of error in the model which makes the model a good tool for LOS prediction.

Table 4.9.
Monthly Throughput Validation Results

Treatment Area	Epic Results	Model Results	% Error
Intake	3632.64	3573.00	1.64 %
LA	2470.57	2420.20	2.03 %
HA	1246.7	1198.50	3.86 %
Shock	218	241.90	10.96 %
Total Average	7567.9	7435.60	1.74 %

4.5 Model Modification Results

Now that the model is verified and validate to be a good tool for LOS prediction of ED, it can be used for testing different scenarios and see if theres a chance to make improvements to the current setting of ED. As mentioned in methodology 4 different what if scenarios are proposed and tested to see the impact on length of stay of patients in ED. An important consideration for having these scenarios is that implementing these settings will make no additional costs to ED management to implement them. The following tables shows the results of having these scenarios and comparison between the new results and current ED settings.

4.5.1 1^{st} what if scenario

In the 1^{st} scenario, one pod from LA will be removed and one pod will be added to the Intake, means 6 rooms will be removed from LA and 3 of them will be designated to the Intake. Additionally, since theres one nurse per pod in LA, associated nurse will work in the added pod to intake. The model predicts that by implementing this scenario, patients will spend almost 17 minutes less than the amount of time they are in ED with current setting.

Table 4.10.
1st What-if Scenario Results

KPI	Current State	New Results
Average LOS	244.08	227.48
Intake LOS	140.24	112.33
LA LOS	282.62	228.11
HA LOS	331.25	301.75
Shock LOS	244.81	235.96

4.5.2 2^{nd} what if scenario

In the second scenario, one pod from LA will be removed and all 6 rooms of that pod will be added to Intake. However, instead of having LA nurse in charge of those rooms, that nurse will not be working anymore. Instead of that, one physician will be working in both LA and Intake from 9am to 5pm, which based on the historical data is the busy time of the day. Model shows 14.81% of improvement in LOS of patients with this scenario, means patients spend almost 37 minutes less than usual in ED.

Table 4.11.
2^{nd} What-if Scenario Results

KPI	Current State	New Results
Average LOS	244.08	209.50
Intake LOS	140.24	98.49
LA LOS	282.62	238.06
HA LOS	331.25	327.29
Shock LOS	244.81	267.92

The comparison between the new study and old study [22] improvements are shown in the following table.

Table 4.12.
Old Study vs New Study Results Comparison

KPI	Old Study improvement %	New Study improvement %
Average LOS for 1^{st} scenario	2.63%	6.8 %
Average LOS for 2^{st} scenario	14.74%	14.81 %

4.5.3 3^{rd} what if scenario

In the 3^{rd} proposed scenario, one pod of LA will be removed, and one pod will be added to HA. It means that 6 rooms will be removed from LA and 4 of them will be designated to HA area. Additionally, One LA nurse will work in that added pod to HA. Making these changes will show 13.55% improvement in the model by decreasing LOS from 244.08 minutes to 211 minutes.

4.5.4 4^{th} what if scenario

This scenario is same as the previous one, however there will be no nurse working from LA in HA. That nurse will be removed from the ED and instead of that, on physician will work from 9am to 5pm in both LA and HA areas. By having the scenario implemented in ED, model predicts that patients will spend 33 minutes less than current ED setting.

Table 4.13.
3^{rd} What-if Scenario Results

KPI	Current State	New Results
Average LOS	244.08	210.43
Intake LOS	140.24	146.17
LA LOS	282.62	245.48
HA LOS	331.25	239.64
Shock LOS	244.81	273.52

Table 4.14.
4^{th} What-if Scenario Results

KPI	Current State	New Results
Average LOS	244.08	211.75
Intake LOS	140.24	137.02
LA LOS	282.62	286.06
HA LOS	331.25	175.75
Shock LOS	244.81	434.59

Following table shows the comparison between current study and old research. These numbers arent saying that any of the models are better or not, this is just proving that these scenarios are showing possible improvements in ED and there are great chances to achieve more patients satisfaction by implementing them.

As being shown, all scenarios are showing improvements in LOS of patients at ED. Scenarios 1 and 2 are making changes to Intake and LA treatment areas, and scenarios 3 and 4 are changing LA and Shock areas. Between the 1^{st} and second one, scenario 1 could make more improvements to the model and on the other hand since both arent adding more costs to ED costs, so scenario 2 will be selected between 1 and 2.

Table 4.15.
Old Study vs New Study Results Comparison (2)

KPI	Old Study improvement %	New Study improvement %
Average LOS for 3^{rd} scenario	14.28%	13.75 %
Average LOS for 3^{rd} scenario	14.47%	13.55 %

4.6 Defining Crowding Conditions in ED

As discussed earlier 2 scenarios were selected for possible improvements in emergency department. However, there are some disaster conditions happening anywhere in the world that can cause crowding occurrence in hospitals. For example, in the time of an earthquake or flood in the city, there will be more patients visiting emergency departments of hospital. This can be a very good testing condition in this study to see how current ED setting and scenarios 2 and 3 would react to a crowding condition occurring. For this purpose, there will be 2 scenarios defined for an increase in the arrival rate of the patients. First, there will be a 10 % of increase in the number patients visiting ED hourly and for the other scenario, there will be a 10 % increase for arrival rate of patients entering the system between 9am to 5pm. The following tables shows LOS for the new arrival rate in the model. With current setting of ED, only with 10 percent increase in patients arrival rate, they may stay up to 6 hours in ED to receive appropriate treatment before they leave ED. On the other hand, with second what-if scenario implemented in ED, patients will stay just 106 minutes more than usual arrival rate. This table can prove that between scenarios 2 and 3, 2^{nd} scenario can have better response in terms of a crowding condition in ED and therefore can be picked as the proposed setting between 4 proposed scenarios.

Table 4.16.
1^{st} Crowding Scenario Conditions Results with 2^{nd} and 3^{rd} What-if Scenarios Settings

KPI	Current State	2^{nd} Scenario	3^{rd} Scenario
Average LOS with current arrival rate	244.08	207.93	210.43
Average LOS with 10% increased arrival rate	600.99	313.94	548.65

Also, by increasing patients arrival rate between 9am to 5pm the following results will be found.

Table 4.17.
2nd Crowding Scenario Conditions Results with 2^{nd} and 3^{rd} What-if Scenarios Settings

KPI	Current State	2^{nd} Scenario	3^{rd} Scenario
Average LOS with current arrival rate	244.08	207.93	210.43
Average LOS with 10% increased arrival rate	289.50	250.58	254.51

The results show that by having an increase in patients arrival rate between 9am to 5pm every day, average LOS of patients is about 289 minutes with current ED settings. However, with having 2^{nd} scenario implemented, Arena model predicts that patients spend 250.58 minutes in average. On the other hand, average LOS of patients with 3^{rd} Scenario is 254.51 minutes. By having intermittent surges, another evidence that 2^{nd} scenario can react better to overcrowding conditions is being collected.

5. CONCLUSION

This chapter presents conclusion of the current research and some suggestions for the future works based on the limitations of the current study.

Conclusions of the current work can be summarized as follow:

1. This research study is implemented based on the Systems Engineering approach to improve quality of care at Emergency Department of Eskenazi hospital. There are 6 specific steps in the SE approach and these steps includes definition of the system and research scope, data collection, model development and verification and validation of the model, investigating current model and proposing model modification scenarios, testing those scenarios and selecting the solution and finally implementing the new changes in the actual ED system to see the results and impacts in Eskenazi hospital (Last step is not included in the scope of this research study)

2. Two rounds of observations were conducted with different scopes and purposes. First round of the observation was conducted with a focus on patients in all ED treatment areas. In first round, patients were observed from the moment they entered ED treatment areas until they left ED. Additionally, the amount of time that each one of ED staff were spending in patients room were collected. Second round of observation was a nurse-based observation, means that nurses were the focus of the observation and data collector was shadowing nurses in the whole time of observation. This lead to have a detailed workflow and categorizing different responsibilities of nurses and how much of their time goes for each type of responsibilities.

3. Developing a comprehensive computerized model of ED of Eskenazi hospital with Arena Simulation software which includes different treatment areas of ED

(Intake, SWAT, LA, HA and Shock) with detailed nurses workflows and including ED staff (nurses, care technicians and physicians) using historical and observation data that can predict patients LOS and monthly throughput of ED.

4. Implementing 4 extreme conditions and one moderate condition in the computerized model in Arena to verify the model. Additionally, Arena model was validated using the historical data of Eskenazi hospital.

5. 4 different what-if scenarios were proposed by changing ED physical and human resources in Intake, LA and HA and it was shown that all 4 scenarios can reduce LOS of patients. As 1^{st} and 2^{nd} scenarios were changing Intake and LA layout and 3^{rd} and 4^{th} scenarios were changing LA and HA resources from each one of them one scenario was selected as the proposed scenario. Scenario 2 was selected between the first two scenarios and it was able to reduce LOS by 37 minutes compared to current ED setting. Scenario 3 was selected between scenario 3 and 4 and it was able to reduce LOS by 33 minutes.

6. 2 crowding conditions were tested with current ED setting, scenario 2 and scenario number 3. Results showed that 2^{nd} scenario can respond in the best possible way against having more patients in the ED and just increases LOS by 106 minutes. However current ED setting will have an increased LOS of 356 minutes and 3rd scenario will increase LOS by 338 minutes. Therefore, scenario number 2 can be selected as the proposed solution to reduce LOS of patients in both regular and crowded condition with no additional cost.

The following section can be considered as suggestion to improve the current study in future research studies:

1. There are patients that leave ED without being seen by any of ED staff and they are called patients left without being seen. The future research study can propose a plan to collect data during observations and include them in the computerized model.

2. Theres one final proposed solution to reduce LOS in ED of Eskenazi Hospital suggested in this research study by model prediction. Implementing this change in emergency department in a pilot study can prove the value of ED simulation and can convince ED managers to implement the changes to reduce LOS in ED.

3. There are different type of patients visiting ED of Eskenazi hospitals with needs for specialized treatment requirements like patients with mental illnesses or patients with chronic obstructive pulmonary disease (COPD patients). These patients may require different types of treatments. Therefore, they can have their own patient flow and data collection methods and new simulation model.

4. Theres a great benefit of having a model to show and predict costs associated with treatment of each ED patient based the treatment area and type of illness. This can be used as a helpful decision-making tool for ED managers to reduce costs of ED and improve quality of care at Eskenazi ED.

5. The other motivation for continuing the research on current topic, is to complete the models integration between MBSE model and Arena Simulation model. Additionally, MBSE has been used to show different diagrams for schematic purposes. Use of other MBSE features like requirement definition and traceability, high level simulation, etc. can be considered for future research projects.

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