Modeling Cardiovascular Patient Pathways in an Accident and Emergency Department from a System Dynamic Perspective Using a Patient Oriented Modeling Approach

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Thesis
Submitted to the Department of Geography
In Partial Fulfillment of the Requirements for the Degree of
Masters in System Dynamics

System Dynamics Group

Department of Geography

University of Bergen

February, 2017

Abstract

This thesis provides a detailed overview of a system dynamics model that focuses on the accident and emergency department and the clinical pathways of cardiovascular patients at Haukeland University hospital. A patient-oriented approach was chosen and sub-models representing patient attributes and accident and emergency resources were developed based on this approach. The simulation model illustrates accident and emergency processes and patient attributes in a disaggregated system. In addition to System Dynamics, other modeling concepts facilitated the modeling process. This included object-based and discrete event modeling concepts where object -based modeling concepts were used to create interactive objects, and stock and flow structures were constructed to be discrete in time and space. As such, the model is considered a hybrid model. The model serves as a network of resources aiding the patient in the most appropriate direction in order to place him or her in the right location at the right time. The patient-oriented modeling approach has proven useful, as it has enabled a systematic observation on the emergence of various cardiovascular pathways based on patient attributes incorporated in the model.

The use of objects to represent attributes and AED processes, make this model a unique take on System Dynamics. The attributes arising from the model were built on predetermined values in the form of graphical functions, enabling scenario testing to capture the resources the patient claimed in the AED. To this end, a successful simulation model has been created that permits a detailed observation of clinical pathways for cardiovascular patients.

Keywords: system dynamics, clinical pathways, accident and emergency department, cardiovascular patient, patient attributes, object-based modeling, hospital simulation, discrete event simulation.

Acknowledgements

First, I want to give my sincere gratitude to my thesis advisor Professor Pål Davidsen at University of Bergen. Prof. Pål has been an encouraging and great advisor to work with, who suggested I should take on the project with Haukeland University Hospital. He has shown engagement and immense knowledge throughout the project, and I am grateful for all the help and assistance throughout my master's thesis. I admire the passion he has for system dynamics and its potential as a useful tool in the healthcare sector. I want to give a big thanks to Kjersti, whose creativity and hard work has helped us get ashore on this project. Thank you to Johannes Kolnes at Haukeland for providing us with useful and valuable information to help us along the way, for taking his time to write up long responses over e-mail in regard to the emergency department and the diagnostic processes, and for taking the time to meet with us on several occasions this past year. This would not have been possible without him. Finally, I want to thank my family, Matt and my friends for helping me survive this master's thesis journey. You have been supporting me through all the frustration and stress, you have listened to me talking about equations, loops and stock and flows while continued to provide me with encouragement and pride. Thank you.

Hannah

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EQUATIONS

Table of acronyms

AED	**Accident and Emergency Department**
AFib	**Atrial Fibrillation**
ABM	**Agent-Based Modeling**
AGB	**Arterial Blood Gas**
cTnT	**Troponin**
DES	**Discrete Event Simulation**
ECG	**Electrocardiogram**
HUS	**Haukeland University Hospital**
MAS	**Multi-Agent System**
MOS	**Multi-Object System**
MIO	**Medisinsk Intensiv overvåking/Medical intensive care unit**
NSTEMI	**non-ST Segment Elevation Myocardial Infarction**
OBM	**Object-Based Modeling**
OR	**Operational Research**
SD	**System Dynamics**
STEMI	**ST-Segment Elevation Myocardial Infarction**
TEWS	**Triage Early Warning Score**
UA	**Unstable Angina**
UMO	**Utgreiingsmottak (referred to as diagnostic unit in the study)**

CHAPTER 1

Introduction

1.1 Healthcare in Norway

Hospitals are intricate social systems with boundary crossing influences coming from multiple social institutions and surrounding communities. Our dependency on healthcare services greatly influence the quality of care in hospitals and thus, providing efficient, cost-effective, quality care is vital (Gunal, 2012). As such, hospitals are often faced with "the consequences of increasing demand in times of limited financial resources and competing social needs" (Harper, 2002). The Norwegian government's responsibility to deliver universal healthcare to all its citizens means it is essential that the medical services provided are adequate to meet the needs of the patient. Access to healthcare services is considered a fundamental right and each Norwegian citizen is entitled to receive healthcare regardless of social or economic status. As such hospitals provide a variety of services to accommodate for different types of patients. One of them is to provide emergency services and treatment. When patients seek medical care in the case of an emergency, it can be done through the accident and emergency department (AED).

The AED's main purpose is to provide incoming patients with the necessary treatments in the event of an emergency (Vanderby, 2009, p.1). The majority of patients arrive by ambulance, while a small percentage enter the AED via other healthcare institutions such as hospitals, nursing homes and emergency rooms (Brailsford, Lattimer, Tarnaras, and Turnbull, 2004). Providing adequate services to the various types of patients entering the AED in the most efficient and cost-effective way, sometimes proves to be a challenge, as there are multiple factors influencing the AED's ability to perform in an adequate and satisfactory manner. According to Harper (2002), complexity, uncertainty, variability, and limited resources significantly influence AED performance:

Complexity

- Complexity in the AED can involve the rules that governs the way patients are sorted after arrival, e.g., the use of triage and prioritization tools.

- The various AED processes and activities, e.g., the patient goes through several stages during his or her patient stay, and activities and processes varies from patient to patient; thus, allocation of resources are altered according to patient type.
- Coordination of resources, e.g., when multiple patients “cross” each other and claim the same resources it can create competition of resources.
- Complexity in patient influx: AED activity is nonlinear and significantly varies from day to day, week, and year.

Uncertainty

- Demand variation and demand uncertainty e.g., elective versus unplanned emergency patients: Emergency patient arrivals are stochastic in nature, arrive at random and are usually prioritized to reduce delay to a minimum (Harper, 2002).

Variability

- Patient type, e.g., patient type introduces variability based on arrival distribution of frequencies of cardiovascular patients; the type of patient will most likely vary from day to day, and week to week.
- Variability in patient influx.

Limited resources

- Resource allocation, e.g., lack of available resources to the amount of incoming patients throughout the day and week, in which coordination of resources is needed. The subject of “fair” resource allocation between different patients and patient groups.

Despite these challenges, hospitals are constantly working to satisfy increasing patient demand. The importance of providing adequate services involves decision-making in terms of planning and healthcare resource management (Harper, 2002). An in-depth understanding of the AED system and involved decision-making processes is therefore necessary.

1.2 Haukeland University Hospital and Motivation for Research

Haukeland University Hospital (HUS) is located in Bergen, Norway and is a part of the Helse Vest region and is the largest of the five publicly funded hospital institutions on the west coast. HUS is also one of the major hospitals in Norway and is also a healthcare provider for people across the country. Approximately 36 000 patients arrived via the AED at HUS to receive urgent care in 2015[1] (Aarøy, T. 2016), resulting in an average of 100 to 120 patient arrivals at the AED on a daily basis. Furthermore, the total patient number is estimated to increase by thousand patients annually and it is expected that the annual number of patients will increase from 36 000 to 45 000 by 2025 (Aarøy, T, 2016; Helse Bergen, 2012). The anticipated patient increase is largely attributed to demographic changes in the Norwegian society, and consequently, an augmentation in demand for efficient health care services is increasing along with it. A growing aging population and a rise in immigration are key factors contributing to the projected increase patient influx to the AED (Tønnsesen, Leknes & Syse, 2016). This population is estimated to grow from 190,000 to approximately 320,000 by 203 and according to the Norwegian Directorate of Health (2012), projections about the proportion of elderly among the general population is said to increase significantly (Nasjonal Helse-og Omsorgsplan, 2011-2015; Den Norske Legeforening, 2014). The proportion of people over the age of 67 years old will increase by 64% by 2030, while the proportion of elderly over 80 years old will increase by 56%. They also state that "based on the knowledge of current health care provision and consumption among the general population, elderly over 70 years old utilize health care services at a rate five times higher in comparison to younger age groups" (p.6). With the impending growth in the proportion of elderly, hospitals are faced with a rise in complexity of diseases and consequently, an increase in patient acuity. The economic cost surrounding adequate and proper patient care exacerbates the situation even further.

As such, an ever-increasing need for "interdisciplinary expertise in the treatment and monitoring of age-related diseases and hospital processes that are more efficient to treat a growing population" are on the rise (Helsedirektoratet, 2012, p. 6). In order cater the

[1] «Slik skal Haukeland sortere pasientene»: (http://www.bt.no/nyheter/lokalt/Slik-skal-Haukeland-sortere-pasientene-305484b.html?spid_rel=2).

growing elderly population and the surrounding institutions whose work is directly affected by the quality of the hospital system, long-term planning and well thought-out strategic decision are absolutely essential (Vanderby, 2009).

1.3 The Accident and Emergency Department at HUS

Though increases in demand are largely attributed to the anticipated growth in the population, which is in turn is a contributing factor to the logistical and operation challenges the AED at HUS might face, the problem is more multifaceted. People turn to the AED when needing immediate medical treatment and when other healthcare facilities such as emergency rooms cannot provide the person with the proper medical attention they. Thus, outside influences from other social institutions greatly impact the daily operations of the AED. Additionally, managerial and organizational decisions also affect the way the AED functions and influences the AED like projections on population increase (Brailsford et al., 2004). Nonetheless, there is a rise in demand on the public for hospitals to provide services that satisfies their needs. In response to the increasing demand, expected demographic changes and associated projections in patient influx, the AED at HUS has been significantly renovated. HUS hopes the renovation of the AED will help facilitate the diagnostic process of incoming patients efficiently than previously.

Though the AED has well-established rules that should ensures critically ill emergency patients are treated within an acceptable timeframe, these rules are frequently challenged because of the unpredictability in patient influx throughout the day and week. When patients enter the AED, a variety of different patient types present themselves and thus uncertainty and complexity dominates the AED environment. Despite this, the main goal of the AED is explicit: To assess and evaluate emergency patients and to place them in the most appropriate location for treatment at the most appropriate time. Medical staff in the AED are specifically trained to care for emergency patients and the facility is built to provide fast and life-saving treatments. The new AED at HUS opened in May 2016 and the renovation of the old AED facility is one of the largest constructional improvements the hospital has carried out in years (Aarøy, T, 2016). The new AED is built to operate and serve as a local hospital by providing improved diagnostic services and should help reveal pressure on in-hospital wards. The expansion should also reduce bed occupancy time in the AED, that should further reduce the bed occupancy time in in-hospital wards. To accommodate for this, the size of the old AED has been expanded significantly and the AED now spans three floors, covering approximately 7100 square meters in total workspace. (Helse Bergen: Nye Byggeprosjekter[2] [31-33]; Aarøy, T, 2016). The new motto for the AED is to "assign the correct diagnose at the right time, and to administer correct and proper treatment at the most appropriate time and place" (Taule, A [p, 24]). As such, the primary goal of the new AED is to improve the quality of the existing diagnostic processes aiming at assessing and categorize incoming patients as early and as efficiently as possible.

The new AED consist of the following units and sites: A general AED area for incoming patients who needs to be triaged. After the patient is triaged and prioritized based on the seriousness of his or her medical condition, they are assigned a room or bed. After triage and the initial clinical assessment, a patient with a confirmed diagnosis will be sent to the short-term unit or an in-hospital ward. A *chest pain* unit is located inside the short-term unit and is allocated for cardiovascular patients who need observation while waiting for lab test results to return. Patients sent to the short-term/chest pain unit, are usually stable, are not experiencing any current chest pain and will stay here for observation before being sent home or admitted if needed. The patient however might have experienced chest pain prior to arrival but is currently not experiencing any pain.

Furthermore, two additional units are located on the second floor which in this thesis will be referred to as the diagnostic unit (UMO 1 & UMO 2). If diagnostic uncertainty still exists after clinical assessment or the patient have multiple diagnostic suspicions that make it difficult to admit them to a specific in-hospital ward, they are transferred here. Lastly, a new research and development site has also been built in the new AED (Helse Bergen: Nye Byggeprosjekter[3] [31-33]; Taule, A [4-10]). For this study in particular, the focus is on the general AED including triage area and the clinical assessment. Patients are then sent to either the short term unit (chest pain unit), admitted to the cardiac care in-hospital ward, sent to the diagnostic unit or discharged and sent home.

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[2],[4] Helse Bergen: Nye Byggeprosjekter: (https://nsh.custompublish.com/getfile.php/.../0000004550.pdf)

Apart from structural upgrades, reorganization on where and how arriving patients are greeted and placed in the AED has been implemented. There are now two main entrances: One door is designated for acute care patients in need of immediate medical assistance, whereas the second door is designated for less critical patients (Aarøy, 2016). The two entrances ensure that critically ill patients are taken care of as soon as they arrive. Moreover, as the AEDs purpose operates as a local hospital, the AED are now providing additional services that other AED's at other hospitals might not offer and is what makes this AED unique. It has now centralized diagnostic imaging (i.e., x-ray, CT and ultrasound). This was previously only located in another hospital department and the patient had to be transported or wait for equipment in order to undergo diagnostic imaging. This is now collocated in the AED in its own radiology unit and enables medical staff to receive imaging results quicker than before.

Head physicians are now available in the initial stages of the AED and will be the first ones to assess incoming emergency patients. Less critical patients are also met by a team of doctors, though not head physicians, and will together with nurses will carry out the initial assessments for these patients. If the new implementations are successfully carried out, the hospital anticipates this will help reduce the number of "unfit" patient admission to the wards and thereby only admitting patients who actually need to be admitted to a specialty ward. HUS estimates that approximately 15 000 out of the 36 0000 patients in the AED are not admitted to an in-hospital ward but is either discharged or sent to one of the AED units before being discharged later on. According to 2012 admission data, 2000 patients were admitted to the wrong ward and they hope the new AED will help minimizing unnecessary admission and transfers (Aarøy, 2016). This means that a big portion the patients entering the AED will not continue onto a specialty ward and it is important that the type of patient designated for in-hospital wards are established as early as possible.

The new and improved AED should help reduce the number of patients being transferred between hospital wards and help reduce the number of patients sent to the diagnostic unit. This should increase the patients chances of being admitted to the appropriate specialized in-hospital ward (Helse Bergen 2012: Konseptfaserapport). The predicament of providing cost-effective, high quality medical services are becoming progressively harder to achieve due to constant pressure from the public. The overall cost-effectiveness must be improved through fast and accurate clinical assessment and this starts with the new AED. Efficient AED processes influences the internal logistics of the hospital and contribute to more efficient in hospital operations. As such, the AED is contingent on having adequate resources at their disposal and utilize those resources efficiently.

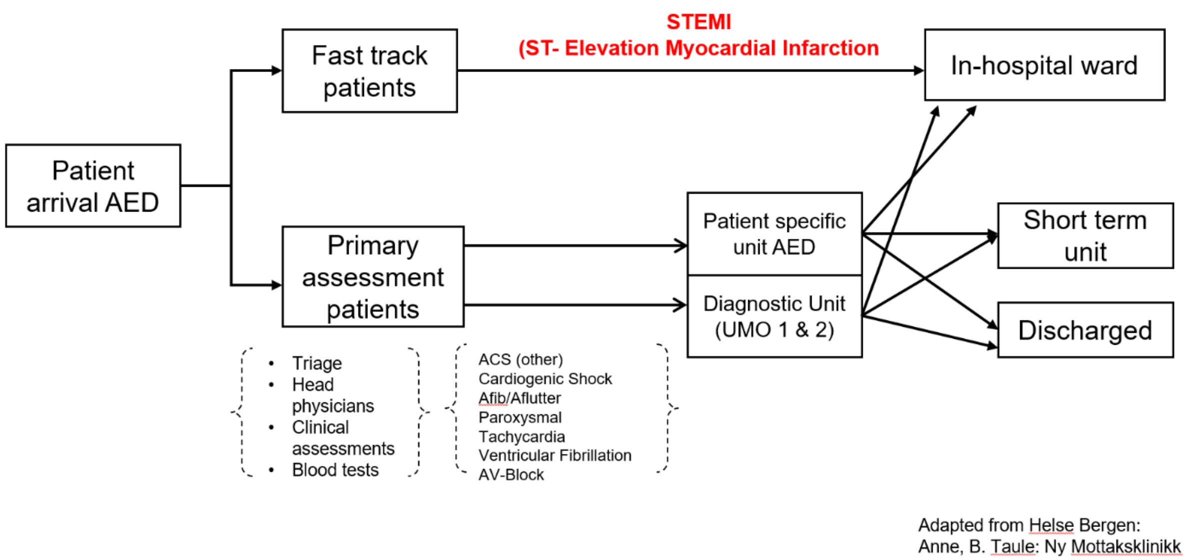

Figure 1. Flowchart of the clinical pathway for cardiovascular patients adapted from Helse Bergen[4]

1.4 Method

The AED remains unquestionably complex and as such, a variety of approaches can be utilized in order to map out and get a clearer understanding of the numerous processes involved. First off, the idea that AED processes should be viewed in the light of the patient is at the center of this study. The patient is undeniably the most valuable aspect of patient care delivery and the primary goal is to work in the best interest of the patient in order for the patient to go through the system in the correct way and be admitted to the correct

[4] Taule, Anne. (2016). Ny Mottaksklinikk- Muligheter og Status: https://www.nsh.no/getfile.php/3679670.2445.../Anne+Taule.pdf

facility at the right time. Therefore, a good understanding of the patient's needs can be achieved by taking the perspective of the patient and using a patient-oriented modeling approach to capture the essence of the AED processes and placing the patient at the center of the model. Ozkaynak et al. (2013) describes a patient-oriented approach as a "philosophy of care delivery in which services are arranged around the needs of the patient. This includes any work or activity carried out by staff members who are engaged in the patient's care". The patient-oriented perspective highlights the essential aspects of clinical decisions and captures the order of the roles' contributions to the care delivery in the AED (Sacristan, 2013). By adopting a patient-oriented modeling approach, it allows for a detailed observation of patients and their clinical pathways in the AED setting.

Second, in order to get a good understanding of how the processes work on an individual level, the model focuses on one group of patients. For this study I am focusing on cardiovascular patients. Cardiovascular diseases are a group of diseases pertaining to the heart and blood vessels and this patient group are frequently seen in the AED. For this study, the following cardiovascular diseases are considered: Acute coronary syndrome (ACS), cardiogenic shock, and variety of arrhythmias and heart blocks. Acute coronary syndrome (ACS) is an umbrella term for a group of conditions that share similar traits and is typically caused by the same medical problems (see Table 16). It is often caused by atherosclerosis (American Heart Association, 2016) and depending on the amount of plaque that builds up in the walls of the arteries, the formation of a partial or full blood clot can occur. As a result, various forms of ACS might develop and some more serious than others. This includes ST-segment elevation myocardial infarction, Non-ST segment myocardial infarction and unstable angina. Another possible disease is cardiogenic shock which is relatively rare but a very critical condition that requires immediate treatment. Cardiogenic shock is a result of the hearts inability to pump enough blood throughout the body. Arrhythmias and heart blocks are two other groups of cardiovascular diseases, usually caused by abnormal heart rhythms (arrhythmias) or impaired or non-transmitted electrical signals from the heart (Heart Blocks) (American Heart Association, 2016). These are the main cardiovascular patients included in the model and variations of the diseases are incorporated and can emerge as a result of patient attributes.

Third, in order to represent the emergence of such diseases from a modeling perspective, the use of object-based modeling concepts (OBM) or agent-based modeling, to represent patient attributes are chosen. Object-based modeling is a method of representing local interaction in which the interaction between objects in a system give rise to emergent states. (Abbas, Alam & Edmonds, 2014). According to Shalizi (2006), when talking about the object paradigm, the article states that everything is a “thing that interacts with other things” and by defining the systems’ constituents and their interactions, we attempt to replicate the environment and observe the behavior of the objects (Van Dam, Nikolic and Lukzco, 2013). In this study, the word object is used, as the model should not be mistaken for an agent-based model. In this study, the OBM approach is used to observe the interactions occurring between the patient and its resources and thus patient attributes and AED entities are represented in the form of *objects*. The chosen approach can also be referred to as a multi-agent/object system (MAS), as the AED model is “set up with precisely the characteristics, connections and choices they needed in order to achieve desired emergent states” (Van Dam et al., 2013, p. 36). When objects interact with each other, decisions are made and actions are initiated which enables the movement of the patient through the AED. The transparency of the model allows for observations to be made in regards to what outcomes are generated when objects are given a variety of attributes, assigned specific rules and decisions. The rules that governs resource utilization are in turn motivated by the overall model goal; to diagnose and assign the patient a proper placement status reflecting the patient attributes. Ideally, an object-based model outcome reflects the most satisfying action in order to achieve the goal of the individual. In this model, this would mean choosing the most resource efficient actions in order to assign the patient a placement status as fast and efficient as possible. As this model simulates one patient and one diagnose at a time, resources are simply made available when needed.

Unlike pure object-based models, objects in this model are not capable of flexible, autonomous decisions on their own as many of the objects are deterministic and dependent on the interactions of other objects in the system. As an example, electrocardiogram (ECG) is used to measure the hearts electrical activity. In this model, the ECG behaves as a resource as well as an attribute. The ECG is located in its own sub-model consisting of deterministic ECG developments. In isolation, the ECG do nothing but provide information the ECG status of the patient. However, when combined with other patient attributes and connected to other sub-models, dynamic interaction emerges.

Further on, discrete event modeling concepts are also applied to this model and the resources available are modeled discretely in time and space. They are expressed as a series of discrete events or activities carried out by AED staff. Specific stock and flow structures in the model are used to confirm the completion of an activity as well as the evaluation of a specific scenarios or procedures at a specific point in time. Once an activity is completed and a decision is made, the stock indicates at what point in time the decision is revealed. This is seen in the figure below:

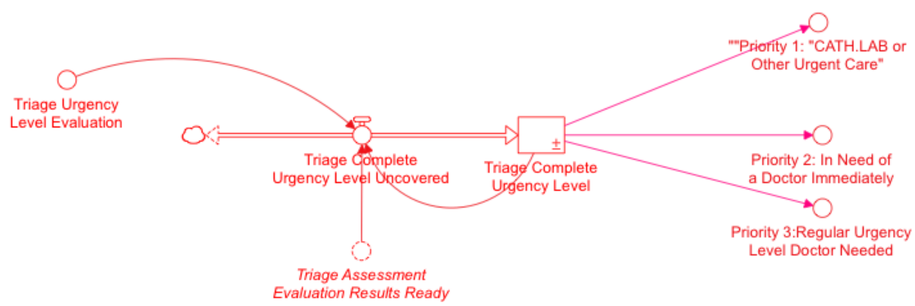

Figure 2. Stock and flow structure indicating triage completion.

Though the model is mostly deterministic, stochastic elements are incorporated to generate random numbers. The random numbers generated, correspond to graphical functions indicating deterministic developments reflecting clinical patient attributes. Some stochastic objects are:

Table 1
Random Number Generators Used in Aiding Patient Attribute Combinations and Developments

Name of generator	Range	Formulation
Age	20-99	RANDOM (20,99)
Gender	0-10	RANDOM (0, 10)

ECG Developments	1-50	RANDOM (1, 50)
Clinical Attributes	0-5	RANDOM (0, 5)
Lab Test Developments	0-5	RANDOM (0,5)
Risk Factor Presence	0-100	RANDOM (0,100)
Resuscitation status	1-5	RANDOM (1, 5)
(Located in clinical assessment)		
Anticoagulation status	5-10	RANDOM (5,10)
Atrial Fibrillation/Atrial Flutter Duration	0-15	RANDOM (0,15)
Asystole Length	10-60	RANDOM(10,60)

The various outcomes of the model are based on predetermined values indicated at the start of the simulation and the algorithms encapsulated in the objects are written based on existing medical literature, clinical pathways, and current practices in the AED. Established relationships among symptoms and clinical findings determine the diagnostic outcomes that are simulated. Attribute combinations are based on actual diagnostic findings that can be found in the AED as well as evidence-based research on clinical pathways. Clinical pathways are used to replicate existing medical practices in order to illustrate the assessment and treatment of cardiovascular patients. The use of clinical pathways, also called critical pathways, care paths, integrated care pathways[5], are standardized and commonly utilized in hospital settings, including HUS. The use of clinical pathways as the basis for this study provides great insight into the intricate process in the AED. By using the pathways as reference and basis for patient development, a mapping process of the diagnostic processes associated with cardiovascular pathways are achieved. Each diagnosis consists of clinical findings likely to occur in an AED setting and the patient is then linked to various resources including medical staff and physical examinations that require the use of different medical equipment.

Allocation of physicians and nurses are embedded into simplified structures shown in chapter 3, section 3.10. These simplified structures record the time spent on AED activities and procedures where medical staff are needed. Due to the simplified resource allocation structure, observations on the type of resources requested easily be done. When resources are needed, medical staff is assumed to be needed as well though not

[5] European Pathway Association: care pathways: (http://e-p-a.org/care-pathways/).

explicitly illustrated and as such, both types of resources are made available at the same time.

The current model disaggregates AED processes and patient attributes and converts them into of sub-models. However, due to the rich array of multiple patient and resource attributes, the attributes will later be organized into arrays. Arrays consists of elements, or array objects that are systematically organized in an index form by columns and rows. This structure the parallel activities and interaction among the objects in a more organized way. Each individual patient and the corresponding resources will eventually be classified into specific groups that will constitute an element in an array. The arrays in this model will have information about the processes in the AED, as well as attributes of the patient. For instance, a patient is an element in an array, which in turn is comprised of attributes and characteristics defining the patient's condition.

Based on the methods described, a simulation model has been developed that represents how the AED is configured and the processes to support clinical pathways. In addition to OBM and DES modeling concepts, information about patient-oriented care and illness trajectories have also been gathered. Model development has been captured through interviewing medical staff, using well-established clinical pathways on cardiovascular diseases. Vital heterogeneities in patient attributes and decision rules have been translated into model objects and presented as various system dynamic sub-models (Sterman, 2000).

1.5 Problem Definition and Research Objective

As outlined above, the projected demographic trends indicate an increase in the elderly population and the AED is likely to face a rise in patient influx accompanied by an increase in illness complexity and acuity. In order to deal with the anticipated demographic changes, an expansion of the AED at HUS has done out as a response. In order to fully reap the rewards associated with the AED expansion, it is essential that patient groups are characterized in more detail. Once the hospital has well documented information for different patient groups and their clinical pathways, the AED can make clinical decisions more confidently. As such this model aims at mapping AED processes that correspond to the needs of cardiovascular patients. I have chosen cardiovascular patients as the targeted patient group as it is a patient group that frequently occupies the AED. Therefore, the use of clinical pathways is essential to this study.

Clinical pathways are standardized treatment pathways for specific diagnoses and it is essentially treatment plans showing the expected clinical course. According to Kinsman, Rotter, James, Snow and Willis (2010), clinical pathways are tools used to guide evidence-based healthcare and by implementing clinical pathways it reduces the variability in the various services provided as standardized rules apply for the handling of the same type of patients. The European patient pathway association[6], states that “the implementation of successful clinical pathways enhances the quality of care throughout the hospital and increases patient satisfaction and optimizes resource utilization”.

Clinical pathways already exist for many patient groups at HUS that covers the clinical pathway from arrival to discharge from an in-hospital ward. The model will use common clinical pathways for various cardiovascular patients as the basis for model development which enables a better understanding of the AED processes linked to this patient group. On the basis of the chosen modeling methods, the model enables comprehensive clinical decisions to be made by use of clinical pathways in order to assign the patient a diagnose and a placement decision. The patient as an object is at the center of the model and is comprised of attributes and characteristics expressed as equations. These equations define the patient’s condition, which in turn dictates the rules that governs the interaction between the patient and its resources. The model aims at decomposing the AED system processes into detailed observable objects that interacts and make clinical and logistic AED decisions. The current model illustrates how cardiovascular patient pathways flow through the AED and how associated resources are utilized according to the type of cardiovascular patient that occupies the system. The model simulates and examines one diagnose and one clinical pathway at a time, which permits the observation of resources allocation to the patient at various points during the AED stay. Current resource policies in the AED at HUS includes the rules used in triage and during the clinical assessment.

[6] European Pathway Association: care pathways: (http://e-p-a.org/care-pathways/).

In triage, a set of specific guidelines applies in which patients are prioritized based on the severity of their medical condition. This ensures the most critically ill patients are being assessed and treated first. During the clinical assessment, resource allocation policies and rules are still influenced by severity of the patient, but the type of resources requested and utilized, depends on a range of attributes (clinical signs and symptoms) of the patient. The clinical status of the patient implies what kind of resources are being occupied, and the clinical pathway for each individual patient decides when and where these resources are requested. As such, observations can be made in terms of how the AED will maintain its function under various types of scenarios, given the available resources in the AED. Though the current model only simulates one patient and one diagnose at a time, the various scenarios provide input as to what might happen when multiple patients enter the system at once. When multiple patients occupy the AED, clinical pathways cross each other and result in patients claiming the same resources at the same time.

The study uses a patient-oriented perspective to model one particular patient group in the context of the new AED. The model as envisioned is expected to be viewed as an exploratory model and the model should initiate discussion on the development of other patient-oriented sub-models of other patient groups at HUS. Once numerous clinical pathways models are developed, a comprehensive examination of HUS as a whole and the interrelatedness between departments and resource allocation may be studied. Such a model should then enable us to capture the influences the AED has on the rest of the hospital and other social systems. In the framework of a bigger and more comprehensive hospital model, all major patient groups and their respective clinical pathways will be modeled. Constrictions on the amount of available resources to patient groups will then become more evident as more patients claim the same limited resources. The benefit of such a model does not only lie within the context of the AED alone, but also in the context of the hospital.

The current model is an element that will be part of a larger model encompassing the entire hospital that will include other patient groups and their clinical pathways. In order for the AED to cater to the increasing demand, AED processes need to be organized and structured in a way that best suits the type of demand without compromising quality and cost. Vanderby (2009) states that “the interactions among hospital care elements are complex and although hospital administrators and medical staff are aware of the inter-relatedness of demand and resources, quantifying these relationships are overwhelming and beyond the scope of their expertise”. Therefore, developing simulation models may help facilitate a better understanding and a clearer visualization of the complex hospital processes administrators and medical staff are dealing with on a daily basis.

CHAPTER 2

Literature Review

2.1 System Dynamics

System dynamics (SD) is an analytical modeling methodology developed by Jay Forester in the 1950s and is based on the modern theory of nonlinear dynamics (Sterman, 2000). The mathematical representations in SD aim at representing real life decision-making and reflect real life reprocesses. Though rooted from complex mathematical formulations, Sterman stated that SD is designed to serve as practical tool for policy makers in organizations looking for a strong tool for strategic problem solving. Brailsford (2008), Implied that the fundamental principle of SD centers on the idea that *structure determines behavior* in which the purpose of SD methodology is to observe and study complex dynamic systems and its behavior over time. It is a method where one can model process structures and analyze their behavior through the investigation of how resources flow, accumulates and interact in the system over time in a dynamic interdependent feedback loops (Larsson, 2009). The key components of the SD modeling method are stock and flow structures, time delays, nonlinearities and feedback loops. Feedback loops are one of the most central components of system dynamic theory and is defined as when components of a system influence each other. SD explains that behavior of a system is the result of interactions between the system components, and the behavior exhibited is a result of those interactions. This is where the feedback loops come into play. In SD, there are negative and positive feedback loops, also referred to as self-reinforcing or self-correcting loops. The positive feedback loops will amplify conditions in the loop and negative feedback loops counteract change or seek balance and equilibrium (Sterman, 2000. p.12). In SD, the flow can be viewed as a faucet filling up a bathtub (the stock) - If the stock and flow structure contains an inflow and an outflow, it can either be drained or filled depending on the rate of the two flows. SD uses causal loop diagrams to represent causal relationships between objects in a system but the relationship does not denote the magnitude of the relationship but the symbols -/+ or (S/O), indicates the direction of the influence that the loops might be taking (Brailsford & Hilton, 2001). Decisions and results regarding the development of any SD model, does in large part depend on the decision maker's perception of the state of the system (Vanderby, 2009).

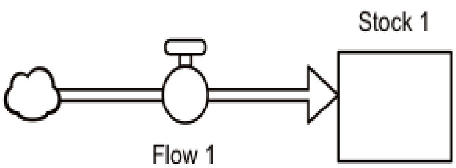

Figure 3. Simple stock and flow structure.

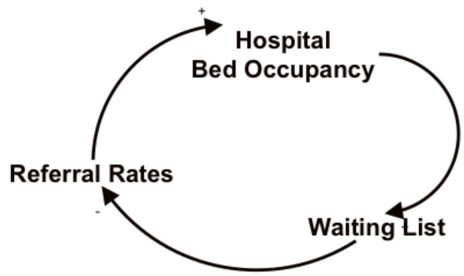

Figure 4. Example of a causal loop diagram (Brailsford, 2008).

2.2 Application of System Dynamic models

In reference to this study and its patient-oriented perspective on hospital modeling, there seems to be a lack of SD models taking this kind particular approach, though research on logistics and clinical pathways of the old AED has been done in the past. (Davidsen, Kråkenes & Dvergsdal), created a SD hybrid model with discrete event methodology components when examining AED processes and various clinical pathways at HUS. They divided patient stay into three stages; pre-diagnostic state, diagnostic stage and post-diagnostic stage and decomposed the diagnostic stage into three components, enabling examinations of the waiting times in three stages. The research gave implications with respect to different cardiovascular patient pathways in the AED.

Other variations of hospital models utilizing SD methodology exist and when developing simulation models from a SD perspective, it is often used as a tool of persuasion, or as a frame for evaluation of tactical studies. Models that highlight scenarios can "act as a catalyst to insightful thinking and policy change" (Dangerfield, 1999), by offering a bigger holistic view on an organization or community. Dangerfield also stated that this holistic whole-systems view might improve the evaluation of tactical initiatives being implemented while in contrast, “other operational research studies that focus on tactical aspects sometime seem to be lacking consideration of context”. He claims that in such instances SD is an excellent tool due to the perspective of SD modeling. Considers the bigger-picture approach and all the dynamic interactions and influences required in order to grasp the totality of the problem in question.

One famous system dynamic study from the health care sector considers interactions in a bigger-picture perspective is a study by Wolstenholme (1993), on community care planning. Wolstenholme’s study modeled and evaluated a new legislation and the financial and social consequences associated with it. The study analyzed what happened when the government switched community care responsibilities from the Department of Social Security, to local government Personal Social Services Directorates. The change was implemented with the intention of saving more public funds as they believed the amount of patients entering the community care cycle would slow down because of the cash restrictions imposed. Consequently, this had effects on the larger system; because they limited the amount of patients discharged from the hospital, the number of patients having to stay in the hospital longer increased and as a result, the hospital had to reduce the admission rate and in turn, the waiting list increased. Wolstenholme’s study demonstrated the usefulness of systems thinking and what could happen with well-intentioned policies. His study is a reminder that when people forget to take into consideration the bigger picture, the feedbacks and interactions in a system can have a rippling effect

Another study focusing on health care policy is a SD study by Taylor and Dangerfield (2005). Their study investigated the consequences of a shift in cardiac catheterization services at two hospitals. The catheterization services were changed from a tertiary level to a secondary level, moving them closer to “home”) for low risk investigations for heart disease patients. The study indicated that the topic of feedback mechanisms and service shifts in the healthcare at the time of the study had been given minimal attention despite increasing emphasis on the need for a more whole-systems thinking. The study addressed the possibility that “shifting services could stimulate demand and effects of such a shift in services would improve access” (Taylor & Dangerfield, 2005). A study by

Royston, Dost, Townshend and Turner (1999), focused on care policy programs that involved looking at the effects of different types of health promotion, disease prevention interventions followed by an investigation on the consequences and benefits of these implementations.

SD studies concerning wait list problems can be found in studies by van Ackere and Smith (1999), who looked at the interaction between supply factors; the resources and the efficiency of those resources, and demand factors; perceptions and preferences from the demand side. Windmeijer, Gravelle and Hoonout (2005), also looked at demand and supply in the light of waiting lists, waiting times and admission, whereas Coyle (1984), (As cited in Vanderby, 2009, p 19), focused on the management of a hospital for short-term psychiatric patients. Studies done by (Cotè, 2000; Brailsford et al., 2004; Lane et al., 2000), looked at hospital processes where his study on an accident and emergency department gave valuable insights on hospital processes including demand patterns, resource deployment and bed capacity problems. (Lane, et al., 2000; Abo-Hamad, Arisha & Rashwan, 2014), examined a health care system and its acute bed blockage problems caused by delayed patient discharge. According to Abo et al., (2014), the model outcome implied that the causes of the delayed patient discharge was the lack of outpatient-care clinic services as well as other alternative healthcare services, particularly for the elderly population. Consequently, this limited hospitals to admit new patients. Townshend & Turner (2000) developed a quantitative SD model hospital model that investigated the effects of Chlamydia screening UK. They chose SD as their modeling tool due to the large population they were investigating. Utilizing SD enabled them to capture the feedback effects due to re-infection of chlamydia treated people. Moreover, a SD model created by Cooke, Yang, Curry, Rogers, Rohleder, Lee and Strong (2007), focused on building a qualitative SD model of objects affecting patient flow in a Health region in Canada. The model consisted of patient flows through the AED where the treatment portion of the AED stay were aggregated into one stock and the stock was affected by doctor availability, patient acuity, and workup time and lab capacity.

Due to the inherent complexity of hospitals and the healthcare system in general, the use of SD as a holistic modeling tool to capture the complex dynamics and the interactions and feedback structures seems appropriate. By using SD methodology, researchers and hospitals can reveal many unintended consequences due to vary policy implementations that failed to look at the bigger picture.

2.3 Discrete Event Simulation

Discrete event simulation (DES) is by far the most frequently used operational research (OR) technique, particularly in the hospital setting. DES is especially appropriate when a research problem has a narrower scope, the simulation period is shorter, or it focuses on a specific event or events. As such, DES emphasizes more on individual entities, and attributes decisions than many SD models tend to do (Brailsford & Hilton, 2001). Traditional system dynamic models on the other hand, take a holistic approach where the complexity of the model lies in the dynamic interactions between the elements of the system as a whole. DES models generally operate on a more disaggregated and detailed level than SD, and is by its name discrete in time and not continuous. Brailsford & Hilton, (2001), characterizes DES as a queuing network of objects going through a series of activities, e.g., a patient going through AED processes. When variables are not engaging in any activities, they are waiting in queues. The state of the system in a DES model changes during specific points in time and in between the changes in the system, no activity is recorded. As such, the modeler only captures the active states of the system instead of capturing the continuous flow. As Maine and Lliff (1985), indicates: “The theory of parameter identification for continuous-time systems with discrete observations is virtually identical to the theory of discrete-time systems in spite of the superficial differences in the system equation forms”, meaning, DES and SD captures the same things in the same system, but DES does not “record” the feedback in their modeling environments. This demonstrates the compatibility that SD and DES have, and that creating a hybrid model for our purpose is of great value. Senge (1990) indicated that there is a clear distinction between detail complexity (DES) and dynamic complexity (SD) and capturing dynamic complexity is significantly harder to comprehend and has a greater impact on system’s performance than detailed complexity. Of course, this depends on the problem in question and the scope that problem.

Some might argue that looking at the details and the micro-behavior of a system is the most integral part of a system, and ignoring the detailed complexity does not yield an accurate result (Axtell, 2010), (As cited by Hartwig, 2011). According to Brailsford & Hilton's (2001) study called "A Comparison Between SD and DES in Reference to Healthcare Modelling", states that besides preferring DES due to its ability to create "queuing systems and therefore reflect the system in question on a more detailed level than SD, modelers choose DES due to the wider selection of literature available. In addition, developing large DES models are expensive to create and requires a lot of data and multiple runs as outcome distributions are made available when multiple runs are made (Vanderby, 2009). Furthermore, simulating large amount of data using DES can get time consuming whereas SD can simulate large quantities of data faster than DES. One example of DES modeling used in a healthcare setting is a study done by Bagust, Place, and Posnett (1999). The study focused on daily bed requirements during a 1000-day period arising from the flow of AED admissions. They concluded that acute hospitals whose bed occupancy exceeded 85 % ran a risk in terms of capacity constraints and as bed occupancy rose to 90% or more, bed shortages and periodic bed crises were likely to occur.

Other hospital-bed models include Hancock and Walter's (1979) study on "reducing variance in occupancy level in a hospital inpatient facility ". A study done by Gabaeff and Lennon (1991), looked at emergency admissions and patient characteristics at Stanford University Hospital, in which they captured deficiencies linked to bed utilization and bed availability. Additional examples of the use of DES in healthcare simulation are mentioned in a survey by Jun, Jacobson and Swisher (1999) in which they cover a number of topics within the healthcare that uses DES. According to a study by Butler, Reeves, Karwan & Sweigart (1992), (as mentioned by Jun et al., 1999), centered around patient misplacements. They looked at patients who were placed in another unit because of bed shortage in their preferred unit and measured the sensitivity of such misplacements against bed allocation policies. Additional studies include Lowery and Martin (1992), on critical care areas in hospitals; Dumas (1984/1985) on the "interrelationship among units within a hospital by comparing bed planning rules"; Cohen, Hershey and Weiss's (1980), study on progressive care hospital bed plans, and Zilm, Arch and Hollis, (1983), on bed levels and future demand.

Table 2
a Meta Comparison of DES and SD (Jovanovski, Minovski, Voessner & Lichtenegger (2012)

DES	SD
Problem	
Seeking to understand the impact of randomness on the system	Aiming to understand the feedback within the system and its impact.
Scope	
Tactica/Operational	Strategic/Policy
High level of detail physically represents the system (detail complexity)	More macro level of detail that summarizes the system (dynamic complexity)
Methodology	
Process view	Systems view
Philosophy	
Randomness	Feedback

2.4 Object-Based Modeling

Though an official or universally accepted definition of Object-based modeling (agent-based), does not exist, Silverman, Hanrahan, Bharathy, Gordon & Johnson (2015), defines the object-based approach as a way where “agents are software entities with mental states and can sense, think, and act with some degree of autonomy to carry out goal of their own choice”. Object-based modeling is an abstracted representation of reality, and often studies emergent states of a system where the overall behavior of a system stems from the complex decisions of individual decisions-making agents within a particular environment. The overall goal of the object in the system dictates the attributes’ actions and the complexity of the system is due to the existence of these attributes. When the attributes “meet” and interact, there are rules applied in the system that activates specific actions motivated by the overall goal. The type of agents used in this simulation model can also be called multi-object systems (Multi-agent system, MAS), as rules and decisions are hand-scripted behaviors (Silverman et al., 2015). Because not every object-based system is a multi-system and vice versa, it is important to emphasize that, the purpose of this model is to use objects to represent processes and attributes. As such, these objects are encapsulated with a variety of functions, which interact and influence each other in some way. Predetermined outcomes based on a variety of possible diagnostic combinations are implemented in the model in order to observe the possible behaviors of the system. The objects can be both active and passive, meaning they can represent humans such as patients and medical staff, or services and other reactive systems such as electrocardiogram or echocardiogram (Taboada, Cabrera, Iglesias, Epelde & Luque 2011).

There are not as many object-based hospital models in operational research and healthcare modeling compared to DES and SD; particularly models that have been validated against the system that it has modeled (Taboada et al., (2011). Taboada et al. (2011) developed and agent- based model, reflecting activities in the AED in order to develop a decisions support system for administrators and heads of the AED. Other studies have looked at patient scheduling under uncertainty (Paulussen, Zöller, Heinzl, Braubach, Pokahr & Lamersdorf, (2004); Hutzschenreuter, Bosman, Blonk-Altena, van Aarle, La Poutr´e, 2008 and Jones & Evans, (2008) looked at scheduling of emergency department physicians, (As mentioned by Taboada et al. (2011). Another object-based model by Christiansen and Campbell (2003), addressed workflows and workloads (as cited by Silverman et al. (2015). In this model, "each agent had physiology models that represented the dynamics of diseases". Workflows were modeled and each step of the workflow process had been transformed into observable steps that each characterized an action or series of actions carried out by participating objects. The objects mirrored patients and hospital staff that carried out actions utilizing the resources made available for them.

Table 3

Comparison of DES, SD and OBM (Adapted from the Meta-Comparison by Jovanoski), (2012).

DES	SD	Object- Based
Problem		
Seeking to understand the impact of randomness on the system	Aiming to understand the feedback within the system and its impact.	Looks at interactive individual objects and collective entities, and assess the impact they have on the system
Scope		
Operational	Strategic/Policy	Operational
System		
High level of detail physically represents the system (detail complexity)	More macro level of detail that summarizes the system (dynamic complexity)	High level of detail within each object. Objects with a function.
Methodology		
Process view	Systems view	Large systems but can also be used for process view
Philosophy		
Randomness	Feedback	Randomness (individual emergent behavior)
Handling of time		
Discrete	Continuous	Discrete or continuous
Level of and type modeling		
Disaggregate	Aggregate	Disaggregation (individual)
Stochastic	Deterministic	Stochastic

2.5 Patient-Centered Care

Besides using simulation models to investigate hospital settings, analytical models studying AEDs' and hospitals have been developed as well. Though analytical models are not as complex and detailed as simulation models, as they are typically based on simplified models of the system in question, they still provide valuable insight to the system properties (Wang, Li., & Howard, 2013). Furthermore, illness trajectories share similarities with patient-centered care. Strauss, Fagerhaugh, Suczek & Wiener (1985), first introduced the concept of illness trajectories in 1985. Illness trajectory is defined as a method concerned with the medical work and the medical staff involved, with the understanding that “the patient is vital to examining care delivery”. Illness trajectories have a broader spectrum than a patient-centered approach when it comes to focusing on the illness and its causes. It also considers interactions with the healthcare institution, as well as other social networks associated with the particular illness in question in addition to the activities to shape the course. A pure patient-oriented workflow on the other hand, focus less on the illness and more on the details of the sequences, activities and the roles involved (Murray Scott, Kendall, Boyd, & Sheikh, 2005). Therefore, synthesis of the two concepts has been created, that focused on the patient’s illness as well as details of the sequences, activities and involved roles in the assessment of the patient (Ozkaynak et al., 2013). An analytical study that has taken a patient- centered perspective is a study done by Ozkaynak et al. (2013) and Ozkaynake et al. (2012). The study focused on capturing patient care in clinics, by looking at hospital staff in the AED setting, and how the work they did affected the patient in which workflow charts were used in order to visualize the study. Applying methods such as direct observation, interviews and data log information, they could observe the factors that affected aspects of the hospital. According to Ozkaynak (2013), a “patient-oriented workflow model defines healthcare delivery from the perspective of the patient and organizes the building blocks of work around the patient and his or her care”. The main purpose of providing health care services are to serve the patient, and as such, centering the modeling purpose on the patient’s needs provides us the opportunity to capture the true workflow (Strauss et al., 1985). When the patient is the reference point, it provides a comprehensive understanding of care delivery. Based on the literature presented, a variety of modeling methods can be used to develop hospital models for various purposes.

CHAPTER 3

Model Description

3.1 General Overview of the AED

Though DES might be preferred over SD and OBM in modeling certain healthcare processes, SD allows for discrete event modeling and the use of SD variables to represent objects that will serve a purpose or have a function. These objects are located in sub-models representing various AED processes and patient attributes. Using SD also allows for a complete AED view where integrated arrays characterize the various mechanisms influencing and driving the system towards its goal. With the future implementation by way of arrays, the current SD model organizes and structure objects that reflect agent-based concepts by the use of sub-models. I, consequently propose the use of a SD/DES/OBM model to facilitate the development of a SD simulation model of the AED at HUS.

In this section, the framework of the model is described and an overview of the care delivery processes for cardiovascular patients in the AED are presented. I present a detailed description of the underlying mechanisms contributing to the AED behavior as reflected in the model. As the aim of the study is to map out AED processes of relevance to cardiovascular patients, the focus of this chapter is on the description of patient attributes and the AED processes specific to this patient group.

The model is constructed in a way that permits one patient to be observed each new simulation run. Every new run generates a new set of attributes that result in a patient status that is either an outcome eligible for cardiac care in-hospital admission or short term unit. Some patients might also be sent to the diagnostic unit if diagnostic uncertainty exist at the end of the simulation. The AED in this model is comprised of triage, clinical assessment, and the underlying mechanisms that contribute to model behavior. For the purpose of this study, the diagnostic unit and short- term unit is excluded and any assessments done here is carried out after the patient is assigned a placement status. As such we are primarily interested in the assessment completed in the main AED area.

Patients who are suspected of having cardiovascular related diseases are admitted to the cardiac care unit. A medical intensive care unit (MIO) is also located in the cardiac care unit for critically ill patients. The other group of patients are transferred to the short-term unit (Chest pain unit), located in the general AED, though separated from the main AED assessment areas. Patients who are sent to the short-term unit are typically stable, with no ongoing chest pain, and stays in the chest-pain unit under observation while waiting for the lab test results to return and to undergo additional assessment if needed. The last group is sent to the diagnostic unit for further assessment if uncertainty in diagnosis still exist. As such, the model covers triage and the initial clinical assessment.

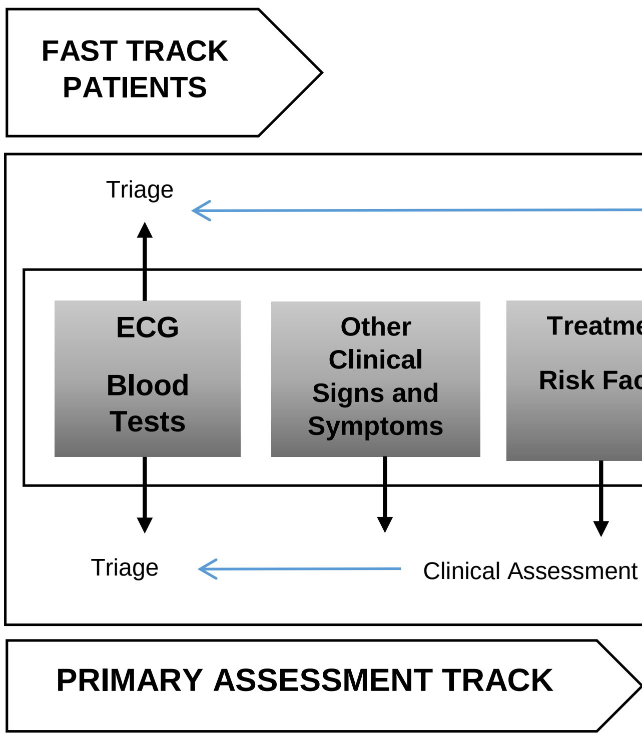

Figure 5. Overview of the AED and the various processes for cardiovascular patients. The flowchart shows the relationship between sub-models and the main AED model process flow.

Table 4

Overview of AED processes

Type	Activity in model
Simplified time structures	Resource allocation and assessment time structures
AED process steps	Triage at arrival Evaluation for placement (1) Fast track, or primary assessment Primary assessment includes: ▪ Evaluation of clinical symptoms ▪ Registration of risk factors ▪ Evaluation for placement (2) ▪ Echocardiogram if needed ▪ Imaging result evaluation ▪ Evaluation for placement (3) ▪ Placement status assigned
Attributes feeding into diagnostic process	ECG developments Symptoms and signs developments Lab test development Presence of risk factors Diagnostic imaging result
Random number generators	Number generator for ECG Developments Number generator for age and gender Number generator for clinical attributes Number generator for risk factor presence Number generator for resuscitation status Number generator for anticoagulation status Number generator for atrial fibrillation/atrial flutter duration

3.2 Formulation of Equations

The formulation of the equations is what makes this patient-oriented model different than your traditional SD model. Many of the equations encapsulated in the various object including flows and variables, use conditional statements such as *IF, THEN, ELSE.* These conditional statements represent actions that describe how the object should react to a certain decision or how to answer a specific question. For example, attribute combinations can differ in urgency and be prioritized from most urgent to less urgent using conditional statements such as *IF Chest pain > 0.70 THEN 1 ELSE 2*, indicating that if chest pain is present at arrival, the variable equals to 1, if not, the variable is equal to 2. These numbers are then further combined with other patient attributes forming combinations that eventually result in a patient status at the end of the simulation period. These conditional statements represent decisions made by medical staff when assessing and diagnosing the patient. A careful mapping process of various cardiovascular diagnoses is carried out, and the conditional statements should reflect the order of prioritization that typically occurs in the AED setting for cardiovascular suspected patients. The model includes common symptoms and findings as well as atypical findings found in the diagnoses mentioned.

3.3 Patient Arrival at AED

Prior to simulation it is assumed that the patient has already entered the system and placed in the triage area. The model reflects what resources will be needed if specific cardiovascular patients present themselves at the AED upon arrival.

3.4 Triage and SATS

The AED at HUS utilizes the SATS: *Standardized emergency medical assessment and prioritization tool*, which HUS implemented in their triage assessment in 2013. The original SATS assessment tool consisted of five urgency levels but Helse Bergen uses four out of the five levels, exempting the blue code *(blue= dead on arrival);* leaving *red*, *orange, yellow* and *green* urgency level. The triage model is comprised of a clinical priority list where nurses conduct a systematic assessment and measures vital parameters of the patient. This assessment process is called the *Triage Early Warning Signs (TEWS).* In an actual healthcare setting, orange and red urgency levels are generally established prior to arrival if they arrive by ambulance but for the sake of this study, all patients are assigned an urgency level in triage. Vital parameters such as systolic blood pressure, heart rate, temperature, respiratory rate, SpO2, indication of trauma, assessment of mobility, and responsiveness of the patient are measured.

Additional investigations are carried out in triage if the patient displays specific symptoms that according to SATS require certain actions. For cardiovascular patients this include the presence of chest pain in which an immediate ECG is administered. In this model it is presumed that patients entering the AED display symptoms typical for cardiovascular diseases. Though the patient might display other symptoms that suggest the need for additional investigations, the model assumes these are taken care of and is therefore excluded in the model. After triage is completed, scores are added up and an urgency level is calculated. Specific symptoms and patient scenarios that upon arrival automatically assigns the patient a red, orange, or a yellow urgency level are made explicit in the model. In this model, urgency signs associated with cardiovascular patients are seen in Table 6. A red urgency level indicates the need for immediate medical attention and a doctor is assigned right away. Orange and yellow patients are assigned a doctor within 10 minutes and 60 minutes respectively. A green urgency level specifies a lower level of urgency and the patient is expected to wait up to 240 minutes. Although the current AED have physicians as the first medical staff the patient sees upon arrival, physicians still remain a limited resource and some waiting is expected.

Table 5. Adult Triage Early Warning Signs (TEWS)

	3	2	1	0	1	2	3
Mobility				Walking	With help	Stretcher/ Immobile	
Respiratory Rate		Less than 9		9-14	15-20	21-29	More than 29
Heart Rate		Less than 41	41-50	51-100	101-110	111-129	More than 129
Systolic Blood Pressure	Less than 71	71-80	81-100	101-199		More than 199	
Temperature		Cold OR under 35		35-38.4		Hot OR over 38.4	
AVPU (responsiveness)		Confused		Alert	Reacts to voice	Reacts to pain	Unresponsive
Trauma				No	Yes		

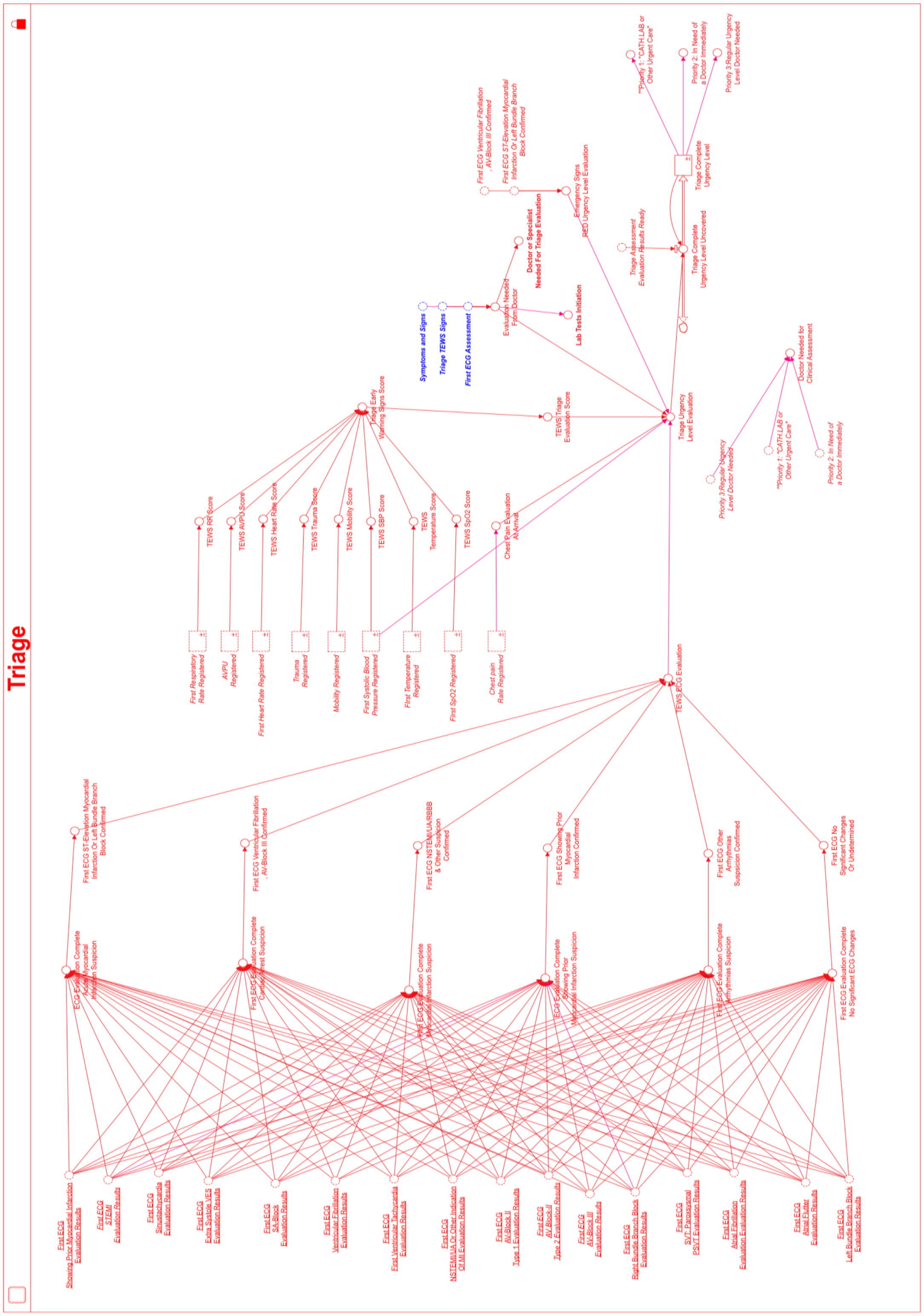

Figure 6. Triage sector showing vital parameters and ECG evaluation.

Table 6
Clinically Priority List Indicating Level of Urgency Assigned in Triage

Definition
RED urgency level Patients who arrive with ECG recordings indicating ST-Elevation Myocardial infarction (STEMI) or cardiac arrest, will automatically be assigned a RED urgency level, denoted by the number (1) in the triage module and should be prioritized immediately. If the patient's potassium levels are over 6 accompanied with ECG-changes the patient is also a RED urgency level. The potassium results used in the assessment, are medical information registered prior to arrival[7].
ORANGE urgency level Patients arriving with ongoing chest pain or significant ECG changes are assigned an ORANGE urgency level, denoted by the number (2) in the triage sector[8].
YELLOW urgency level Patients who have experienced chest pain within the last 24/hours but are currently not experiencing any, and the ECG recordings appear normal, assigned an automatic YELLOW urgency level[9].

3.5 Clinical Assessment Sector

Once the patient is triaged it is assumed the patient is assigned an assessment room, or moved immediately to a resuscitation room/trauma room. In the model, the clinical assessment includes three parts; the physical examination and treatment followed by a registration of risk factors. Though these activities are completed simultaneously in the AED, they are for visual purposes separated from each other. Treatment of the patient is assumed to happen automatically unless explicitly illustrated in the model. Treatments or procedures included in the model are resuscitation, anticoagulation for atrial fibrillation/Atrial flutter, and antiplatelet therapy. Any other treatments are assumed to be administered and considered to be part of the total clinical assessment period. Most of the clinical symptoms are evaluated during clinical assessment, except certain symptoms assessed in triage. During the clinical assessment, the model can suspect multiple diagnoses despite no indications of them during the triage. For instance, certain ECG readings can be negative during triage but the presence of other ECG readings coupled

[7] SATS Norge, Standardisert Akuttmedisisnk vurderings-og prioriteringsverktøy
[8] SATS Norge, Standardisert Akuttmedisisnk vurderings-og prioriteringsverktøy
[9] SATS Norge, Standardisert Akuttmedisisnk vurderings-og prioriteringsverktøy

with additional clinical symptoms might signal that other diagnosis might occur. That is because certain ECG results can contribute to the development of another diagnosis. In addition, certain ECG results can occur as part of another diagnosis. For example, different types of arrhythmias can cause myocardial infarction and conversely, arrhythmias can occur during myocardial infarction as part of the infarction but is not the origin of the infarction. Furthermore, an arrhythmia can cause a myocardial infarction, which in turn can result in heart failure. In addition, symptoms that are often seen in multiple diagnoses can be present, and the model can therefore suspect multiple diagnoses at a time.

When assessing the patient, the point of interest is the status of the patient attributes at the exact moment the assessment is carried out. The stocks containing patient attributes give indications about whether or not symptoms are considered a determinant during evaluation. In order for the value to be considered significant and of interest to medical staff the value has to be either equal to or above a given threshold. Once the assessment is completed, a confirmation of suspicion is disclosed in the stock and a decision about the next step in the clinical pathway is made. Based on the assessment, the evaluation result appears in the stock and considers all relevant symptoms of the patient. The assessment also considers significant symptoms and ECG findings from triage that are likely to persist during the clinical evaluation. If ECG findings in triage are significant, suspicion during the initial clinical evaluation is revealed, even without the presence of other clinical symptoms.

If initial ECG findings are negative but specific symptoms are observed, a suspicion is revealed in the stock at the end of the evaluation. The attribute combinations of the patient are registered and can indicate the patient’s condition and severity and places the patient into different categories. In addition, if echocardiogram is carried out, echocardiogram results can show indicate something different than the initial suspicion and as such, the status of the patient can change throughout the AED process. Once clinical evaluation is completed a status is calculated based and revealed in the stock. In many of the scenarios, the presence of ongoing chest pain or lack of ongoing chest pain is a deciding factor for placement. A clinical assessment structure as shown in Figure 7 illustrates how symptoms and signs are combined and evaluated over the duration of the clinical assessment period.

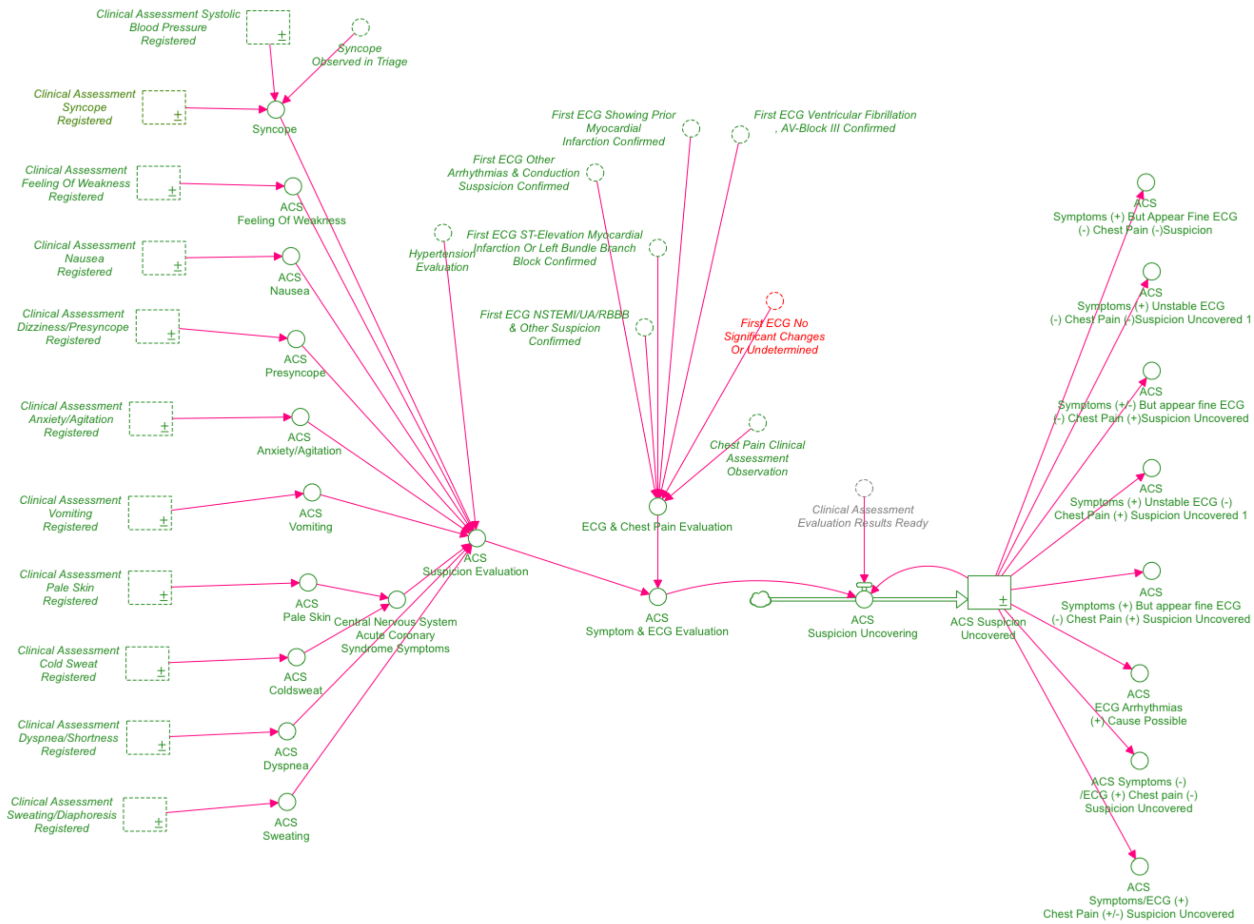

Figure 7. Example of structure in the clinical assessment sub-model.

Inside the circled variables are equations that determines possible outcomes in the stock called *ACS Suspicion Uncovered* in Figure 7. An example of the type of equation embedded in these variables are shown below:

Equation 1: ACS Suspicion Evaluation

IF ACS_Vomiting+Syncope <> 0 AND ACS_Feeling_Of_Weakness+ACS_Nausea+ACS_Dyspnea+ACS_Presyncope+"ACS_Anxiety/Agitation" +Central_Nervous_System_Acute_Coronary_Syndrome_Symptoms+ACS_Sweating+Hypertension_Eval uation >=0 THEN 1 ELSE

(IF Syncope+ ACS_Feeling_Of_Weakness+ ACS_Nausea+ ACS_Dyspnea+
ACS_Presyncope+ ACS_Sweating+
Central_Nervous_System_Acute_Coronary_Syndrome_Symptoms+ ACS_Vomiting+
"ACS_Anxiety/Agitation" +Hypertension_Evaluation <> 0
THEN 2 ELSE
IF Syncope+ Hypertension_Evaluation+ ACS_Feeling_Of_Weakness+ ACS_Nausea+ ACS_Dyspnea+
ACS_Presyncope+ Central_Nervous_System_Acute_Coronary_Syndrome_Symptoms+ ACS_Vomiting+
ACS_Sweating+ "ACS_Anxiety/Agitation" = 0 THEN 3 ELSE 0)

The ECG findings from triage is combined with an evaluation of current chest pain level:

Equation 2: ACS Symptom and ECG evaluation.

IF ACS_Suspicion_Evaluation= 1 AND ECG_&_Chest_Pain_Evaluation = 1 THEN 2 ELSE
IF ACS_Suspicion_Evaluation = 2 AND ECG_&_Chest_Pain_Evaluation = 1 THEN 2 ELSE
IF ACS_Suspicion_Evaluation = 2 AND ECG_&_Chest_Pain_Evaluation = 2 THEN 3 ELSE
IF ACS_Suspicion_Evaluation = 3 AND ECG_&_Chest_Pain_Evaluation = 1 THEN 4 ELSE
IF ACS_Suspicion_Evaluation <> 0 AND ECG_&_Chest_Pain_Evaluation = 3 THEN 5 ELSE
IF ACS_Suspicion_Evaluation = 3 AND ECG_&_Chest_Pain_Evaluation = 5 THEN 7 ELSE
IF ACS_Suspicion_Evaluation = 1 AND ECG_&_Chest_Pain_Evaluation= 4 THEN 8 ELSE
IF ACS_Suspicion_Evaluation = 1 AND ECG_&_Chest_Pain_Evaluation= 5 THEN 9 ELSE
IF ACS_Suspicion_Evaluation = 2 AND ECG_&_Chest_Pain_Evaluation = 5 THEN 12 ELSE
IF ACS_Suspicion_Evaluation = 2 AND ECG_&_Chest_Pain_Evaluation = 4 THEN 10 ELSE
IF ACS_Suspicion_Evaluation = 3 AND ECG_&_Chest_Pain_Evaluation = 4 THEN 11 ELSE 0

The incorporation of ECG findings and status of chest pain with the clinical evaluation of symptoms, result in the creation of a variety of clinical outcomes. Once an evaluation is completed, the possible outcomes are shown, that further aids in the diagnostic process:

Table 7

Possible ACS Outcomes from Clinical Assessment

Acute Coronary Syndrome outcomes
▪ ACS accompanied by symptoms, appear stable, ECG is negative and no chest pain
▪ ACS accompanied by symptoms, appear unstable, ECG is negative and not chest pain
▪ ACS symptoms might be present, appear stable, ECG is negative and chest pain is present
▪ ACS accompanied by symptoms, appear unstable, ECG is negative and chest is present
▪ ACS accompanied by symptoms, appear stable, ECG is negative and chest pain is present.
▪ ACS accompanied by ECG findings of arrhythmia
▪ ACS no symptoms, ECG findings are positive but no chest pain
▪ ACS accompanied by symptoms, ECG is positive and chest pain might be present (an absence of chest pain does not make a difference)

3.6 Patient Evaluation for Placement or Echocardiogram

Once the clinical evaluation is completed, the model evaluates the patient's status and calculates the next step (see Figure 8). The diagnostic suspicions or confirmations are then grouped together based on where the patient can be placed:

1) A STEMI heart attack is the first priority the evaluation structure looks for. If STEMI is established, it will stop the rest of the diagnostic process because the patient will be transported to the catheterization lab immediately after triage. If STEMI is not confirmed, it will look for the next highest priority on the list called *Patient Scheduled for Echo or Placement* in Figure 8.
2) In the variable scheduled for echo or placement, the model first looks for a positive signal for a patient suspected of cardiogenic shock. If cardiogenic shock is suspected an echocardiogram is carried out. If no cardiogenic shock signal is present, an evaluation of whether or not the patient should be transferred to the short-term unit or admitted to the cardiac care unit is calculated. However, there are a couple of

instances in which cardiogenic shock is not of highest priority. If ventricular fibrillation or AV-Block III happens at the same time, the patient should be transferred to the cardiac care unit immediately.

3) Depending on the patient's current condition, he or she will be admitted to the cardiac care unit or transferred to the short-term unit. Placement in the cardiac care unit applies to the following scenarios:
   - ACS suspected patients with ongoing chest pain, with or without significant ECG changes. That is, a patient with no significant ECG findings who is currently experiencing chest pain but appears to be stable is sent to the cardiac care unit for further assessment and observation.
   - AV-Block III patients should be admitted to the cardiac care unit promptly.
   - Unstable AV-Block II patients are admitted and should receive cardioversion.
   - Atrial fibrillation/Atrial Flutter patients are admitted to the cardiac care unit.
   - Ventricular Fibrillation and Ventricular Tachycardia patients are admitted to cardiac care.

These scenarios are considered early placement eligible because the patient appears hemodynamically unstable, the patient is experiencing chest pain (cardiac care unit), the patient is stable and the likelihood of cardiovascular disease is lower (short-term unit), or the condition is critical and requires immediate treatment (cardiac care and MIO). If no signal is observed indicating cardiac care admission, the model checks any signals for the short term unit. If a patient appears stable and no significant findings in the initial assessment is observed that indicates admission to an in-hospital ward, the patient is sent to the short term unit. A patient who appears stable, with no significant ECG findings and is currently not experiencing chest pain are sent to the short term unit.

If several of these priority placements are activated at the same time, explicit rules apply regarding prioritization. For instance, if the variable *STEMI CATH.LAB Patient, Short- Term unit and* the variable *Placement Hospital Admission Doctor Required* in Figure 8 are positive at the same, the STEMI CATH. LAB is prioritized first, followed by *Placement Hospital Admission Doctor Required*.

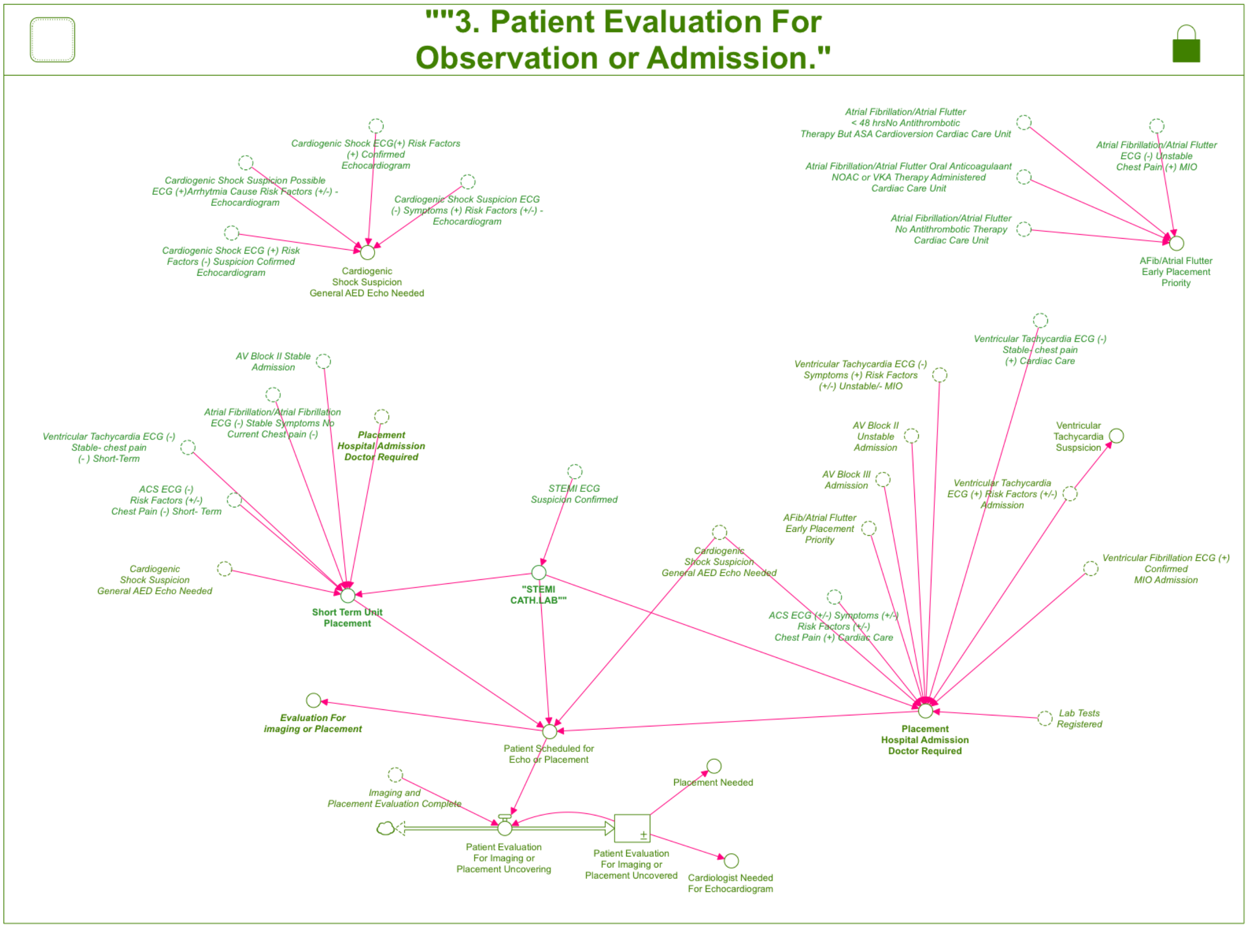

Figure 8. Structure demonstrating patient type prioritization.

3.7 Diagnostic Imaging

Diagnostic imaging is a sub-model influencing the patient pathway in the AED. Besides ECG, Echocardiogram (ultrasound of the heart) is a tool used when assessing patients for heart failure and can also be used to uncover other cardiovascular diseases. Echocardiogram is in many instances used for patients in the chest- pain unit in conjunction with ECG, but is also utilized in the AED if there is any uncertainty regarding the ECG results or suspicion of heart failure. If the model signals the need for diagnostic imaging due to cardiogenic shock, a cardiologist or other physician will carry out an echocardiogram test on the patient. Once the echocardiogram assessment is activated, the variable called *cardiologist needed for echocardiogram* (see Figure 9), is triggered in the sub-model. This is followed by a random generated number that corresponds to an echocardiogram result (see Table 6). When the assessment is completed, a result is revealed in the stock *Echocardiogram evaluation results revealed* reflecting any clinical findings based on a percentage scale of the ejection fraction in Table 6. Echocardiogram is well suited to increase the diagnostic confidence of heart failure though the results can come out normal, or the ejection fraction can reveal an increased risk of life-threatening irregular heartbeats.

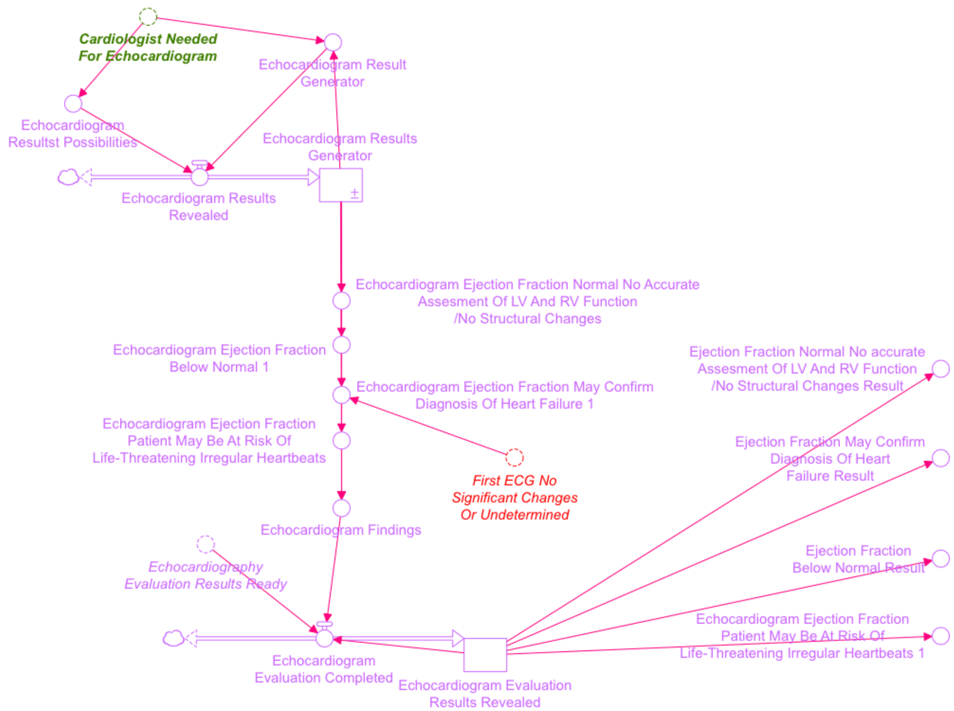

Figure 9. Echocardiogram structure, including the result generator.

Table 6

Ejection Fraction Measurement

Percentage of the ejection fraction	**What it means**
55-70%	Normal
40-55%	Below Normal
Less than 40%	May confirm diagnosis of heart failure
< 35%	Patient may be at risk of life-threatening irregular heartbeats

*Cleveland clinic: (http://my.clevelandclinic.org/health/articles/ejection-fraction),

(http://my.clevelandclinic.org/health/articles/heart-failure/ejection-fraction)

American Heart Association:
(http://www.heart.org/HEARTORG/Conditions/HeartFailure/SymptomsDiagnosisofHeartFailure/Ejection-Fraction-Heart-Failure-Measurement_UCM_306339_Article.jsp#.WI9olrGZNsM).

If cardiogenic shock is suspected an echocardiogram is completed, an evaluation is done (see Figure 10). In this model, an x-ray and CT structure is excluded and we assume the clinical findings are not lung-related and thus x-ray and CT are not needed. However, once a placement decision is assigned and the patient is transferred, an x-ray or CT may be carried out.

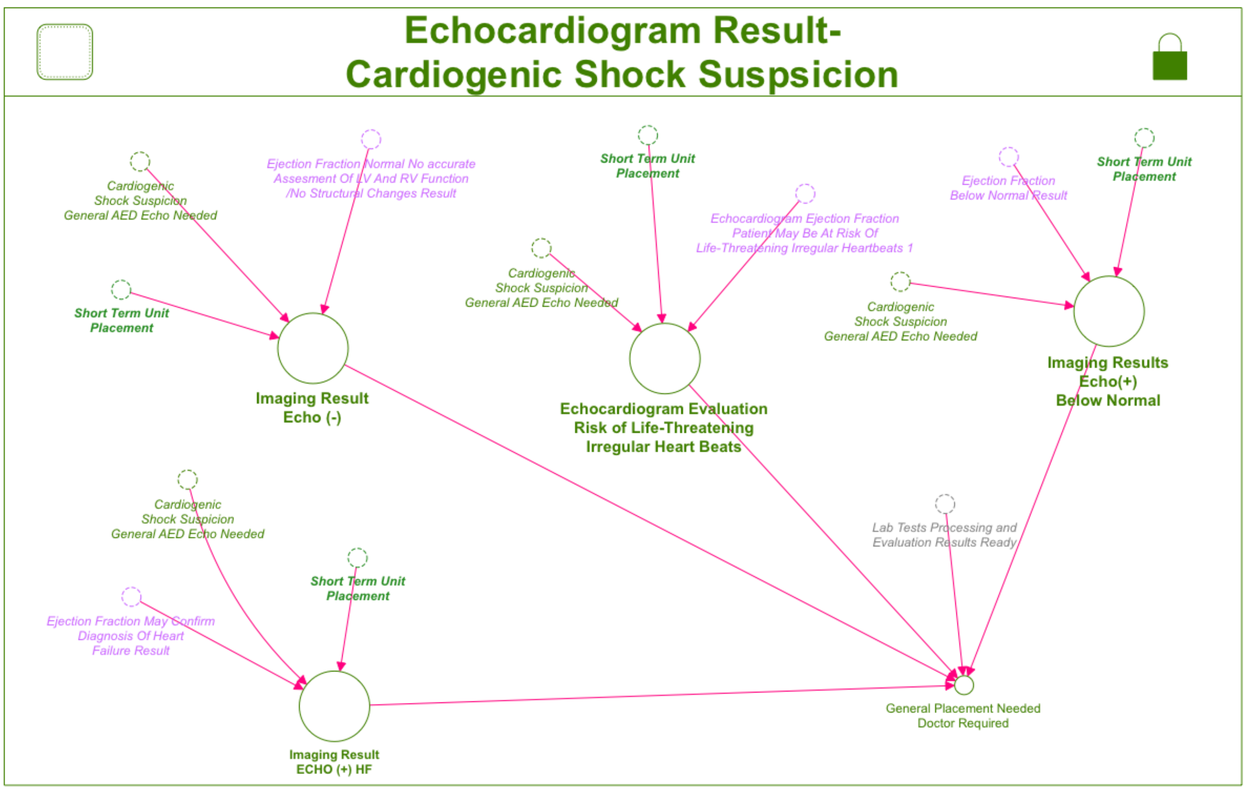

Figure 10. Imaging evaluation: Combining the results from echocardiogram.

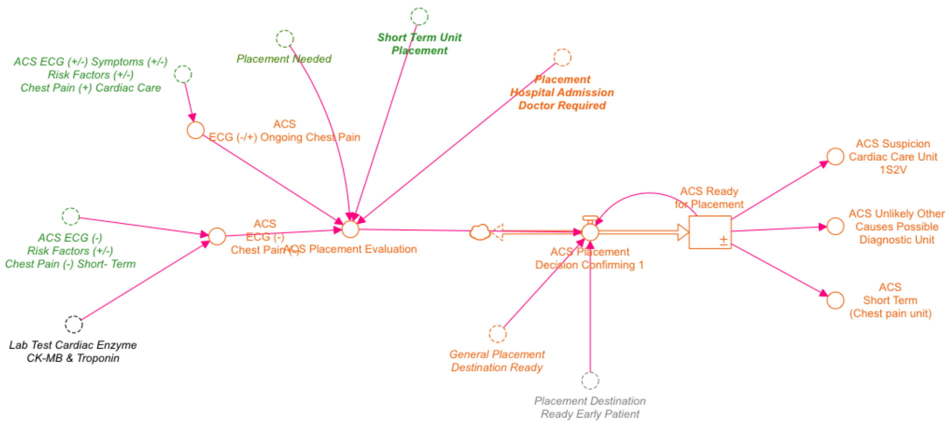

Figure 11 . Placement evaluation at the end of the AED process.

3.8 Evaluation for Patient Placement

ACS (Acute Coronary Syndrome) - As the fast track in Figure 1 indicates, STEMI qualifies for immediate hospital admission. STEMI is a type of ACS and considered the most critical type of heart attack. If STEMI or left bundle branch block is discovered on ECG during triage, the patient goes straight to the catheterization lab and other suspected diagnoses is canceled out. Diagnosing ACS without STEMI takes longer as additional assessments are needed to confirm it. Though an initial lab test such as Troponin T, cardiac form (cTnT) is sampled during triage, a second cTnT sample is required before confirming ACS with more confidence. An ACS patient can be placed in the following locations:

1. Catheterization Lab
2. Cardiac care unit and/or (MIO)
3. Short-term unit (chest pain unit)
4. Diagnostic unit (if diagnostic uncertainty is confirmed or the presence of multiple diagnoses at the same time makes it difficult to place the patient in a specialized unit, the patient is moved here.
5. Patient is discharge and sent home. Most cardiovascular suspected patients, stay in the AED for longer than the duration of the simulation period indicated in this study. Often they are transferred to the short-term unit and stay overnight or until they are ready to be discharged.

ACS patients are grouped based on combination of attributes and the types of ACS patients admitted to the cardiac care unit is more likely to be actually have a heart attack than an ACS patient transferred to the short-term unit. If ACS appears to be unlikely or multiple diagnoses occur at the same time, the patient is sent to the diagnostic unit for further assessments and observation. Based on the time the placement status is assigned, three possible placements statuses activates the placement decision structure pictured below in Figure 12. The grey variable is called: *Placement Destination Ready Early placement* & the orange is called *General placement Destination Ready.*

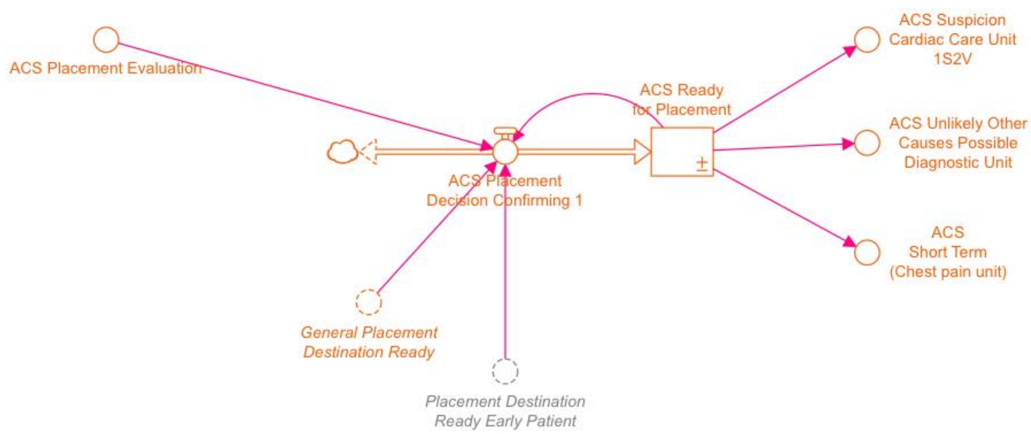

Figure 12. Structure indicating possible placement decisions.

Cardiogenic shock- Cardiogenic shock can occur during heart attack or when arrhythmias are discovered during an ECG test. It can also occur when both heart attack and arrhythmias develop at the same time and based on clinical symptoms, lab test results, and findings on echocardiogram. The presence or likelihood of heart failure can be revealed in the model and is prioritized over certain scenarios as listed in section 3.6. In the model, high values of the cardiac marker NT- ProBNP can be found in heart failure patients and is an important determinant for cardiogenic shock/heart failure. If NT-ProBNP is within the normal range but other findings are leaning towards heart failure, such as arterial blood gas and echocardiogram, pulmonary causes might be more probable and the patient is transferred to the diagnostic unit.

Arrhythmias- In the model, the placement of arrhythmia patients depends on several factors such as the type of arrhythmia revealed at arrival, the stability of the patient and a variety of risk factors. If the clinical assessment and ECG results from triage indicates a new-onset arrhythmia or life-threatening arrhythmias, the patient should be sent to the cardiac care unit for necessary additional assessments and cardioversion. If the model leaves before the lab test results can be interpreted, these will be evaluated once the patient is admitted. Abnormal levels of electrolytes such as calcium, potassium, sodium and magnesium can increase the physician's confidence of arrhythmias (Trappe, 2010). High levels of cardiac enzymes such as cTnT and CK-MB can be found in arrhythmias. The presence of other clinical symptoms and the patient's risk profile is also considered, though the risk profile is merely present to indicate that they are in fact being registered.

Atrial Fibrillation/Atrial Flutter- If atrial fibrillation or atrial flutter is revealed in the model the patient is admitted to an in-hospital ward for cardioversion. Any necessary treatments before admission is present in the model, though not all treatments are made explicit.

AV-Block- If AV-Block III- The confirmation of AV- Block III or AV-Block II in a patient, results in admission to the cardiac care unit. Some cases of AV-Block III might require resuscitation. This will be done in the trauma room, and if successful, the patient will be transferred to the cardiac care unit.

Ventricular fibrillation and ventricular tachycardia: Ventricular Fibrillation is a serious condition as it often lead to cardiac arrest. A ventricular fibrillation patient is admitted to the cardiac car unit. However, a patient entering the AED with ventricular fibrillation might need resuscitation and is admitted if resuscitation is successful. A ventricular tachycardia patient is also considered a critical condition because there is a risk of transitioning into ventricular fibrillation, and thus such a patient should be admitted to the cardiac care unit. In addition, ventricular tachycardia is often seen during or prior to myocardial infarction and should be taken seriously.

Table 8

Diagnose and Patient Placement Destination

Diagnoses	Placement Status
Acute Coronary Syndrome STEMI	Catheterization lab
Acute Coronary Syndrome- other	Cardiac Care MIO
	Cardiac Care Unit 1S2V
	Short-Term Unit
	Diagnostic Units
	Discharge
Atrial Fibrillation	Cardiac Care Unit 1S2V
	Short-Term Unit
Atrial Flutter	Cardiac Care Unit 1S2V
	Short-Term Unit
AV-Block	Cardiac Care Unit 1S2V
	Short-Term Unit
Cardiogenic shock	Cardiac Care MIO
Ventricular Fibrillation	Cardiac Care MIO
Ventricular Tachycardia	Cardiac Care MIO

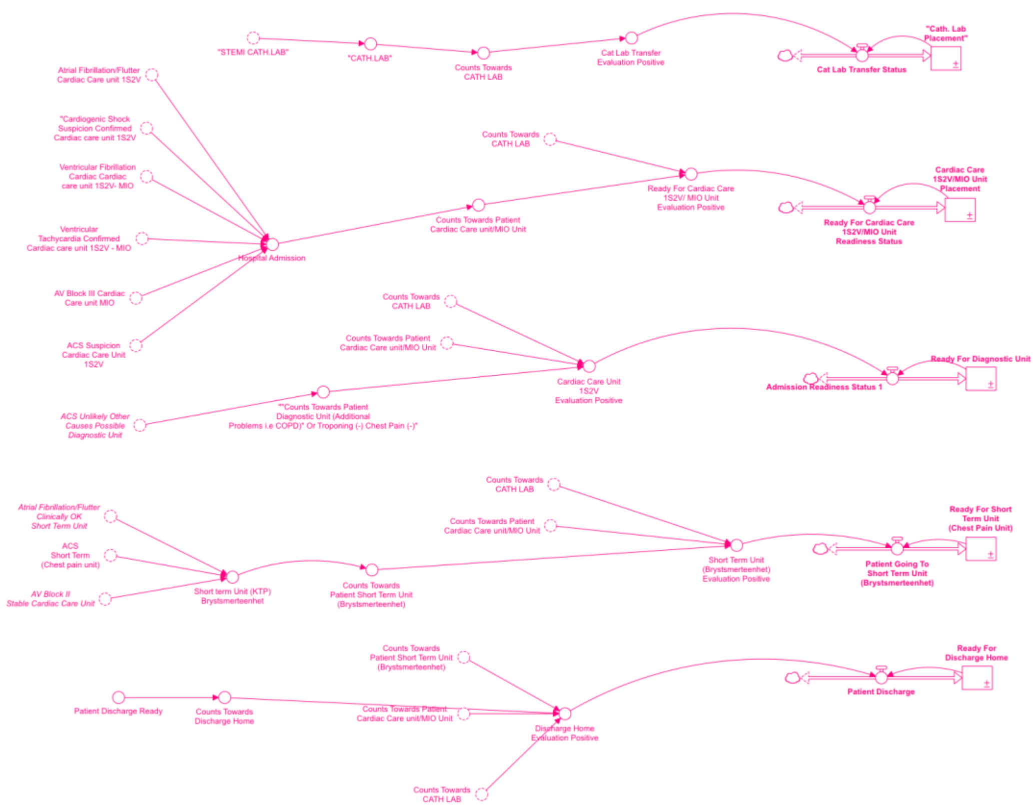

Figure 13. Placement decision overview.

The placement structure above shows the prioritization of diagnoses when a placement status is assigned. The structure first checks for a signal that will place the patient in the catheterization lab. If no signal from the model indicate a STEMI patient, the model checks for any signals indicating admission to the cardiac care unit. This is followed by signals for the diagnostic unit, short term unit and then patient discharge. In instances where there are multiple signals for placements, the model will prioritize the catheterization placement and go down from top to bottom as indicated in Figure 13. For example, if the model signals that a patient should be admitted to an in-hospital ward, be moved to the diagnostic unit and the short-term unit at the same time, the in-hospital ward structure will have first priority. Once a placement decision is made, the decision is registered in a stock as portrayed in Figure 14. This lets the modeler observe how many suspected diagnoses the patient has once he or she is placed.

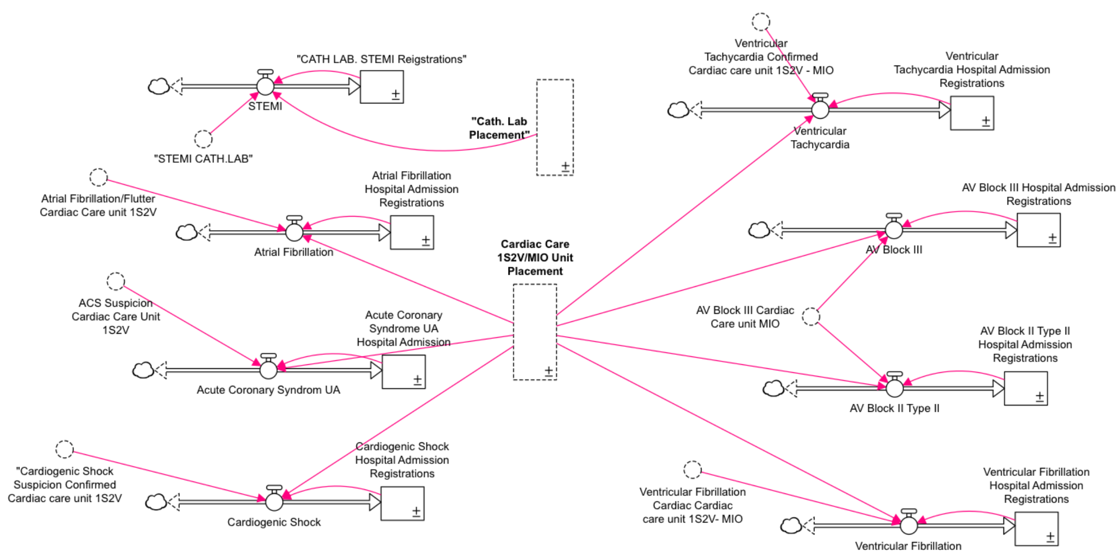

Figure 14. Registration of the number of diagnoses suspected when the patient departs the AED.

3.9 Underlying Mechanisms

As demonstrated, the activities carried out in the AED result in a placement decision for various cardiovascular patients. This is possible due to multiple underlying mechanisms that influence and moves the patient through the AED. Based on the interaction between the underlying mechanisms, information is sent to various AED stages various clinical decisions are made. In order for the model to simulate patient attributes and the many possible combinations, a variety of sub-models are constructed that represent these mechanisms. These sub-models will be compartmentalized into smaller sub-models in a future model and incorporated into arrays to make the easier to handle but in this study the following sub-models are:

Table 9

Sub-models in Simulation Model

Sub-model	Sub-model purpose
Simplified activity time structures	Simplified structures that represent the time it takes to complete AED activities
ECG Developments	Indicates the deterministic ECG Developments
ECG Test	ECG tests and telemetry monitoring during observation based on the deterministic ECG developments
Lab Test Developments	Indicates deterministic lab test developments
Lab Test Evaluations	Blood test evaluations
Signs & Symptoms Developments	Indicates a variety of deterministic patient attributes
Risk Factors and Patient History	Indicates risk factors that contribute to cardiovascular diseases, and might be present in cardiovascular patients upon arrival
Risk Score Evaluation Tools	Calculates risk scores based on existing risk score tools
Number generator	Generates random numbers that corresponds to objects and variables in the model. Contributes to some random variation in the way diagnoses develop
Blood Chemistry	A selection of blood chemistry for future references

3.10 Simplified Processes and Activity Time Structures

For this study, resource allocation of available doctors and nurses is simplified and embedded into the activity time structures as pictured in Figure 15. Therefore, a doctor is presumed to be available shortly or immediately after request except from when the patient is waiting for the clinical assessment. Due to the implicit resource assumption of medical staff, it is assumed that when an activity or procedure is requested, the equipment is made available. It is assumed that medical staff is available upon request as the activity cannot be carried out without available staff. Though this is not the case in the AED, the activity and associated staff are embedded within each other and operates as one activity. This applies for all steps in the diagnostic process that involves a physician or other specialist, while nurses are assumed to be available whenever a physician is requested, or an assessment is done where a doctor is not needed. Once a doctor is requested, the assessment time structures indicates how long a patient has to wait before the resource is made available, how long the assessment will take, as well as an indication of when it is completed. Once completed, a signal appears in the last stock of the activity structure and the next step in the AED process can be initiated. Examples of the simplified structures are indicated below.

Table 10

Simplified Process and Assessment Time Structures

Process Type	
Triage assessment time	Risk evaluation and treatment
Echocardiography assessment time	Lab test processing for arterial blood gas
Clinical assessment time	Priority placement for STEMI patients
Observation and monitoring	Early placement
Patient evaluation for imaging type	General placement
Lab test processing for cardiac enzymes time	

Figure 15, is an example of the activity time structure linked to the clinical assessment structure. During simulation, the structure receives a completion signal from triage and the clinical assessment can start. The first stock indicates the waiting time before the clinical assessment is initiated. Once an urgency level is established, the corresponding waiting time is activated by the second flow from the left. The lab test process starts shortly after triage is initiated as nurses takes necessary blood samples and send it to the lab for processing. In the new AED samples are sent through tubes that arrive at the lab faster than in the older AED. However, this model operates on the assumption that the lab test results are delivered to the lab the old way. This can be regulated by changing the time it takes to send it to the lab and thus reducing the total time and thereby reflecting the new way of sending blood samples to the lab. The waiting time for the urgency levels can also be regulated to illustrate different scenarios. By altering the waiting time for procedures and assessments for various activities, observations can be made on the length of patient stay in the general AED.

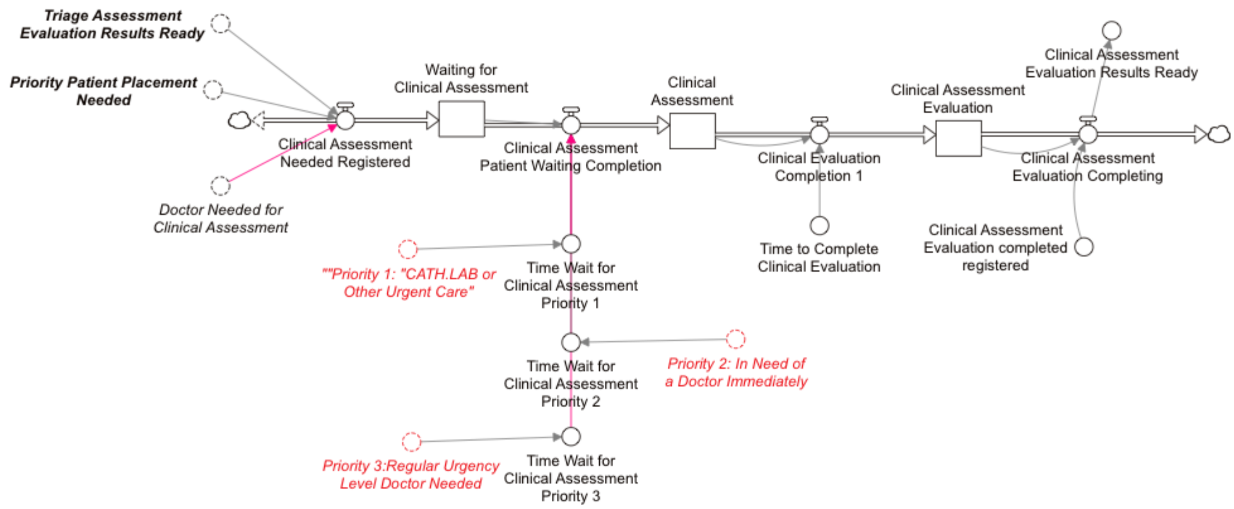

Figure 15. Activity time structure of the clinical assessment including waiting time, assessment and evaluation.

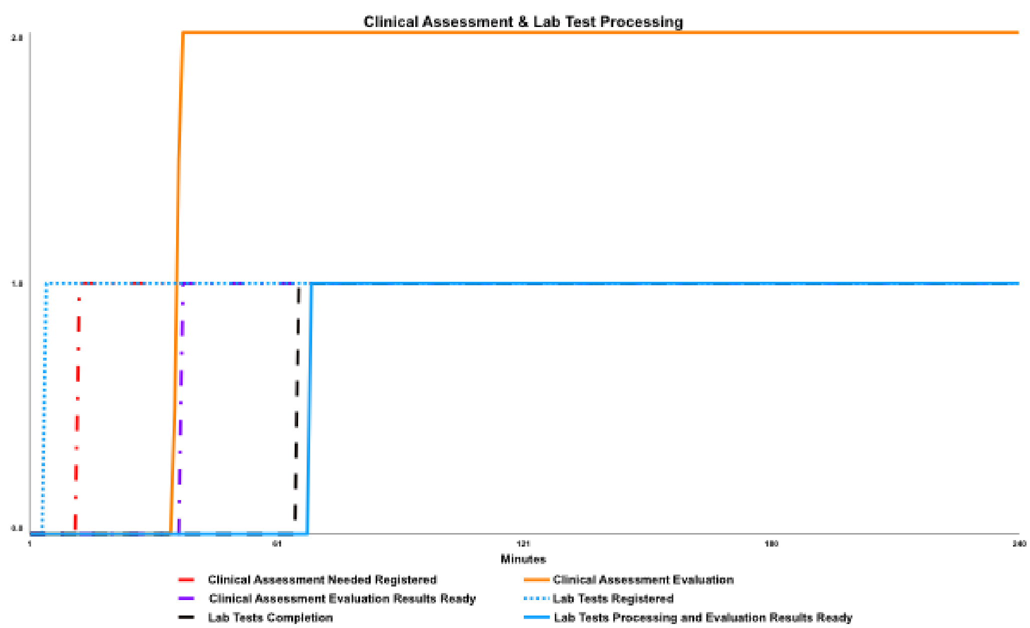

Figure 16. Graph showing that lab test processing is initiated shortly after triage starts and the evaluation is ready about an hour after patient arrival.

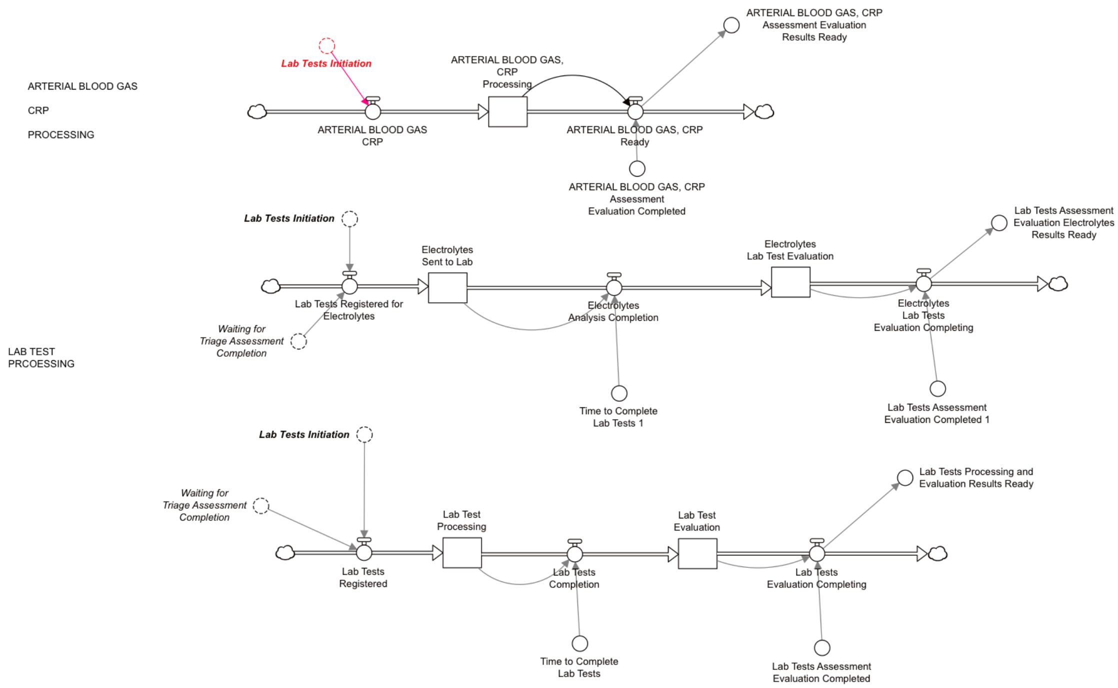

Figure 17. Lab test process.

3.11 Placement of Patient

Placement of a patient can occur directly after triage or after clinical assessment. The placement possibilities in the model are denoted by *urgency placement, early placement and general placement* pictured in Figure 18*.* An urgency placement includes patients ready for admission right after triage in which the manifestation of ECG findings with a higher priority qualifies for urgency placement. Based on the clinical priority, a STEMI patient will be transported directly to the catheterization lab without completing the clinical assessment. A patient in cardiac arrest goes directly to the resuscitation room in the AED, where proper measures are initiated and is then admitted based on *Early Placement.* Early placement is allocated for patients who complete the clinical assessment, treatment and risk evaluation and qualifies for placement or transfer based on ECG findings, presence of symptom and severity of symptoms. The *general placement* is allocated to patients whose clinical pathway is longer and requires to stay in the AED longer. In the model, this applies to cardiogenic shock suspected patients.

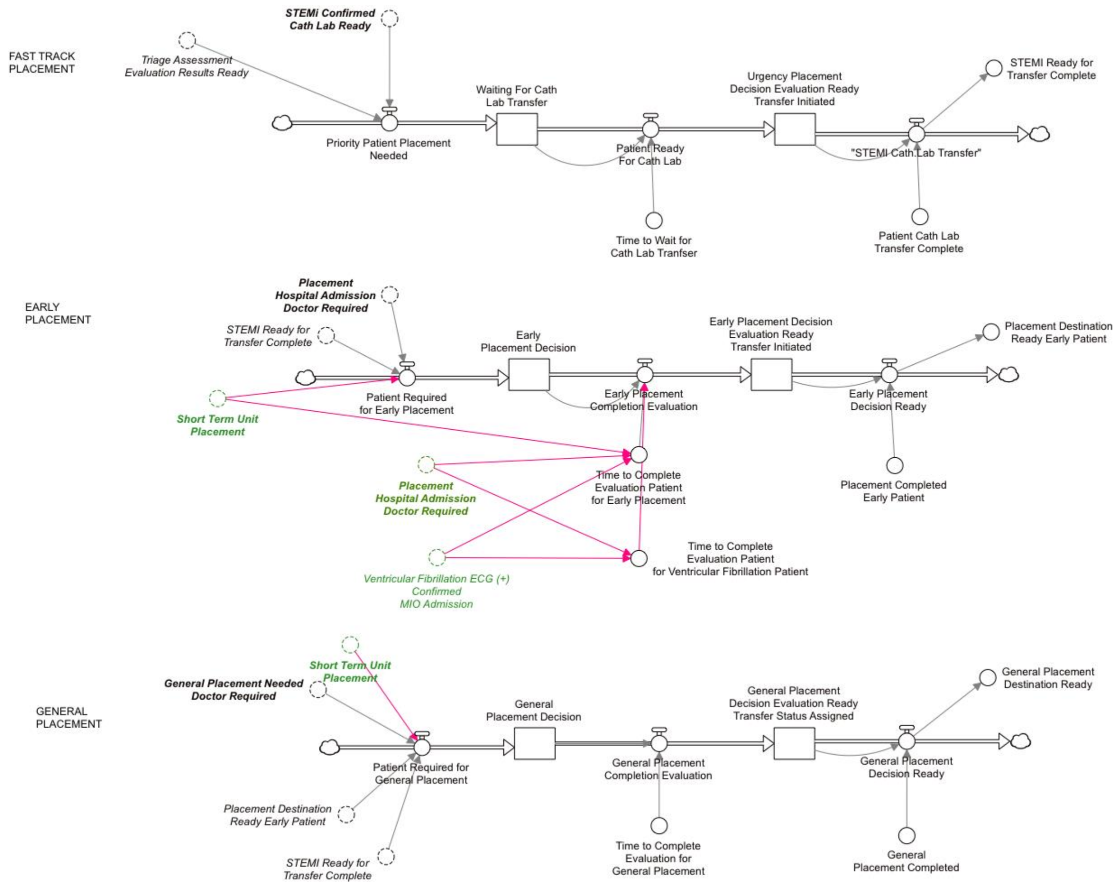

Figure 18. Placements that will be chosen based on the patient’s status.

3.12 Developments

The best approach to mirror the patient’s outcome is to create deterministic developments to reflect the condition and possible diagnosis/diagnoses of the patient. Prior to simulation, the patient already has a set of attributes with specific predetermined values that will give rise to suspicion of one or more diagnosis. The model assumes the patient receives the appropriate treatments during his or her AED stay, unless explicitly mentioned, and the attribute-developments are assumed to reflect the overall result including any treatment effects. Changes to attribute combinations observed in the AED, dictates the outcome for the patient. As such, attribute levels have a profound effect on when the patient departs the AED. This is achieved by creating a deterministic graph and plotting in specific values over the course of the simulation. A variety of cardiovascular diagnoses are integrated in the model and symptoms associated with these illnesses are incorporated and activated depending on the diagnose the modeler wish to observe. There are four key points of attribute-developments linked with cardiovascular patients:

Table 11

Patient Attribute- Developments

Definition	
ECG/EKG – also called electrocardiogram	Other Clinical Symptoms
Echocardiogram	Risk Factors and Treatment
Lab Tests	

Note. Lab tests includes all necessary tests the doctor wants the lab to look at. This includes the ones not mentioned in the model that is not of significant for the type of patient in the model.

For this study, symptoms occurring in lung patients in cases of heart failure often complicates the diagnostic process and were excluded in this model. The model primarily focuses on symptoms that aids the patient in the direction of the cardiac care unit or short-term unit- However, some patients will go to the cardiac care unit and might display symptoms that are associated with lung related problems. If such symptoms are present, it is assumed that appropriate measures are taken care of once the patient is admitted.

3.13 Electrocardiogram Development and Evaluation

An electrocardiogram (ECG) is a frequently used cardiac investigation device to measure the hearts electrical activity. It is the primary tool when investigating the hearts function and assessing the patient for cardiovascular related diseases such as heart attack, arrhythmias, and heart failure (National Institutes of Health, 2010) and the ECG remains the corner stone for uncovering a variety of heart diseases. In the model, an ECG is administered in triage, shortly after the patient enters the AED. In an actual medical setting, if the patient arrives by ambulance, the ECG results are taken prior to AED arrival and should be available at the first assessment. For the sake of this study, the first ECG administered in triage is the first ECG recorded and it is assumed the result in triage equals any ECG test done prior to arrival.

The most suitable method for depicting ECG interpretations for this study is determined based on discussions with two physicians. They agreed that the degree of complexity of real-life ECG interpretations was too complicated to properly be incorporated into the model. Therefore, a simplified ECG development indicating the magnitude of the ECG findings is observed and seen as sufficient to represent the ECG tests in an actual setting. As such, the significance of the ECG tests is determined by a random graphical function where *x –axis* is the simulation time and *y-axis* corresponds to the ECG development. The ECG development is indicated by a value between zero and one. A value equal to or greater than 0.70 is considered a significant value and is detected as an ECG change that will give rise to suspicion. The developments are classified into 6 groups as illustrated below in Table 12.

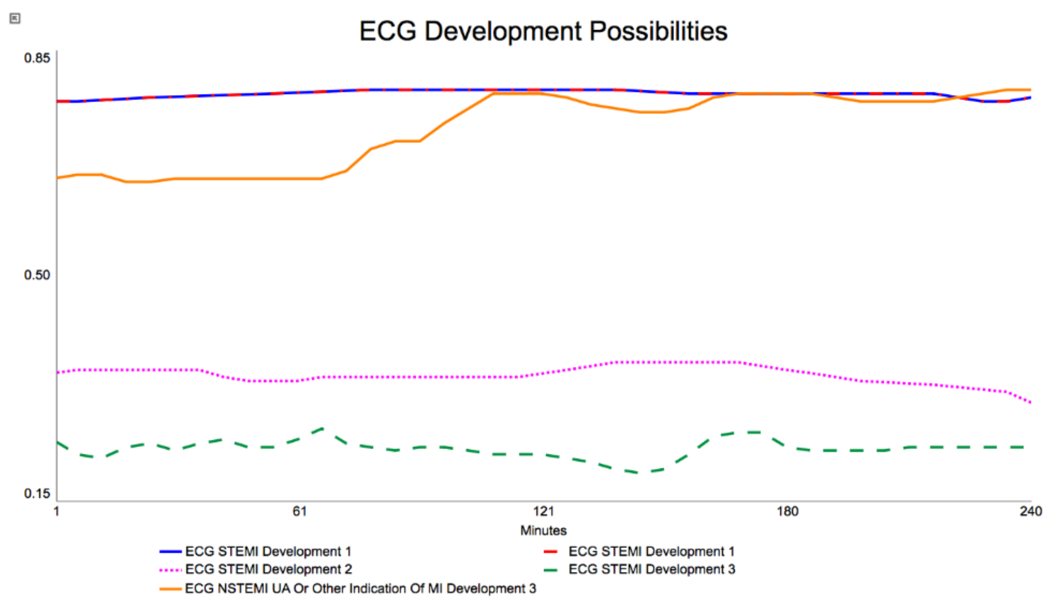

Figure 19. Graph illustration the ECG development possibilities.

Table 12
Electrocardiogram Developments Classification in Triage

Definition of Electrocardiogram developments
ECG changes signifying ST elevation myocardial infarction and/or left bundle branch block
ECG changes signifying cardiac arrest (ventricular fibrillation)
ECG changes signifying Non-ST elevation myocardial infarction /unstable angina/right bundle branch block)
ECG changes signifying indicating prior myocardial infarction
ECG changes signifying other arrhythmias
ECG changes signifying no significant changes

Note. ECG recordings include the necessary changes on the ECG in order to confirm it.

To be able to interpret the clinical results, numerous ECG developments are incorporated in the model. The model consists of 15 possible ECG results (see Table 13), which each have three possible developments that can appear in the stock and flow structure (see Figure 20) and the ECG development appears in the stock called *current indication*. The development appearing in the stock is chosen based on a random number generator that corresponds to a number in one of the ranges in the flow in Figure 20. Examples of model equations can be seen in Equation 5 and 6, and Appendix C)

In the model, some number ranges repeat themselves, whereas some number ranges are limited to a couple of ECG findings. For example, the stock and flow structure for STEMI contains number ranges ranging from (less than 15), (15 to 19) and (19 to 25), while seven of the ECG findings have number ranges ranging from (26 to 30), (30 to 37) and (40 to 45). By creating different ranges, the priority rule applied to STEMI does not happen every single simulation run. However, some ECG findings can occur during a heart attack or be observed prior to a heart attack and as such, this is exemplified by having some number ranges overlap each other. Furthermore, AV-Blocks have ranges ranging from (0 to 10), (23 to 35), and (45 to 50), and can occur at the same time as STEMI if the number generated is between 23 and 25). If so, the STEMI rule of prioritization applies.

The ECG developments are indicated at the start of the simulation and reflects the ECG condition throughout the entire simulation. That is, if the patient experiences any significant ECG changes, it is due shape of graphical function prior to simulation. For example, if the patient displays an ECG reading below 0.70 at arrival but the deterministic function indicates the reading to be above 0.70 an hour later this is due to the pre-determined graphical function. As such, if an ECG test is administered again, this change will be recorded and can possibly change the pathway of the patient.

Table 13 Electrocardiogram Developments

Types of Electrocardiogram Developments	
Atrial Fibrillation	SA-Block
Atrial Flutter	Sinus Tachycardia
AV-Block II Type 1	STEMI
AV- Block Type 2	Ventricular Extra Systole
AV- Block III	Ventricular Fibrillation
Left Bundle Branch Block	Ventricular Tachycardia
NSTEMI (non-ST Segment Elevation Myocardial Infarction	Showing prior Myocardial Infarction

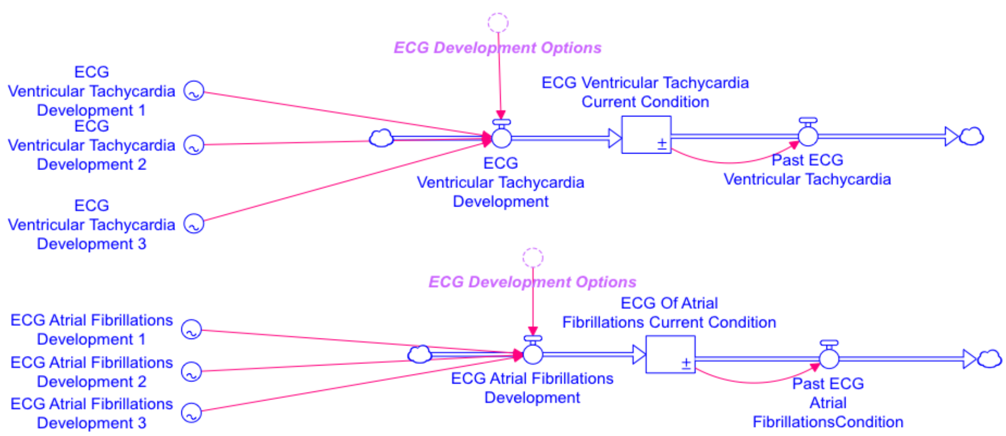

Figure 20. Examples of ECG developments structure.

The first ECG recorded at arrival is exemplified by the stock and flow structure below in Figure 21, where the inflow is activated by a variable signal from the triage stock called *Evaluation Needed from Doctor,* colored red in Figure 21. If no ECG tests are registered in the stock when evaluation is needed, a test is completed based on the stock *ECG development current condition*. The second stock and flow structure is not used during simulation but illustrates a telemetry machine the patient is connected to if observation and monitoring is needed. HUS had in 2013 33 telemetry machines for monitoring patients at risk for severe arrhythmias or other significant ECG changes (Fålun, Hoff, Norekvål & Langørg, 2014), and it is assumed that the second ECG is 'recorded' while the patient is monitored and waiting for lab test results to come back. This however will be done in the short-term unit. This is calculated based on the first ECG test and the ECG reading during observation in the short-term unit. If the second reading is greater than the first reading, but above the 0.70 threshold, then any findings considered to be critical such as arrhythmias, will lay ground for hospital admission.

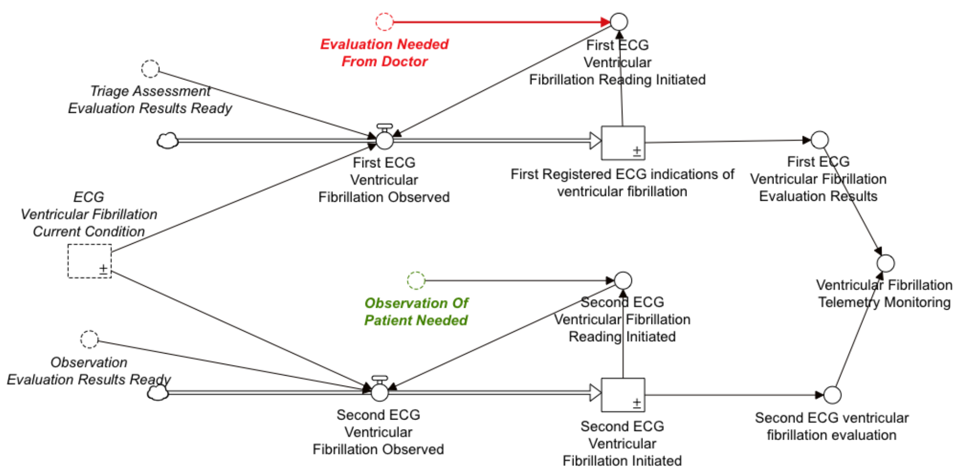

Figure 21. ECG readings structure.

3.14 Underlying Mechanisms in Triage

Triage is influenced by a variety of sub-models and underlying mechanisms. The model signals that a physician is needed based on the variables *Triage TEWS signs*, *First ECG assessment*, and *symptoms and signs,* colored in blue (see Figure 24). These are located in their own sub-models and signals that the developments should be activated. The physician in triage assigns the patient an urgency level based on vital parameters, ECG findings and TEWS emergency signs. An activity time structure is linked to the triage sub-model and after

Figure 22. Triage Assessment Time Structure.

Nurses are assumed to be in triage, taking vitals, recording ECG and taking the necessary blood samples. Based on these combinations the model generates the most appropriate level of urgency, which determines how the patient is prioritized. Once the urgency level is established, the patient is ready for the clinical assessment and is assigned a physician. The physician becomes available and the assessment starts either immediately, after 10 or 60 minutes.

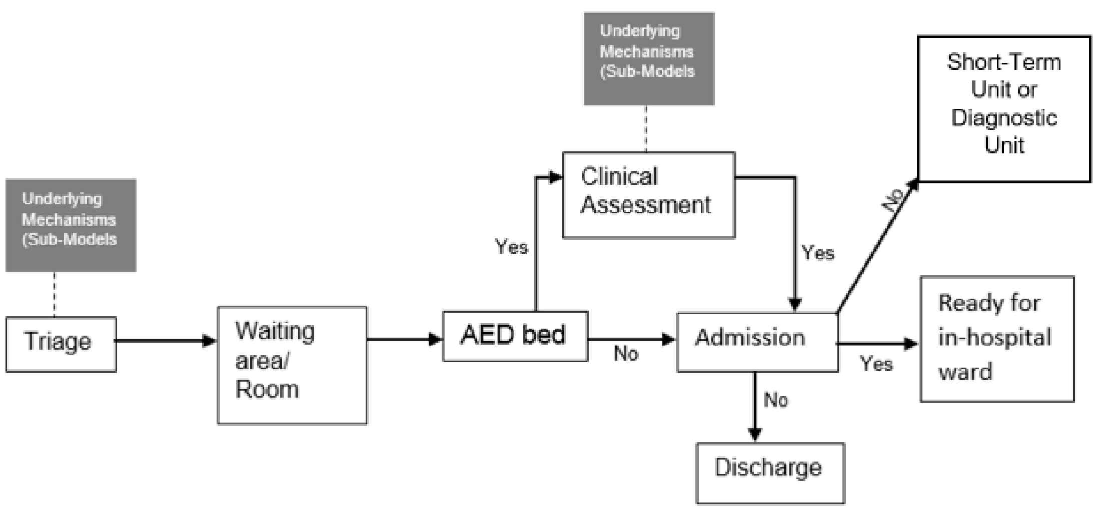

Figure 23. Patient Flow indicating location of sub-models in grey (adapted from Vanderby, 2009)

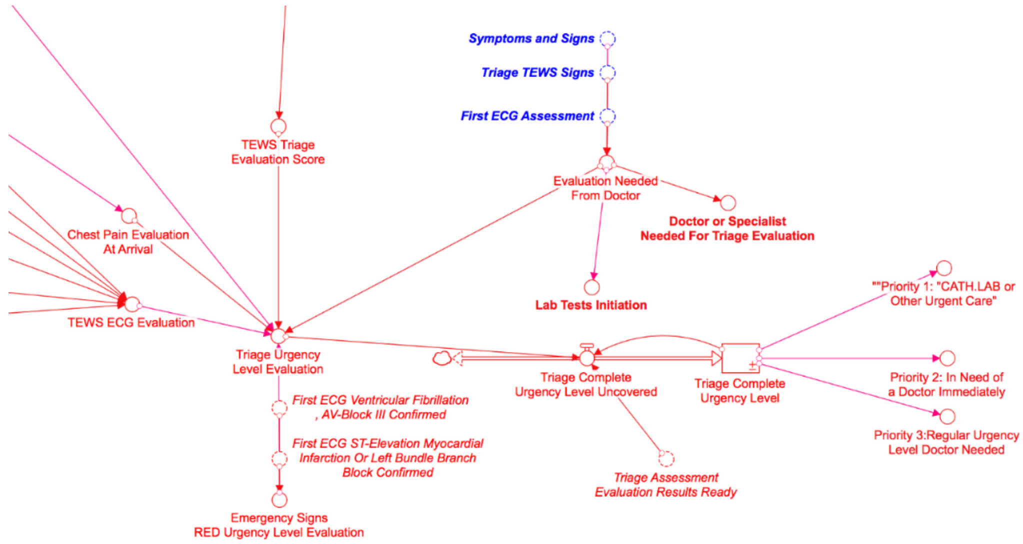

Figure 24. Triage Urgency evaluation structure.

Equation 3: ECG Development STEMI

(IF ECG_Development_Options <= 15 THEN ECG_STEMI_Indication_Development_1
ELSE
IF ECG_Development_Options > 15 AND ECG_Development_Options <= 19 THEN
ECG_STEMI_Indication_Development_2
ELSE
IF ECG_Development_Options > 19 AND ECG_Development_Options < 25 THEN
ECG_STEMI_Indication_Development_3 ELSE 0))

The above equation indicates how graphical function or developments are chosen. If the number generated from the *ECG development* variable is equal to, or less than 15, development option number one will be preferred. If the number generated is greater than 15 and less than or equal to 19, development number two will be chosen, and if the number generated is greater than 19 but less than 25, the third development is chosen.

Equation 4: ECG Development NSTEMI/UA

(IF ECG_Development_Options <= 30 AND ECG_Development_Options > 26 THEN
ECG_NSTEMI_UAP_Indication_Development_3
ELSE

IF ECG_Development_Options > 30 AND ECG_Development_Options < 37 THEN

ECG_NSTEMI_UAP_Indication_Development_1

ELSE

IF ECG_Development_Options > 40 AND ECG_Development_Options < 45 THEN

ECG_NSTEMI_UAP_Indication_Development_2

ELSE 0)

Similar to equation 4, a random number is generated that corresponds to a graphical function. However, the ranges above in equation six are different so that the same developments will not occur every run. In this case, if the number generated from the ECG developments are equal to, or less than 30, development option two is chosen. If the number generated is greater than 30 and less than or equal to 37, the first development is chosen, and if the number generated is greater than 40 but less than 45, the second development is chosen. The ranges are selected randomly and do not reflect any specific pattern or established rules. However, some number ranges account for certain ECG developments more common to occur together in which those equations have more or less the same range or the ranges overlap each with a few numbers. This method creates some randomness in the development selection without the use of number generators but the variables containing the individual graphical functions stay the same unless the modeler changes it manually.

3.15 Lab Test and Developments

Cardiac markers, arterial blood gases and electrolytes are located in the lab-test development sub-model and share the same structure as ECG developments. Unlike the 0.70 threshold utilized in the interpretation of ECG developments, lab tests are based on actual reference ranges of the test in question (see Table 14). The ranges might differ from hospital to hospital, as laboratories sometimes have different ranges.

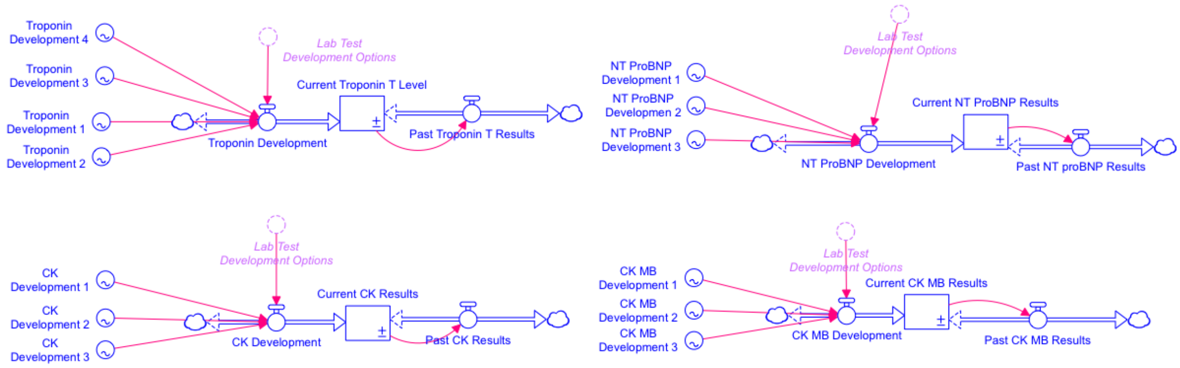

Figure 25. Lab Test Developments structure.

Troponin T (cTnT) is the primary cardiac marker in this model, and is the most frequently used cardiac marker in assessing patients for ACS. Though the majority of patients depart the general AED before lab tests are available, a lab test structure and lab-test evaluations are included in the model. Patients who receive an urgency level of 3 (yellow) and thus wait longer for the clinical assessment are still in the AED when lab test results are available and can be used in the placement evaluation. In addition to cTnT, additional blood test samples are also sent to the lab, but the model is predominantly concerned about cTnT levels for ACS patients. NT- ProBNP and Arterial blood gases are used in the assessment of heart failure, whereas electrolyte results are used as indicators of the presence or likelihood of arrhythmias and other illnesses (Zipes DP, Camm A, Borggrefe M, et al. 2006 p. 23). These tests are all sampled and processed together and become available for all diagnoses.

Table 14 Blood Tests.

Cardiac Markers	Arterial Blood Gas	Electrolytes	Other
Troponin T (cTnT)	HCO3	Magnesium (Mg++)	GRF Renal Function
CK	pH	Sodium (Na+)	Test
CK-MB	BE	Potassium (K+)	White blood count
Myoglobin	pCO2	Calcium (ca+)	CRP
Hemoglobin	PO2	Chloride (Cl-)	

Note. Lab tests included in the model are evaluated in the lab test evaluation structure. However, not all tests are used in the placement evaluation.

Equation examples for blood tests:

Equation 5: Troponin (cTnT) Developments

(IF Lab_Test_Development_Options <=2 THEN Troponin_Development_1 ELSE
IF Lab_Test_Development_Options >2 AND Lab_Test_Development_Options < 4 THEN Troponin_Development_2 ELSE
IF Lab_Test_Development_Options >= 4 AND Lab_Test_Development_Options < 5THEN Troponin_Development_3 ELSE
IF Lab_Test_Development_Options = 5 THEN Troponin_Development_4 ELSE 0)

Equation 6: NT ProBNP Developments

IF "First_ECG_NSTEMI/UA_Evaluation_Results" <> 0 THEN
(IF Lab_Test_Development_Options <= 2 THEN NT_ProBNP_Development_1 ELSE
IF Lab_Test_Development_Options >2 AND Lab_Test_Development_Options < 4 THEN NT_ProBNP_Developmen_2 ELSE
IF Lab_Test_Development_Options >= 4 THEN NT_ProBNP_Development_3 ELSE 0) ELSE 0

The lab test evaluations are structured in the same way as the ECG evaluation. A signal from the triage sector called *Lab Test Initiation* signifies that a blood test is taken and sent to the lab. If the stock containing the lab test results of a particular test is zero, it indicates that no tests are currently available for evaluation and the inflow is activated and the lab test process begins. One of the developments then feed into the stock and become available for evaluation after a lab process time denoted by the ghost variable *Lab Test Assessment Evaluation Results Ready* (see Figure 27 below). Each individual lab test evaluation is based on normal ranges set by the specific hospital lab.

In the model, blood gas is measured during the clinical assessment, and can be used to indicate the suspicion of cardiogenic shock. If the evaluation result pointed to metabolic acidosis as seen in Figure 26, it is an indication of a possible heart failure (cardiogenic shock), though it needs to be evaluated in conjunction with other assessment results.

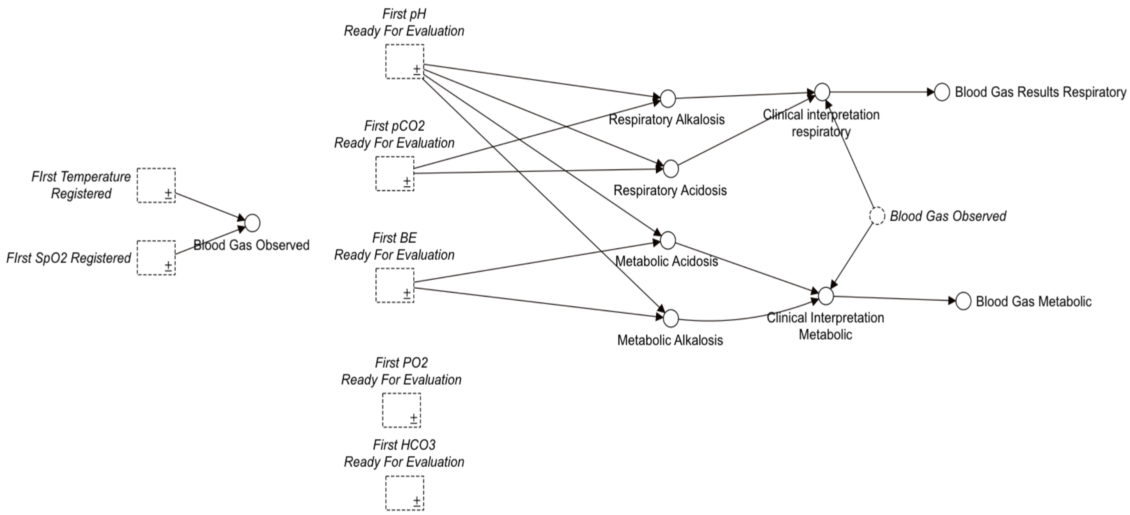

Figure 26. Lab test evaluation of arterial blood gas structure.

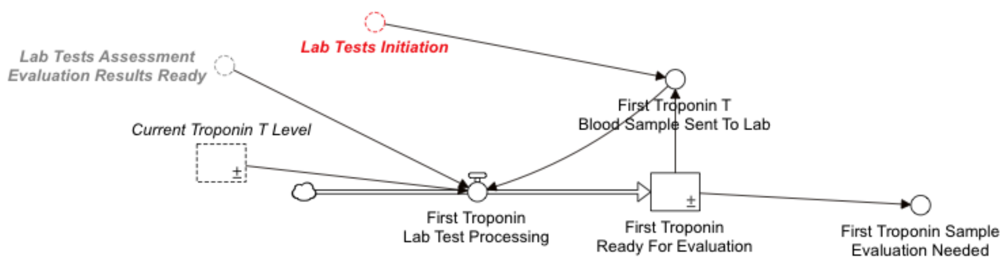

Figure 27. Lab test structure of the cTnT lab process structure.

In the example above, the normal range for cTnT is set to 0-14 ng/L (Thue & Aakre, 2014) and values higher than 14 ng/L (The 99th percentile), raises the suspicion of myocardial infarction. However, only one cTnT test is sent to the lab while the patient is in the AED and a second cTnT evaluation is needed in order to establish a more confident diagnosis. The second cTnT will be taken and evaluated in the short-term unit or cardiac care unit together with the first lab test result. Decisions determining the placement of the patient cannot be done exclusively on the basis of the first cTnT result alone but needs to be evaluated in conjunction with other clinical findings. ECG and other clinical symptoms are used in the evaluation to strengthen the suspicion of the diagnose in question and is the determinants for placement before lab test results are available. Once lab test results are processed, lab test results are combined and evaluated together.

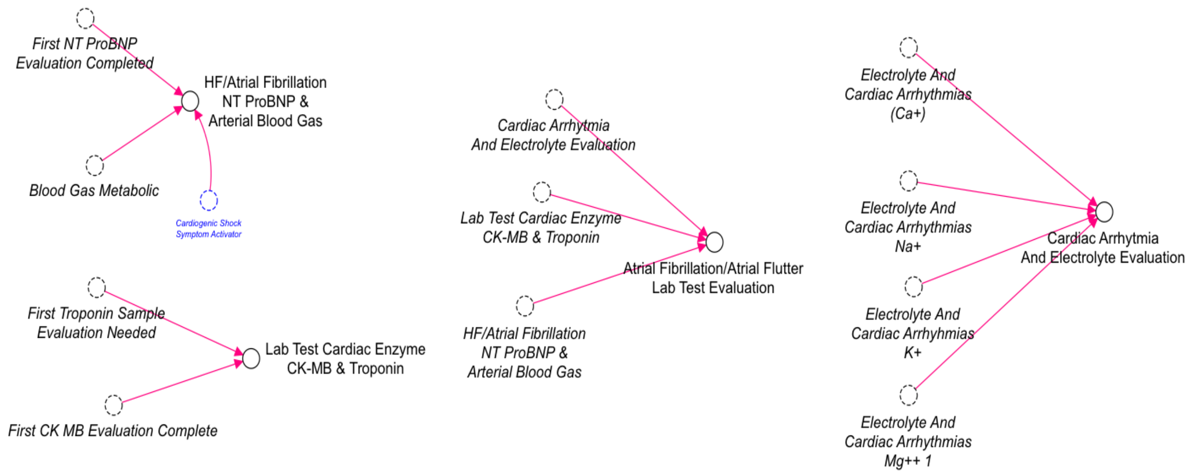

Figure 28. Lab test combination structures used in evaluation for patient placement, in combination with other diagnostic results.

Equation 7: Cardiac Marker Evaluation Equation

IF First_Troponin_Sample_Evaluation_Needed >= 14 AND First_CK_MB_Evaluation_Complete >5 THEN 1 ELSE
IF First_Troponin_Sample_Evaluation_Needed >= 14 AND First_CK_MB_Evaluation_Complete =0 THEN 1 ELSE 2

The equation states that if cTnT is above the 99th percentile and the CK-MB evaluation is greater than 5 µ g/L myocardial damage might be present. CK-MB levels can be negative even in the event of increased cTnT levels. Though cTnT levels is increased, the model cannot say with absolute certainty that myocardial damage is present unless other clinical findings point in the same direction.

Equation 8: Electrolyte Equation

IF "Electrolyte_And_Cardiac_Arrhythmias(Ca+)"+
"Electrolyte_And_Cardiac_Arrhythmias_Na+"+
"Electrolyte_And_Cardiac_Arrhyhmias_K+"+

"Electrolyte_And_Cardiac_Arrhythmias_Mg++_1" > 0 THEN 1 ELSE 0

The electrolyte equation states that if any electrolyte results deviate from the reference ranges and indicate values that correspond to arrhythmia disturbances or other cardiovascular issues, the variable *Cardiac Arrhythmia and Electrolyte Evaluation* equals one. The equation below shows values from lab test results that can be found when a patient displays atrial fibrillation or atrial flutter.

Equation 9: Cardiac Markers (2)

IF "Lab_Test_Cardiac_Enzyme_CK-MB_&_Troponin"<> 0
AND Cardiac_Arrhytmia_And_Electrolyte_Evaluation<> 0
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas"<>0 THEN 1 ELSE

IF "Lab_Test_Cardiac_Enzyme_CK-MB_&_Troponin" >=0
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas" <3
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas">0
AND Cardiac_Arrhytmia_And_Electrolyte_Evaluation <> 0 THEN 2 ELSE

IF "Lab_Test_Cardiac_Enzyme_CK-MB_&_Troponin" >=0
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas" <3
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas">=0
AND Cardiac_Arrhytmia_And_Electrolyte_Evaluation <> 0 THEN 3 ELSE

IF "Lab_Test_Cardiac_Enzyme_CK-MB_&_Troponin" >=0
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas" <3
AND "HF/Atrial_Fibrillation_NT_ProBNP_&_Arterial_Blood_Gas">=0
AND Cardiac_Arrhytmia_And_Electrolyte_Evaluation >= 0 THEN 4 ELSE 0

3.16 Clinical Signs and Symptoms – Patient Attributes

Numerous signs and symptoms associated with heart disease exist and sometimes a patient might experience atypical symptoms or no symptoms at all. The model includes the most common symptoms and signs for a variety of cardiovascular diseases.

Table 15 Clinical Signs and Symptoms

Symptoms	Signs	Triage Signs
Altered mental status	Asthma cardiale	Heart rate
Anxiety	Clammy skin	Respiratory rate
Chest pain	Cold extremities	SpO2
Clouding of consciousness	Cold sweat	Systolic BP
Confusion/Impaired thinking	Congested lungs	Temperature
Decreases physical performance	Cough	
Dizziness	Cyanosis	
Exhaustion	Diastolic Blood pressure	
Feeling of weakness	Dyspnea/shortness of breath	
Headache	Fast & irregular heart beat	
Heavy breathing	Jugular vein distention/pressure	
Nausea	Oliguria or anuria	
Unrest shivering in chest	Pale skin	
Pre-syncope	Palpitations	
	Papilledema	
	Sweating/diaphoresis	
	Syncope	
	Vomiting	

Note. Additional symptoms can be added but this represents the most common symptoms occurring for the diagnoses in the model.

The same structure used for lab test and ECG developments are used in the development of clinical symptoms and signs. The patient attributes are chosen by a variable called *Clinical Signs and Symptoms Development Options* located in the generator sub-model. A random number is created each new run that corresponds to a development depicted by a graphical function. This graphical function can be modified by regulating the input for the attribute combinations according to what the modeler is interested in observing. It is assumed that a value equal to or greater than 0.70 is significant enough for the patient to be bothered by the symptom. Symptoms that are evaluated during triage and clinical assessment are also observed during observation but only includes symptoms that in isolation can result in hospital admission or transfer to the diagnostic unit e.g., syncope and severe bradycardia.

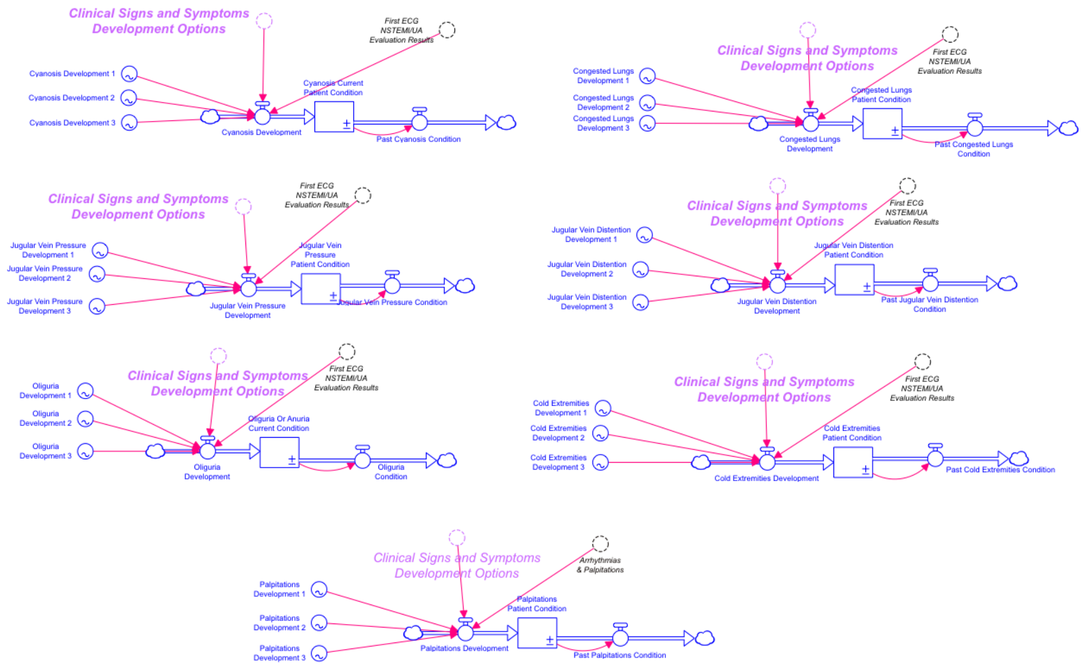

Figure 29. Stock and flow structures showing of clinical signs and symptoms development.

Some clinical signs and symptoms give rise to suspicion faster and diagnosis can sometimes be made during triage or bedside during the clinical assessment. Clinical signs that give rise to suspicion quicker and is linked to certain heart diseases will only be activated when certain ECG findings are positive. For example, cardiogenic shock often shows specific symptoms and signs such as oliguria, cyanosis, cool extremities but these symptoms are not activated unless ECG indicates any findings that might suggest the occurrence or possibility of cardiogenic shock or systolic blood pressure is less than 90 mmm/hg. As such, the flows of these symptoms are connected to a stand-alone variable that is either zero or one. If the variable is one, these symptoms are activated otherwise they remain inactive (see Figure 30). Palpitations on the other hand can be observed in arrhythmias unless they have no obvious cause. Therefore, if the ECG indicating NSTEMI (non- ST segment elevation myocardial infarction or UA (unstable angina) is observed during triage evaluation is equal to, or above the 0.70 threshold then cardiogenic shock symptoms receives a signal, and symptoms that can be seen in cardiogenic shock patients might occur. Because cardiogenic shock is often caused by acute heart attack, these symptoms might be activated when relevant ECG results are positive. However, the graphical functions containing developments are randomly chosen by the generator and whether or not these symptoms are activated depends on the number range in the stock and flow structures.

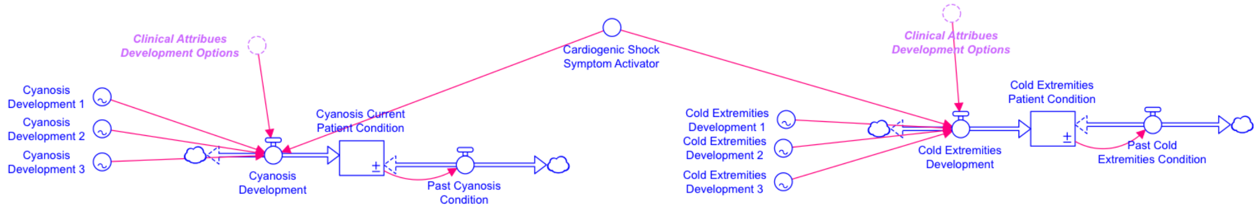

Figure 30. Cardiogenic Shock Symptom manually activated when the modeler wants to observed cardiogenic shock.

3.17 Risk Factors and Evaluation

In addition to clinical symptoms observed at arrival, risk factors and patient history are an important part of the diagnostic process. In this study, risk factors are made observable during the clinical assessment and medical staff register the risk factors. Risk factors are divided into two sectors: Risk factor score evaluation tools used in the hospital setting and a general group of risk factors that increases the risk of developing various types of heart disease (see *Appendix* B for details). The risk factor evaluation tools utilized in the model are based on a random number generator in the generator sub-model. The risk score tools used, follow the general guidelines set for the evaluation tools and is constructed to best reflect the risk factor criteria’s used in the AED setting. Depending on the diagnose, combinations will result in risk a factor presence. The risk factors however, does not influence the clinical pathway for every diagnose but it is an important indicator for treatment once the patient is admitted. For certain diagnostic suspicions, such as atrial flutter and atrial fibrillation, risk factors are considered when choosing anticoagulation.

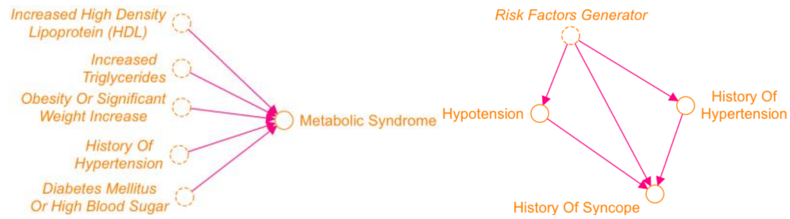

Figure 31. Structure showing risk factor structures and combination.

Table 16 Risk Factors

Example of Risk Factor Calculations
▪ The variable ‘Obesity or Significant Weight Increase’ becomes positive if the number generated by the risk factor generator is < 20 but > 10.
▪ The variable ‘History of Hypertension’ becomes positive if the number generated is <30 but >10.
▪ The variable ‘Diabetes Mellitus or High Blood Pressure’ becomes positive if the number generated is < 35 but > 10.
▪ The variable ‘Increased High Density Lipoprotein (HDL)’ becomes positive if the number generated is < 20 but > 12.
▪ The variable ‘Increased Triglycerides’ becomes positive if the number generated is < 28 but >= 15.

3.18 Number Generators

Though patient outcomes are based on deterministic outcomes, stochastic elements are incorporated. A number generator sub-model generate random numbers and choses attribute combinations for scenario runs. The number range are randomly selected and is not based on specific number range rules. The objects used for creating a random number is listed in Table 15 and a variety of generators are utilized throughout the model. For example, age and gender plays a role when evaluating risk factors and clinical symptoms. Instead of manually modifying the age for every single run, a random number is chosen via a generator. Based on a random function with the number ranges i.e., RANDOM (0,10) RANDOM (0,5), RANDOM (0,100), a number is generated for each new run. The AED sub-models that require a random number in their evaluation process, sends a signal to the generator sub-model indicating the need for a number. This number then feeds back to the location where the signal originated and a calculation is completed based on the number. For example, the deterministic lab test developments are randomly chosen and stock and flow structures for the lab tests contain 3-4 possible graphical functions. One of these graphical functions will feed into the flow and reveal a development. This is done when the generator sub-model generates a random number that corresponds to one of the number ranges in the stock and flow structure in the lab test development structure. This is given by the function:

Equation 10: Number Generator for Lab Test Developments

(IF Lab_Test_Development_Options <=2 THEN Troponin_Development_1 ELSE
IF Lab_Test_Development_Options >2 AND Lab_Test_Development_Options < 4 THEN
Troponin_Development_2 ELSE
IF Lab_Test_Development_Options >= 4 AND Lab_Test_Development_Options < 5THEN
Troponin_Development_3 ELSE
IF Lab_Test_Development_Options = 5 THEN Troponin_Development_4
ELSE 0)

Some stocks have similar ranges while some stock have different ranges. This create randomness in terms of what outcomes emerges. Despite the randomness the generators provide, the equations are structured and organized in a logical way, so that developments that do not normally occur together, will not occur in the simulation. However, one issues the random number generators might introduce are the possibilities of producing what is called *random algorithm cycling* or *exact run replication* (Van Dam et al., 2013). This means that the random numbers can repeat themselves. In the case of this model, they will most likely repeat themselves as the random number generators have smaller ranges in the stock and flow structures.

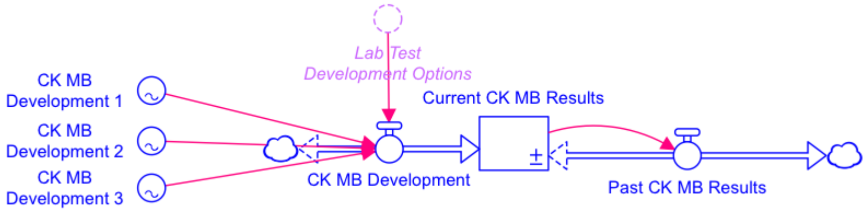

Figure 32. The purple variable called Lab Test Development Options originates in the random generator sector.

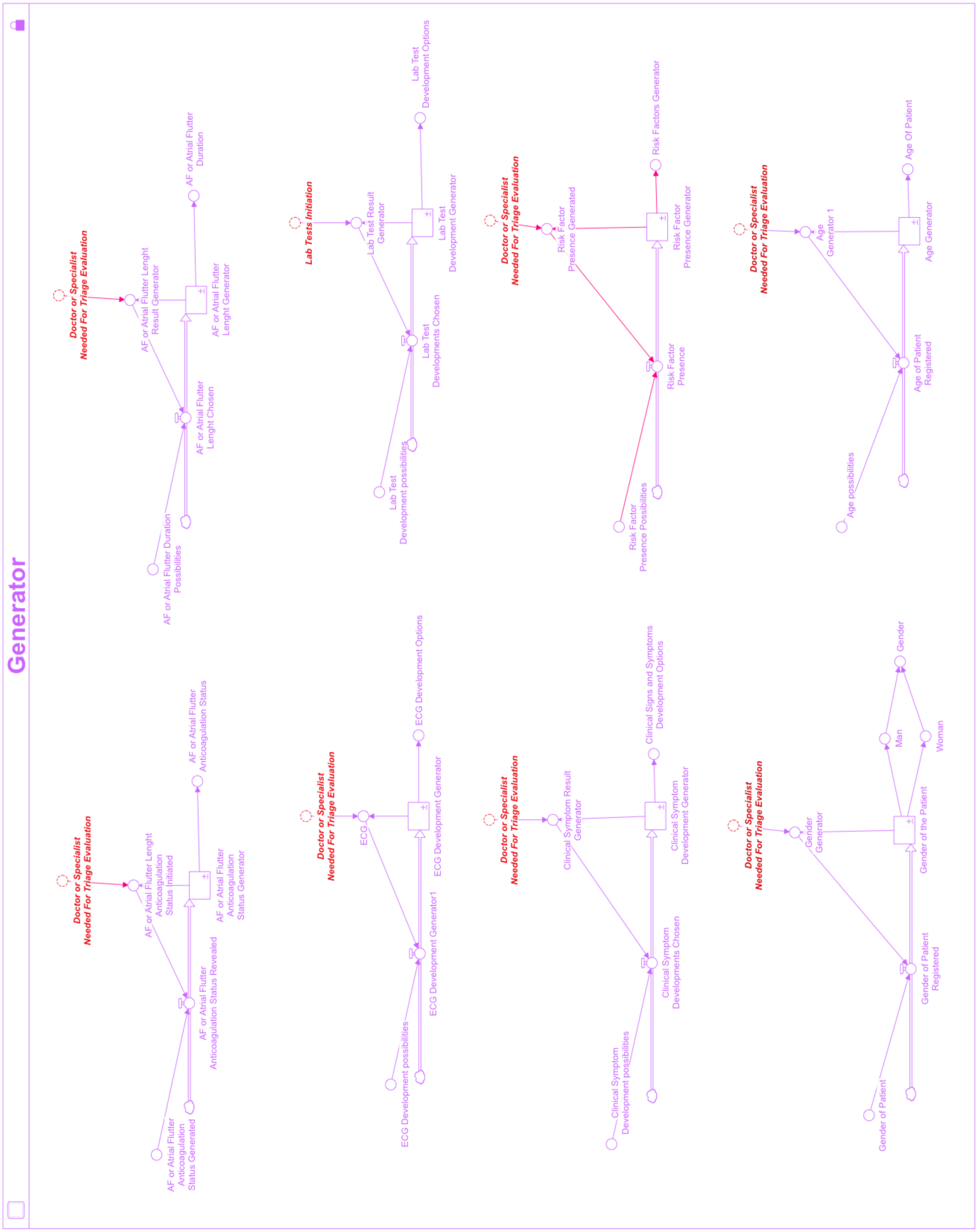

Figure 33. Sub-model showing number generators used in the model.

3.19 Model Validation and Verification

Validation of the model through expert opinions are important and some validation concerning the clinical, medical and structural content has been done. The information in the model is based on literature and conversations with nurses and physicians at HUS, on how patient attributes can play out in different patient scenarios. Discussions surrounding the layout and organization of the AED was done over the course of the first project-year. Although several conversations via e-mail and in person was conducted, a validation from medical staff regarding the validity of the information used in the model, and whether or not it reflected the AED was not achieved. As a result, the model is mostly based on diagnostic literature obtained by myself, and general confirmation from medical staff that the literature is in compliance with current practice and vice versa. The clinical pathway that the various cardiovascular patients are following are based on medical literature and current practice. However, some modifications in terms of when certain AED procedures and assessment are carried out might vary because of the new AED that opened in 2016.

3.20 Sensitivity Analysis

A comprehensive sensitivity analysis will require testing of all possible variables and combinations and will be overwhelming to do. Therefore, the sensitivity analysis focuses on variables that are considered uncertain and variables that are likely to be highly influential (Sterman, 2000). To test the robustness of this model, the sensitivity analysis simulated what happens to the model outcome when variables that should not occur at the same time are modified to do so. Observations on how prioritization rules plays out when certain variables should be prioritized over another group are done. If the prioritization is not initiated; even in extreme cases, it indicates that the model is sensitive to changes that are not fixed or specific. By virtue of the deterministic perspective, the patient has a set of attributes pre-determined for each run and a diagnostic suspicion should only emerge based on these pre-determined patient attributes. Therefore, any changes that might be sensitive to any numerical modifications is modified manually by changing the input.

In this sensitivity test, numerical values in the ECG are tested. Some ECG findings indicate a more serious condition and is considered to be of higher priority than others. Therefore, the model simulates scenarios in which ECG values are modified and an observation is made on whether or not the priority rules applied in the model actually work. In the model the numerical ranges in the ECG STEMI flow shown in Figure 34 are for the most part different from other ECG flows though, a few numbers might overlap with some ECG developments. This is because the model makes sure the STEMI development is not chosen every simulation run as it is of highest priority. However, if ECG flows containing some of the same number ranges occurring in the ECG STEMI flow, ECG STEMI should be prioritized first, despite other ECG developments occurring during the same run has the same number range.

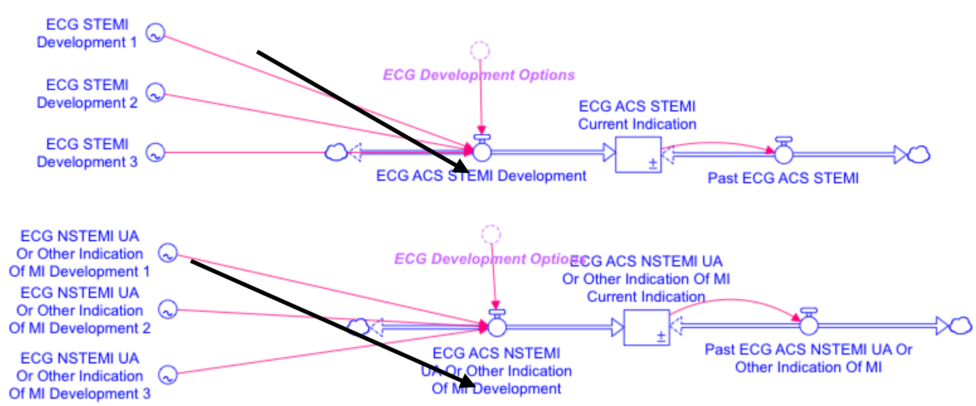

Figure 34. Example of stock and flow structures, where the inflows contain numerical ranges linked to a random number generator.

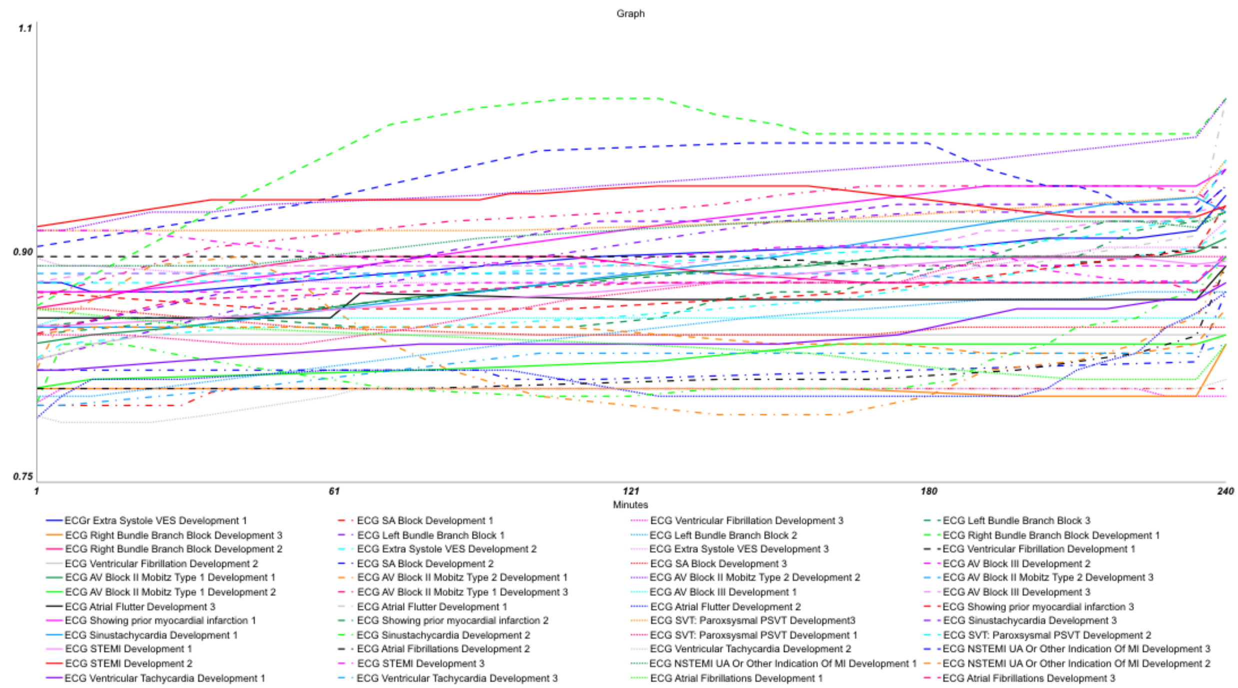

Figure 35. Graph showing all ECG developments, where the variables containing developments have all been modified to be above the 0.70 threshold.

Based on 239 runs, the ECG STEMI reading was chosen 219 times. The 20 first runs resulted in the model not choosing STEMI, whereas the other remaining runs chose STEMI. This might have to do with the range in the ECG flows but according to the prioritization, ECG STEMI should be always be prioritized as long as the range is correct. Because of the deterministic values used to simulate diagnostic outcomes, sensitivity analysis might be challenging, as it might not reflect real model sensitivity. Nonetheless, it confirms that the model does prioritize specific variables over others.

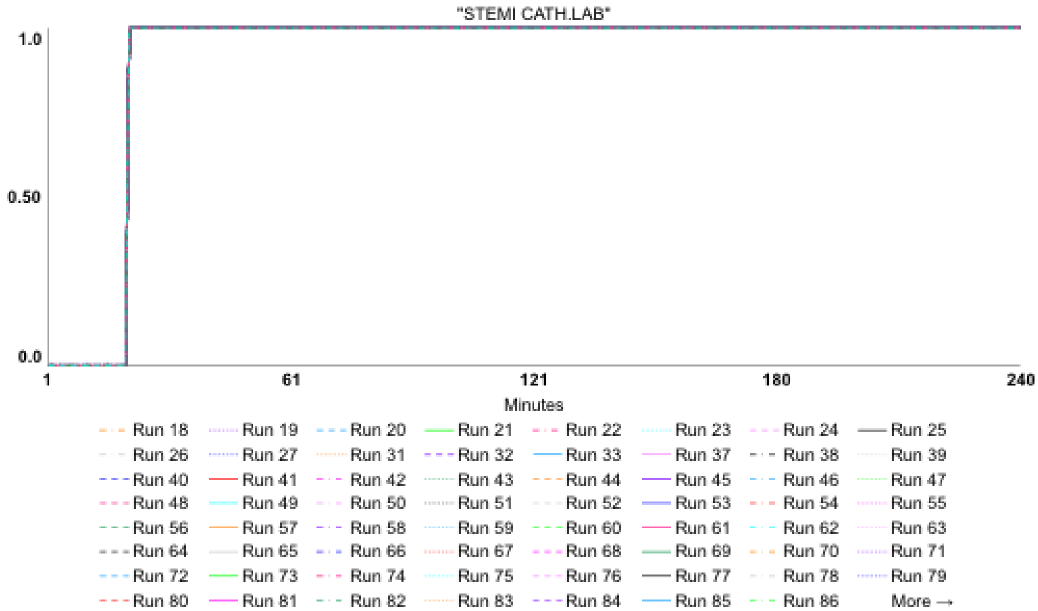

Figure 36. Graph indicating ECG STEMI results.

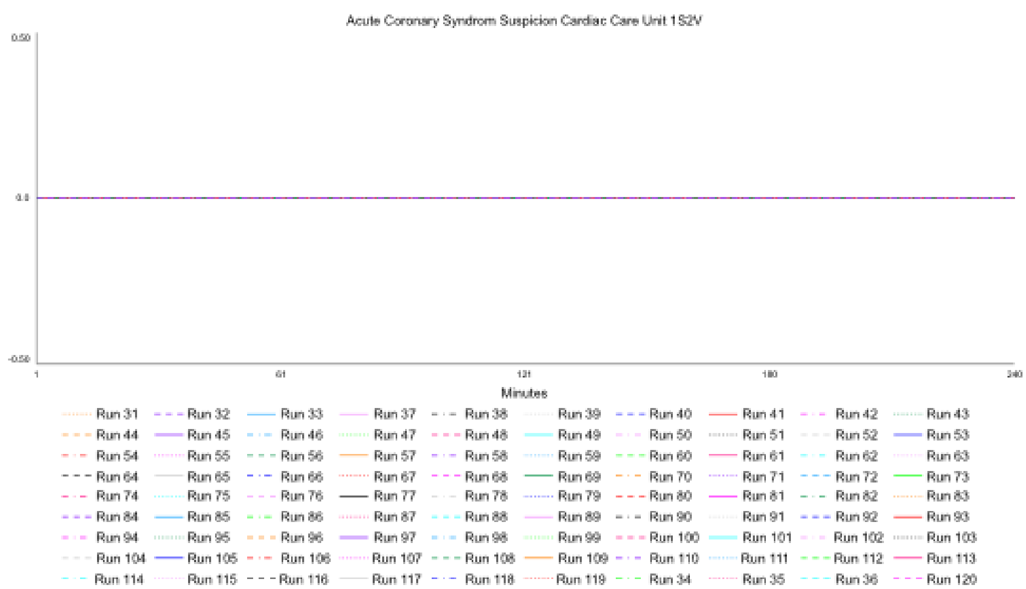

Figure 37. Graph showing ACS runs when all STEMI developments were changed to > 0.70.

CHAPTER 4

Scenario Testing

4.1 Introduction

The model is well suited for scenarios testing due to the multiple objects in the system that can be altered to investigate a variety of possible diagnostic outcomes. Most of the sub-model objects (e.g., ECG, signs and symptoms, blood tests), can be modified in order to look at specific outcomes, or a range of outcomes for a particular disease. A variety of cardiovascular scenarios are investigated during simulation as attributes emerged. This comparison contributes to a better understanding of the complexity that lies within each patient type and how some variations in patient attributes leads to patients claiming different resources. The length of assessments and procedures affecting the admission time for different diagnoses are analyzed and a closer look at the priority placement scenarios are carried out. The scenarios simulated are illustrated by graphs that show the patient pathway in the AED for a variety of diagnostic combinations. Unlike your traditional SD model, where the graphs typically show continuous flows over the simulation period, the following scenario graphs show segmented AED processes as discrete in time and space.

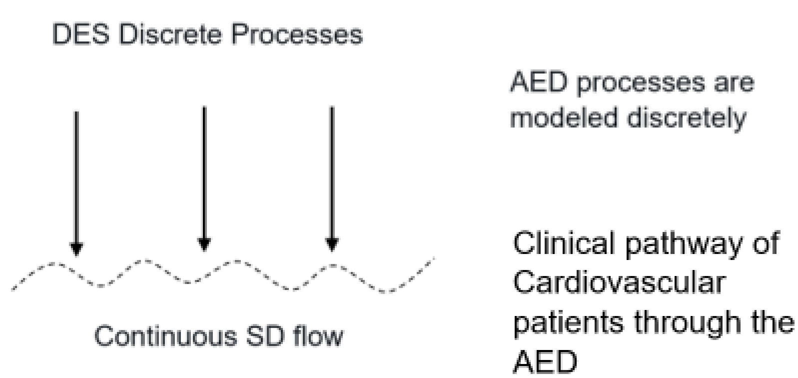

Figure 38. Example showing how the graphical functions are presented: AED processes are modeled discretely.

4.2 Acute Coronary Syndrome: Variations

Besides ST- Segment elevation myocardial infarction (ACS type STEMI) indicated in the model by ECG findings during triage and considered the most critical type of ACS, other types of ACS can occur. ACS can occur with or without arrhythmias and patients can display an array of symptoms, or no symptoms at all. The type of ACS will depend on the combination of ECG findings, symptoms and lab test results, which further determine the placement of the patient. The steps in the care for Non-STEMI type of patients are not as clear cut as STEMI who goes directly to catheterization lab after arrival or triage, but there are guidelines for the assessment and treatment for this ACS group.

NSTEMI (Non-ST segment elevation myocardial infarction), is another variant of ACS and though not as severe as a STEMI heart attack, it is still a serious condition and should be taken care of promptly. The degree of coronary obstruction varies within this ACS group which complicates the diagnostic process. Unlike STEMI the patient remains in the AED longer, to undergo more assessments before being admitted to an appropriate ward or unit. NSTEMI can indicate either unstable angina or NSTEMI with elevated cardiac markers. Unstable angina findings on ECG can indicate several abnormalities but are not the same as STEMI or NSTEMI. Cardiac markers are typically not elevated or only minimally elevated in UA cases. As such the model differentiates between unstable angina and NSTEMI by the use of the cardiac enzyme cTnT.

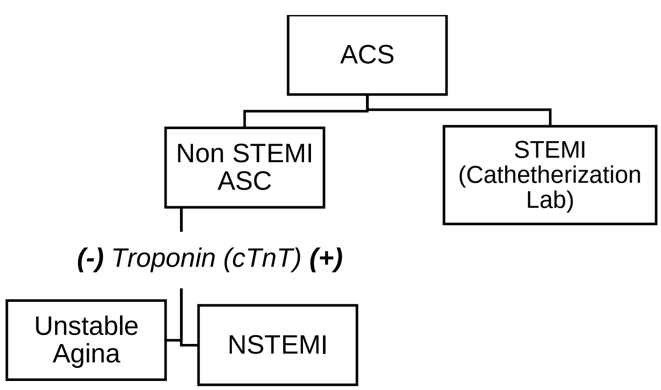

Figure 39. ACS Classification. Cardiac Markers, usually Troponin determines the patients ACS diagnose. In the general AED however, the patient is placed based on the current chest pain indication.

As there are many combinations of ACS, a patient may arrive with or without ongoing chest pain, clear ECG indications though some patients have normal ECG findings. In the assessment of acute coronary syndrome, cTnT is especially important, as elevated levels may be a sign of myocardial cell necrosis, particularly in the absence of any significant ECG findings and the patient may or may not have elevated cTnT levels. This may be indicated before or after the patient is assigned a placement status. A minimum of two consecutive cTnT blood samples were required in order reject or confirm ACS in the absence of other significant findings. The first sample is taken at arrival, but in this model, some patients departs the general AED before lab test results are available, while others remain longer in the AED due to waiting time or additional assessment, and as such, lab test result may become available for interpretation which further facilitates the placement of the patient. As such, the patient is placed based on current chest pain indications and ECG findings.

Table 17 Acute Coronary Syndrome Variations

Diagnose/Findings	Definition
ST-elevations on ECG	STEMI
NSTEMI ECG findings Chest pain Troponin (+)	NSTEMI
No significant ECG findings Chest pain Troponin (-)	Unstable angina
Undetermined ECG findings Chest pain Troponin (-)	Unstable angina

4.2.1 Scenario 1:
Acute coronary syndrome- STEMI

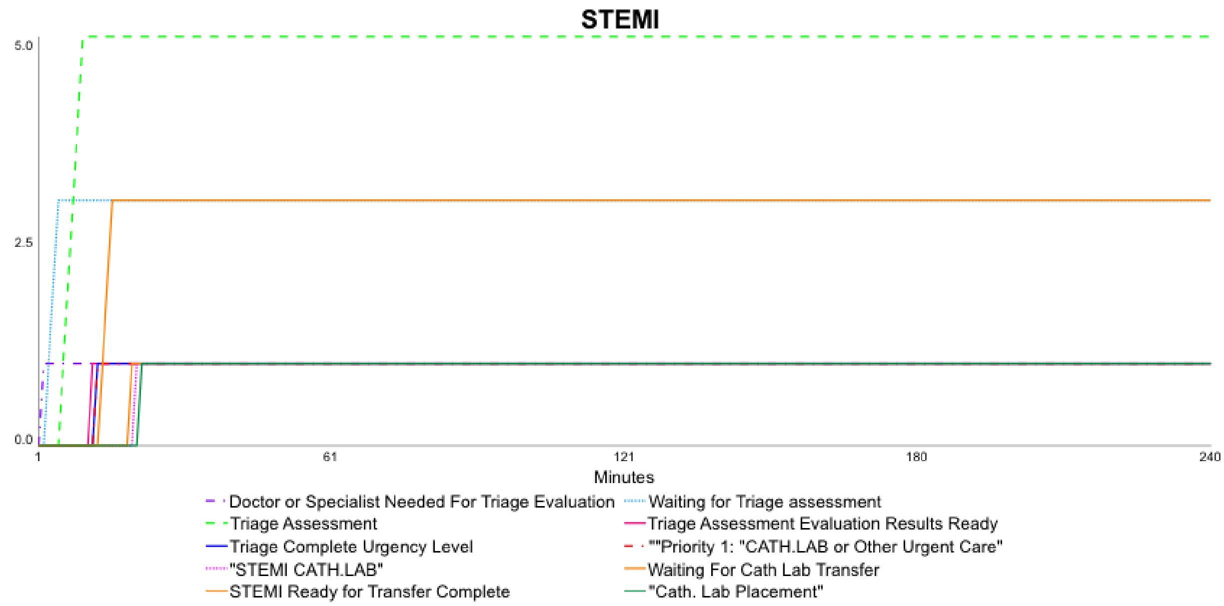

Figure 40. Graph showing STEMI patient and its clinical pathway in the AED.

STEMI is a medical condition of extremely high priority with a substantial risk of death and is according to triage rules considered an immediate red urgency level. In the scenario above a patient is suspected of having a STEM heart attack. To achieve this diagnostic outcome, patient attributes in the sub-model are modified and the stock and flow structure for STEMI developments are modified to specify a STEMI heart attack during triage. STEMI is then observed on the ECG and the variable priority 1: *CATH. LAB or Other Urgent Care* is prioritized and the patient is classified as eligible for transportation the catheterization lab immediately via the fast track patient lane or urgency placement lane pictured in Figure 1. The time spent in the AED is shown to be approximately 22 minutes. Out of the 22 minutes, triage took up about 13 minutes indicating that most of the time is spent in triage before receiving a placement status for the catheterization lab. This included measuring vital parameters, recording and interpreting ECG results and the confirmation of patient status. The priority of STEMI cancels out any additional diagnostic suspicions and STEMI is the only listed diagnosis in the registration sector at the end of the simulation. Other diagnostic suspicions at the time of triage is assumed to taken care of after the patient has gone through necessary procedures necessary to take care of STEMI.

4.2.2 Scenario 2:
Acute Coronary Syndrome- NSTEMI

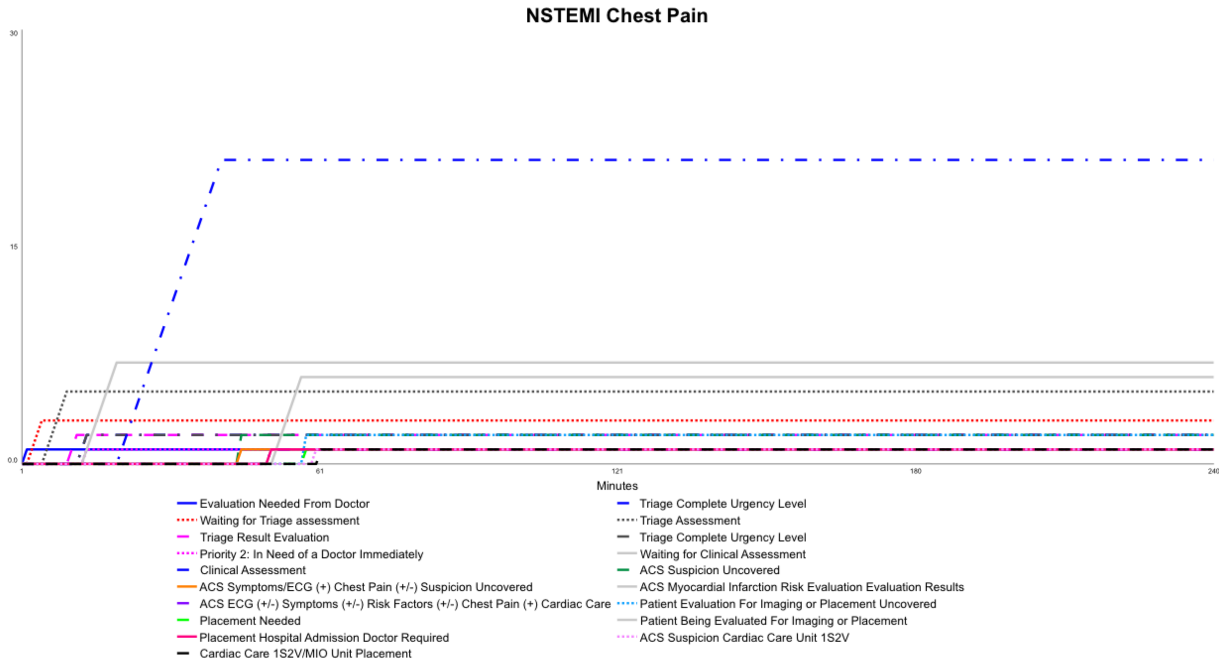

Figure 41. Graph showing NSTEMI diagnostic process.

The scenario in Figure 41, simulated an NSTEMI patient. NSTEMI is confirmed on the ECG during triage and the patient is experiencing chest pain at arrival. Based on the calculation, the patient is assigned an urgency level 2 (orange), and the patient is allocated a doctor within 10 minutes. Clinical symptoms are present during clinical assessment. On the basis of the aforementioned findings, a potential risk of heart attack is established and the patient is admitted to the cardiac care unit. The clinical combination of this patient results in an assigned placement to the cardiac care unit. The patient is ready for admission after approximately 61 minutes. The table below divides the AED stay up and the activity time structure below indicates the length of the various activities carried out and shows that certain variables contributing to the total time is not included in the graph in Figure 41. Because no ECG is registered prior to arrival, a longer time is spent in the AED compared to what a patient might traditionally do. At the time a placement decision is made, the patient has been triaged, clinically assessed; which included risk evaluation and any treatment and imaging necessary. To give an overall process time overview for each phase for this particular diagnose, the diagnostic process is divided up the following way.

Table 18 Patient AED Time for a NSTEMI patient

AED Activity		Length of Activity
1	Waiting for triage assessment	*3 minutes (total simulation time: 5 minutes)*
2	Triage assessment	*5 minutes (total simulation time: 11 minutes)*
3	Urgency level revealed (Priority 2 (yellow urgency level)	*2 minutes (total simulation time: 14 minutes)*
4	Doctor requested	*1 minute*
5	Waiting for clinical assessment	*7 minutes (total simulation time after waiting time is over: 20 minutes)*
6	Initial clinical assessment and assessment results revealed	*21 minutes (Total time 41 minutes)*
7	Risk factors registered	*1 minute (Total time 45 minutes)*
8	NSTEMI confirmed,	*1 minute (Total time 51 minutes)*
9	Placement decision evaluation: placement status ready	*6 minutes (Total time 57 minutes)*
10	Placement status: cardiac care unit	
11	Placement made after 89 minutes	*Ready for Cardiac care unit after 61 minutes*

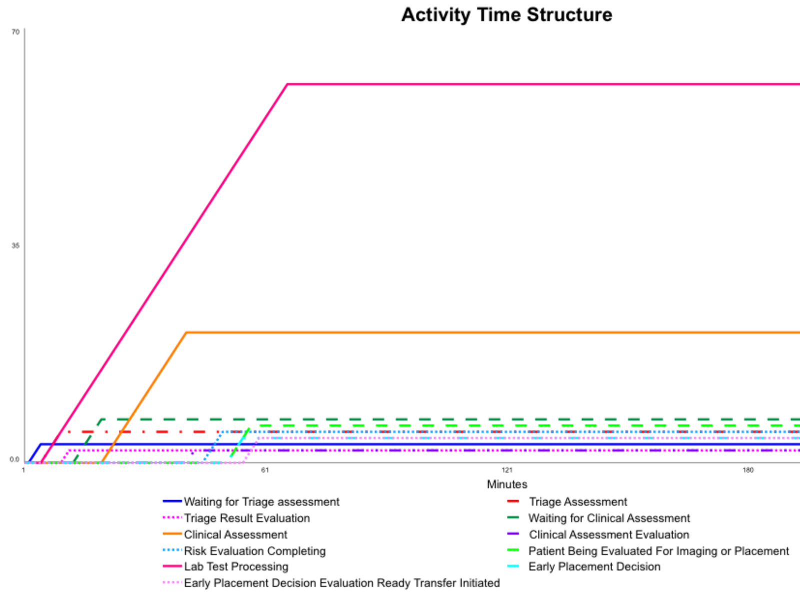

Figure 42. Activity Time Structures indicating the time spent for various procedures. The total time when looking at the activity time structures are approximately 87 minutes.

4.2.3 Scenario 3:
ACS- NSTEMI with Arrhythmias

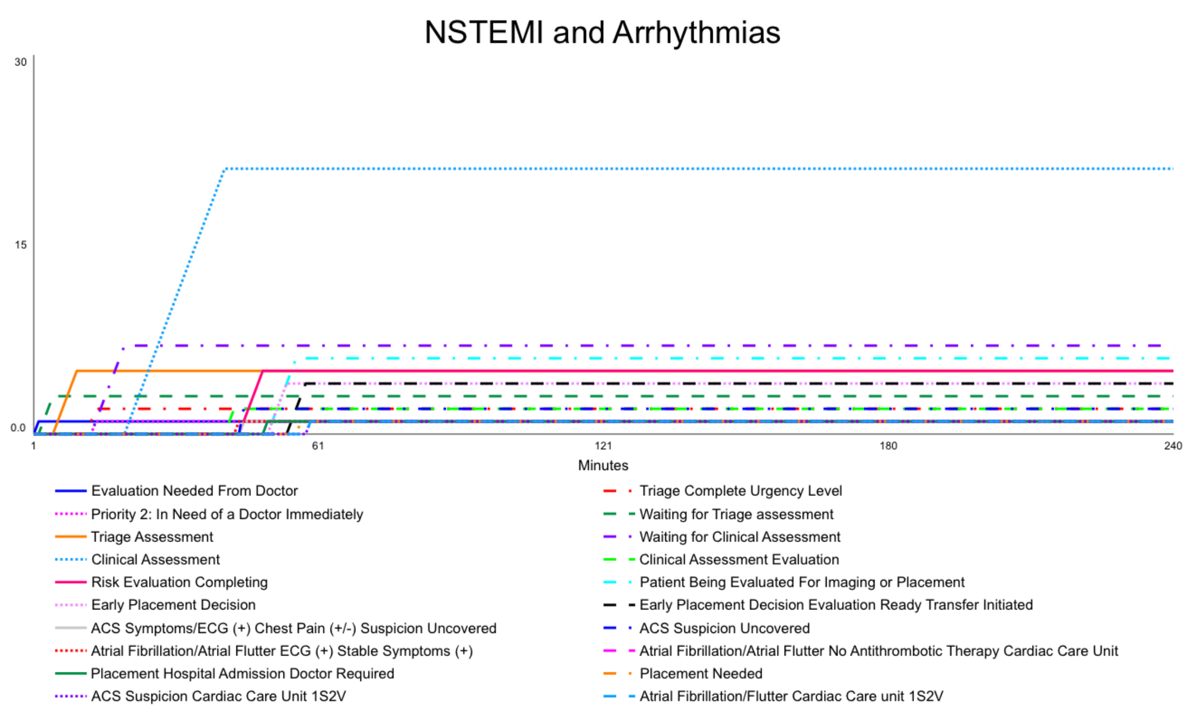

Figure 43. Graph showing NSTEMI Arrhythmias AED Placement Process.

Scenario 3 in Figure 43, simulates a patient displaying signs of NSTEMI with associated arrhythmias recorded on the ECG test during triage. Because the ECG indicates a possible NSTEMI heart attack in addition to arrhythmias, i.e., atrial fibrillation (AFib), or Atrial flutter, another element is added to the diagnostic process. In this case, the AFib/Atrial flutter patient is admitted to the cardiac care unit for observation and possible cardioversion. This specific action will be taken regardless of the duration of the arrhythmia, and so the NSTEMI/AFib/Atrial flutter will always qualify for early placement. Interpretation of lab test results is done in the cardiac care unit. Indications were made that these two scenarios were present, the model prioritized the AFib/Atrial flutter, and an early placement is prioritized. NSTEMI and the arrhythmias occurring alongside is listed and handled accordingly once the patient is admitted.

4.2.4 Scenario 5:
ACS- No Chest Pain at Arrival: cTnT Positive

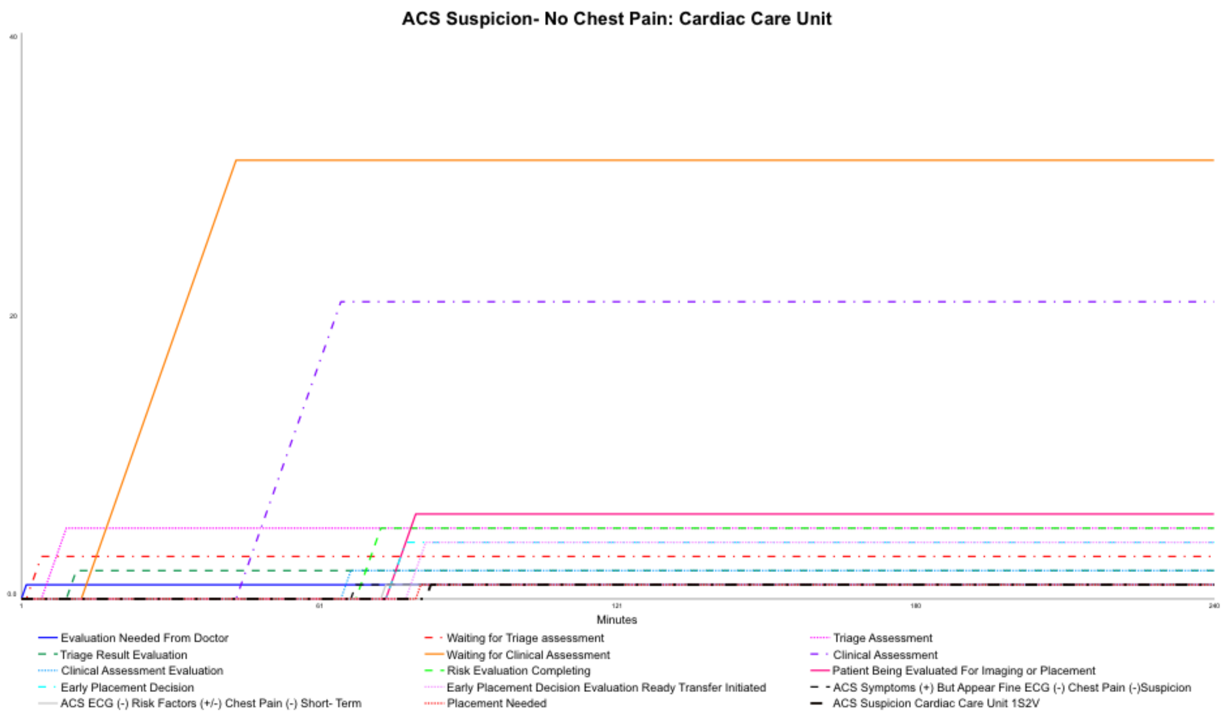

Figure 44. Graph showing acute coronary syndrome suspected patient without chest pain at arrival.

This scenario shows a patient entering the AED with no current chest pain but has experienced some chest pain within the last 24 hours. According to the vital parameters no critical symptoms are detected. The waiting time for the clinical assessment is longer for this patient than a patient arriving with chest pain and is therefore assigned an urgency level 3. The waiting time is maximum 1 hour before being assigned a doctor and the clinical assessment can start according to SATS. In this case, the waiting time for urgency level 3 is fixed and set to 30 minutes. Due to the extended waiting time to be assigned a doctor, the lab test results are made available once the clinical assessment is completed. The assessment shows that the patient has symptoms seen in ACS while the lab test results indicates elevated cTnT levels. Based on these combinations, the patient qualifies for general placement and is admitted to the cardiac care unit for further assessment. A second cTnT lab test is assumed to administered upon cardiac care admission. As the figure above demonstrates a lower urgency level with early placement criteria, resulted in a placement decision after 1.25 hour. If the waiting time to see a doctor is reduced, the lab test results will not be available before placement of the patient, and the patient will most likely be transferred to the short-term unit.

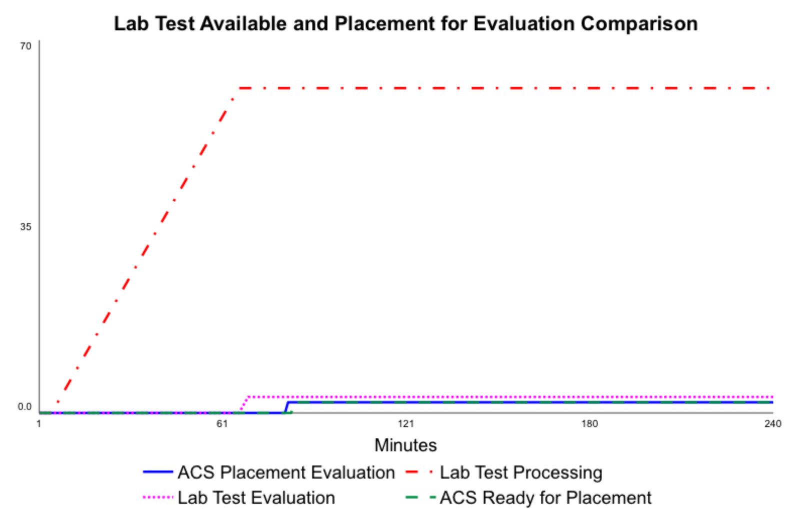

Figure 45. Lab Test Availability and Placement Evaluation Comparison.

4.2.6 Scenario 6:
ACS- No Chest Pain and Normal Troponin Levels

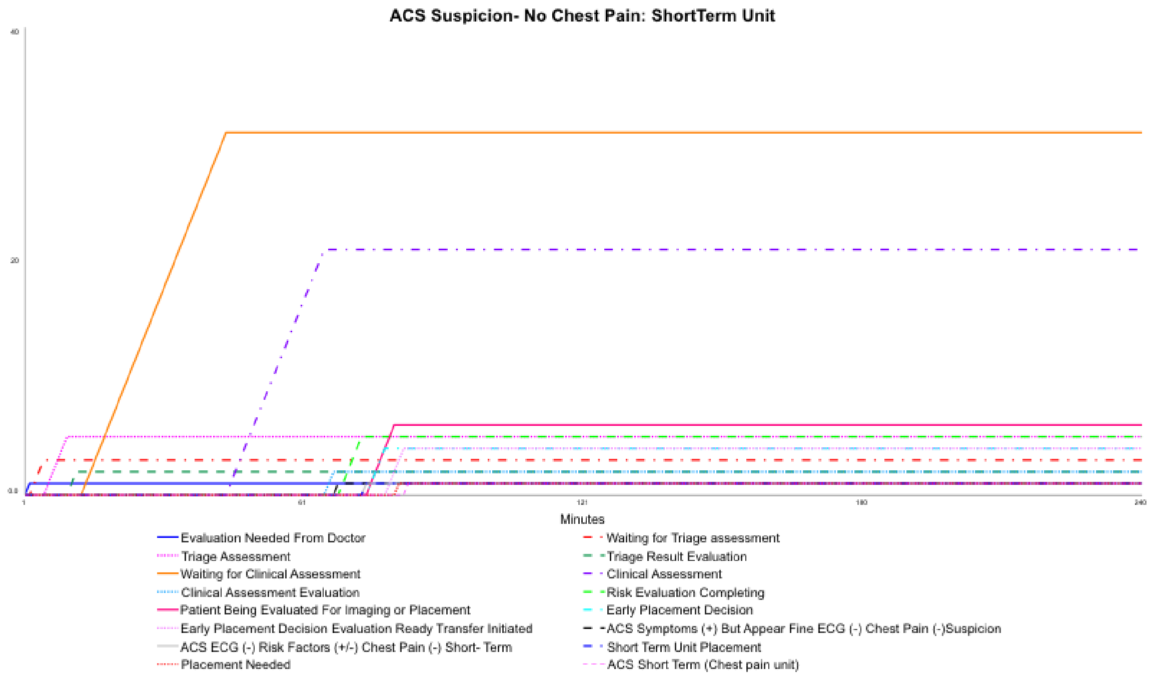

Figure 46. Graph showing a patient arriving with no ongoing chest pain, no significant ECG findings, and normal cTnT levels but appears unstable.

The scenario in Figure 43, simulates a patient that arrives with no ongoing chest pain. At arrival, the patient receives an urgency level 3 based on the chest pain indications and no significant findings on ECG. Symptoms might be present but the patient appears stable and the lab test indicates no increase in cTnT. On the basis of the attributes of the patient, he or she is placed in the early placement category and can be transferred to the short term unit.

4.3 Cardiogenic Shock

In the event of cardiogenic shock, systolic blood pressure is generally less than 90 mm/Hg. The scenario below in 4.3.1 indicates exactly this and based on the triage assessment, the patient should be assigned an urgency level 1. The model assumes the patient do not display any signs or symptoms suggesting pulmonary embolism, or other lung related indications, e.g., heavy breathing or congested lungs, low respiratory rate, very low oxygen levels. By excluding these clinical signs in the model, the possibility of confirming cardiogenic shock to be of another origin than a heart attack is eliminated. Instead, the primary diagnostic imaging tools is ECG and echocardiogram. For patients designated for the cardiac care unit, a cardiogenic shock can occur due to an arrhythmia/heart block or heart attack.

4.3.1 Scenario 7: ACS- Cardiogenic Shock

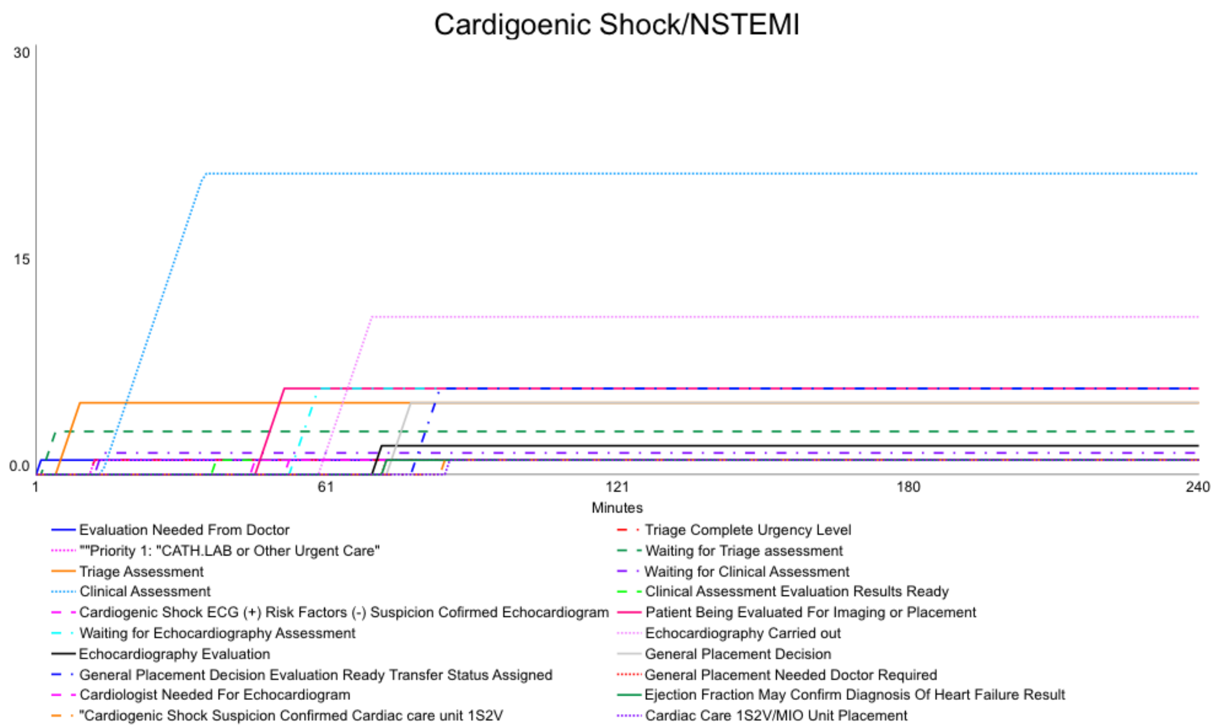

Figure 47. Graph showing cardiogenic shock & NSTEMI**.**

The cardiogenic shock patient in this scenario have a systolic blood pressure of < 90mm/hg, and an immediate urgency level of one is assigned and a doctor is requested immediately. Blood samples are taken and sent to the lab, which included a group of cardiac enzymes, e.g., cTnT, Hb, CK MB, as well as NT-ProBNP. Blood gas is measured and made available within minutes. According to the modified attribute-developments the clinical assessment revealed suspicion of ACS and additional confirming symptoms of cardiogenic shock is registered, e.g., cyanosis, low blood pressure, cold extremities, cold sweat. Based on the status of the patient and echocardiogram assessment is completed in order to establish the cause of the potential heart attack. The model assumes the patient is given the necessary treatments/medications in order to maintain blood pressure and cardiac output according to diagnostic guidelines (Ren, 2017). Once echocardiogram is completed and lab test results made available, a placement evaluation is made. The use of echocardiogram is an excellent tool to investigate the possibility of heart failure. Though the echocardiogram can show up normal, as well as indicate below normal results, cardiogenic shock should not be excluded. The presence of other significant clinical findings of cardiogenic shock should be used to aid the placement of the patient including clinical symptoms and lab test results. Because of the additional echocardiogram in this scenario, lab test is made available while the patient is still in the general AED. In this scenario, the evaluation establishes the presence of ACS and cardiogenic shock and the patient is eligible for the cardiac care unit for treatment observation and treatment after 1.17 hours. In the registration sub-model, it is observed that both ACS and cardiogenic shock is registered.

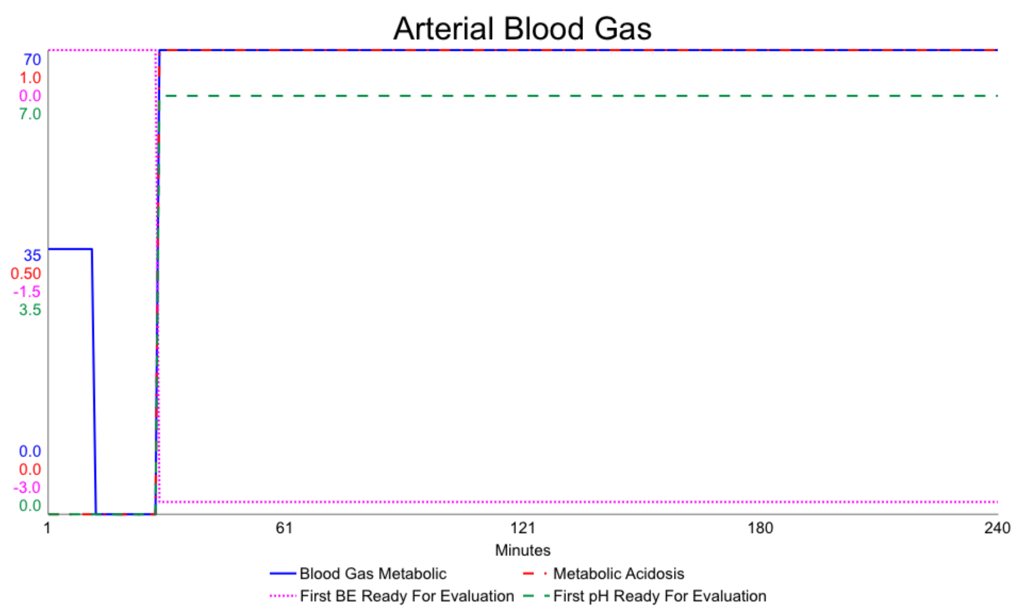

Figure 48. Graph showing arterial blood gas observed during the clinical assessment evaluation of cardiogenic shock, indicating metabolic acidosis.

4.3.2 Scenario 8:
Cardiogenic Shock - Unstable Arrhythmia

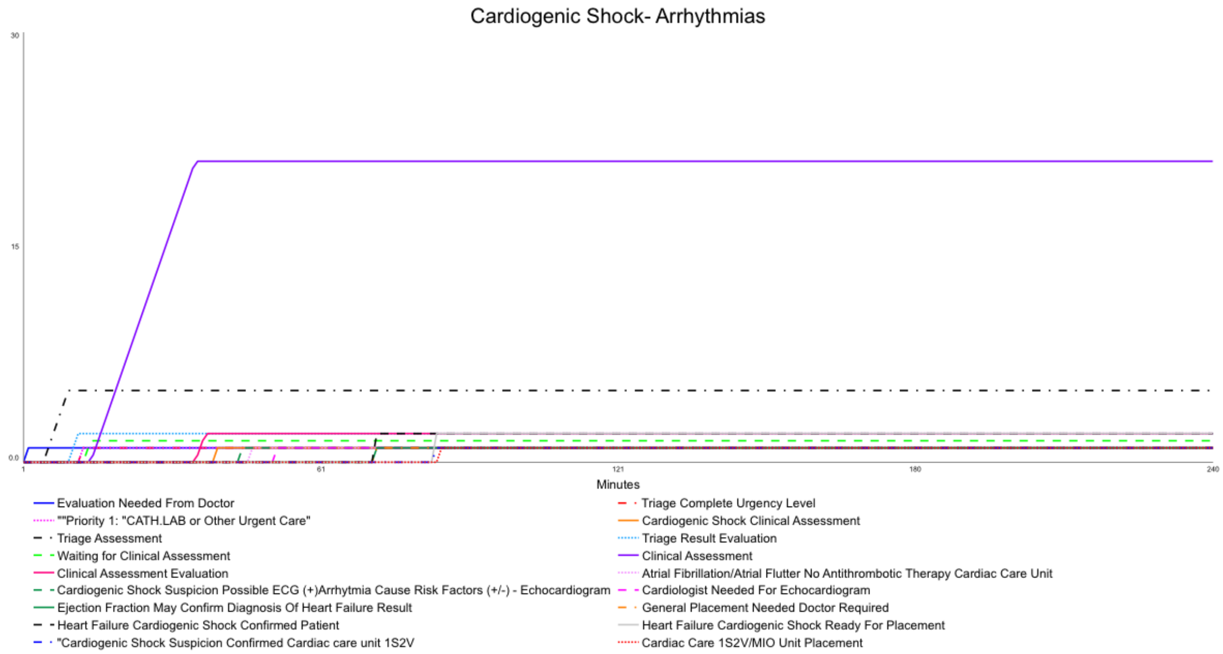

Figure 49. Graph showing the diagnostic process for cardiogenic shock with discovered Ventricular Tachycardia.

A cardiogenic shock can also be triggered by ventricular arrhythmias or atrial arrhythmias and though the presence of ventricular arrhythmias is far more threatening than the presence of atrial arrhythmias, the patient should be admitted promptly whenever cardiogenic shock occur as the result of an arrhythmias. Though the occurrence of cardiogenic shock and arrhythmia is small (5%), the mortality rate is close to 40-50%, and therefore requires immediate care. (Saidi, Akoum, & Bader, 2011). In this scenario the patient display symptoms of cardiogenic shock, such as a systolic blood pressure of < 90 mm/hg and cyanosis, oliguria and cold extremities in addition to arrhythmias (Atrial fibrillation). After the initial clinical examination, the patient is scheduled for echocardiogram in which the results indicate that a possibility of heart failure. Due to the echocardiogram results, the patient is admitted to the cardiac care unit where treatment for both scenarios are being taken care of.

4.4 AV- Blocks (Atrioventricular Heart Blocks)

AV-blocks conduction disorders and are partial or complete blocks of the heart's electrical rhythm. AV-Blocks can be a congenital heart condition or an acquired condition (Legevakthåndboka, 2015). However, in this model the focus is on the acquired type of AV-Block. Patient history is accounted for and congenital AV-Block may be registered as a risk factor. In this model, AV Block-II and AV-Block III are included and the model assumes both types of AV-Block qualifies for hospital admission. AV-block III and AV Block type II with unstable symptoms such as syncope, qualifies for early placement. If a patient with AV-Block II appears stable, he or she can stay in the AED while waiting for lab test results and hospital admission will be required later. The scenarios are the following:

4.4.1 AV-Block II, Scenario 9:

Patient is assigned a placement status to the cardiac care unit after approximately 59 minutes.

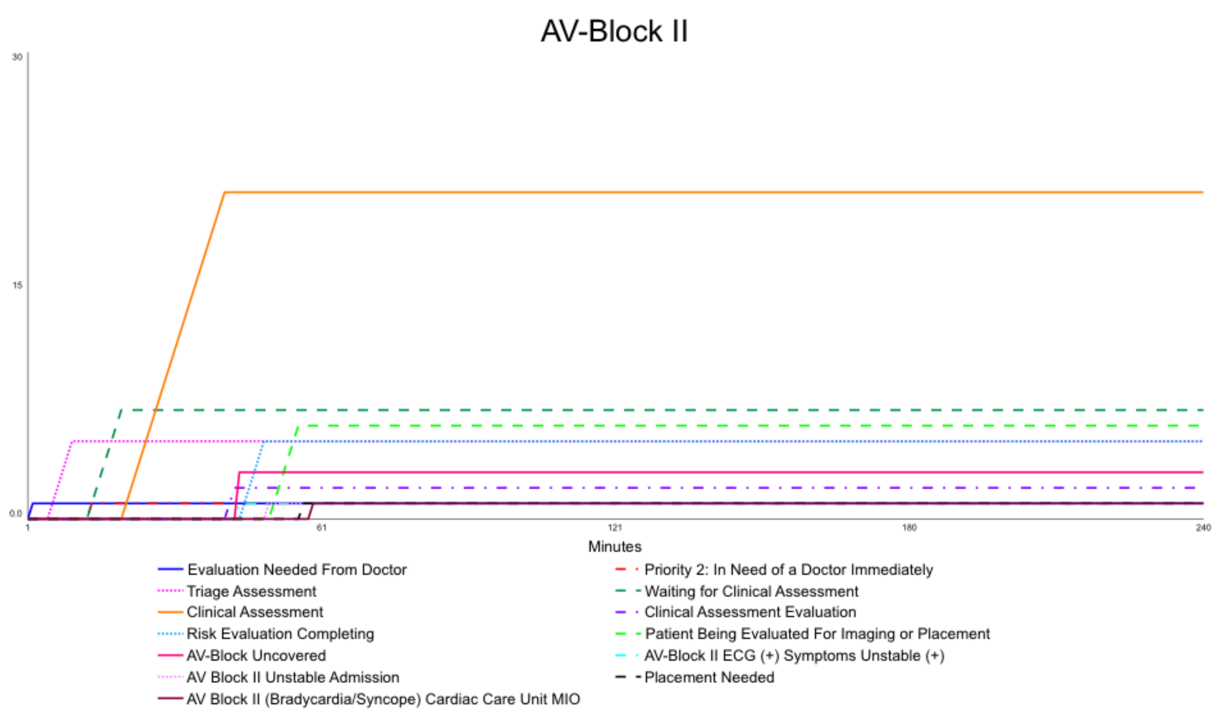

Figure 50. Scenario 9: Graph showing AV-Block II patient.

4.4.2 Scenario 10:

AV-Block III resulting in unconsciousness, or seizure

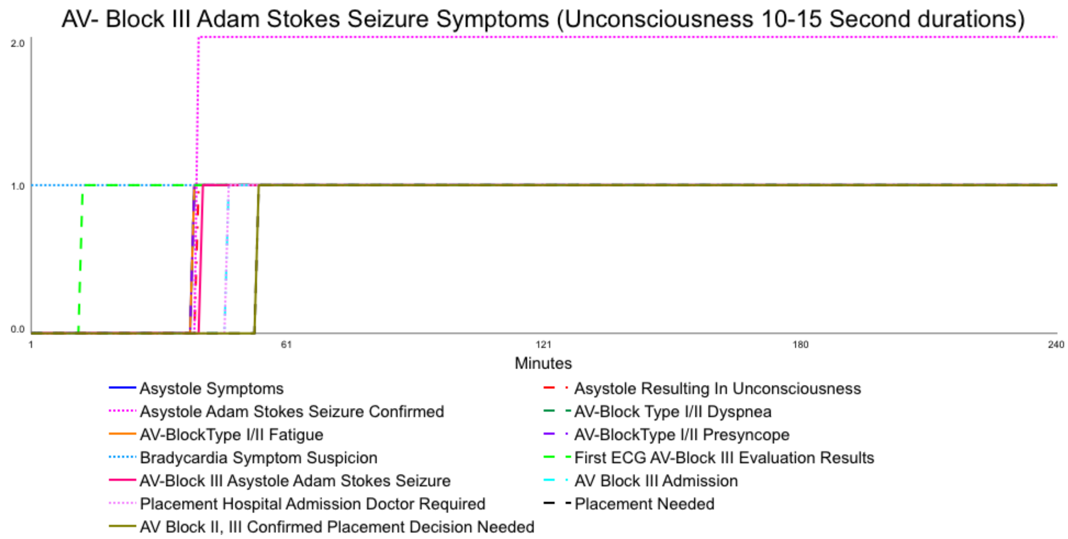

Figure 51. Graph showing AV-Block II resulting in Asystole unconsciousness or seizure.

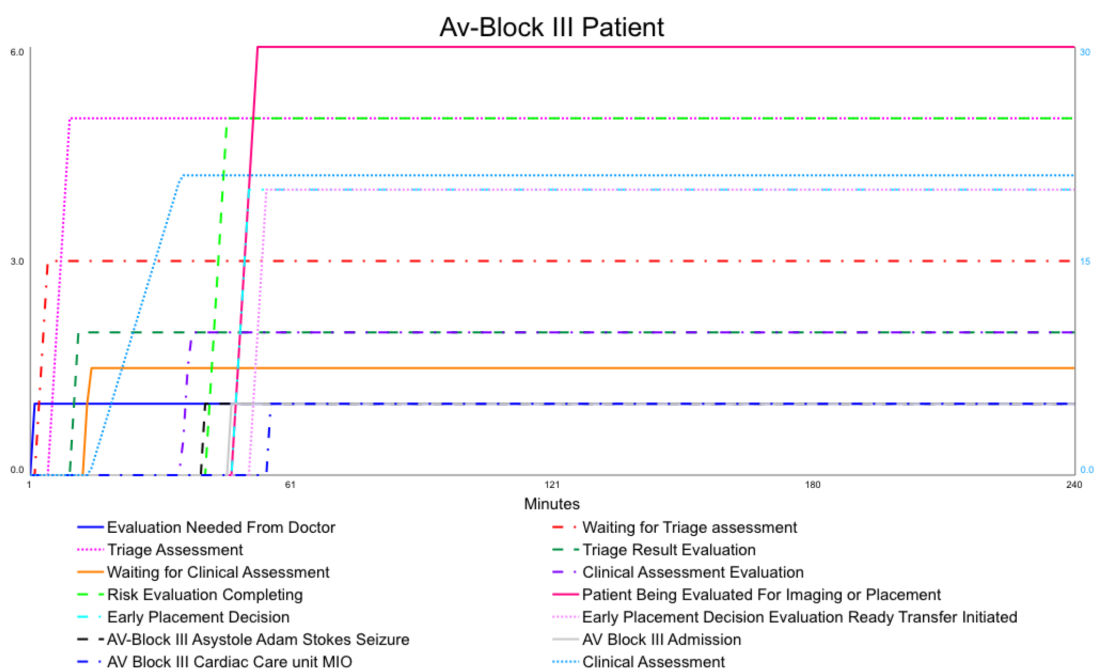

Figure 52. Av- Block III Patient admitted to the cardiac care unit.

The graph above simulates an AV-Block III patient who suffers from unconsciousness or seizures in which the patient is admitted to the cardiac unit.

4.4.3 Scenario 11:

AV-Block III resulting in respiratory arrest in which resuscitation is initiated.

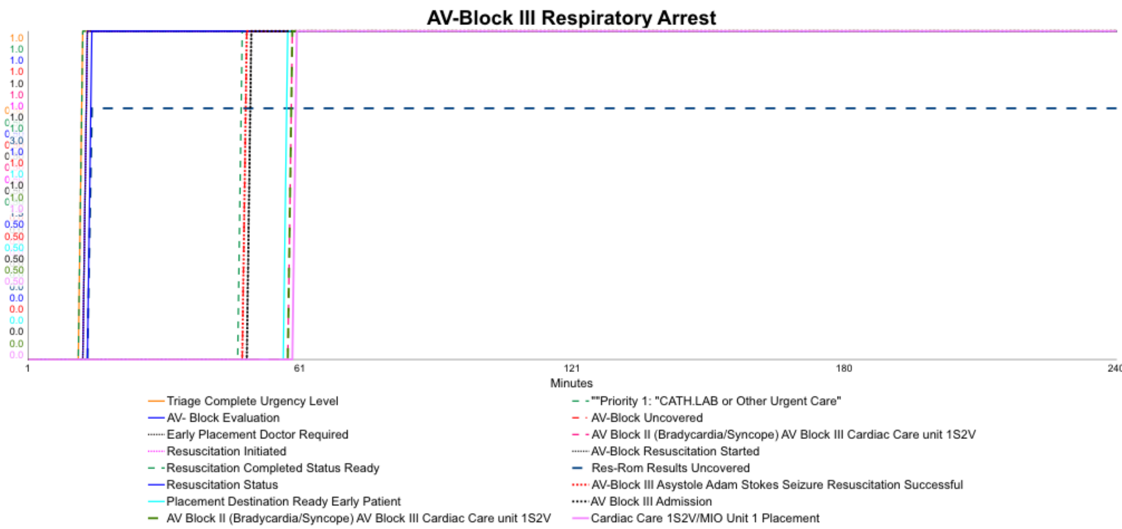

Figure 53. Graph showing AV-Block resulting in respiratory arrest.

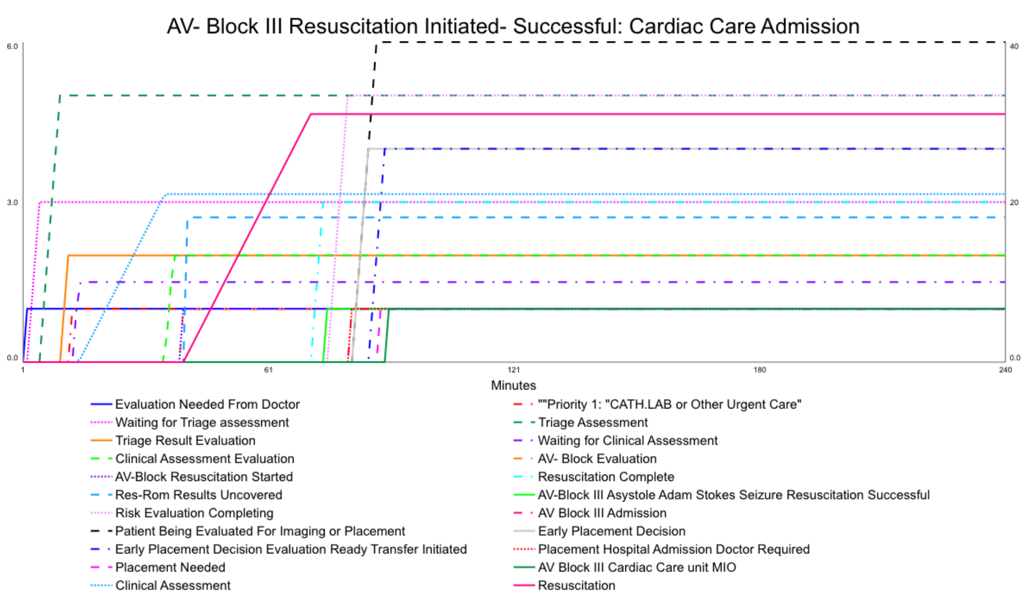

Figure 54. Graph showing AV-Block III patient requiring resuscitation.

AV-Block III is a critical condition and can lead to cardiac arrest. AV-Block III is often indicated by Asystole Adam Stokes seizures, i.e., syncope, bradycardia, pale skin, and depending on the length of the asystole it can lead to respiratory arrest. The scenario in Figure 53 and 54, indicates a patient that displaying signs of AV-Block III and the patient is assigned an urgency level of one. Respiratory arrest is present and resuscitation is initiated via the resuscitation stock and flow structure before the patient is admitted to the hospital. Based on a number generator, the successfulness of the resuscitation is calculated and the resuscitation time from initiation to resuscitation available result is 47 minutes. In this case, resuscitation is successful and the patient is admitted to the cardiac care unit (MIO). The placement status is revealed after 60 minutes from arrival.

4.5 Scenario 12: Atrial Fibrillation and Atrial Flutter

In the emergency phase, Atrial fibrillation and Atrial flutter are treated the same. Atrial fibrillation (AFib), are irregular fast heartbeats, whereas atrial flutter is typically regular fast heart beats (Mayo Clinic, 2015). In most of the clinical pathways, medical treatments are assumed administered unless mentioned. However, for AFib and Atrial flutter the evaluation for choice of treatment is included as an illustration on how this can work and how it can be incorporated in a future model. Though some of these treatments might be initiated once admitted to an in-hospital ward, it is still a useful illustration of the diagnostic process.

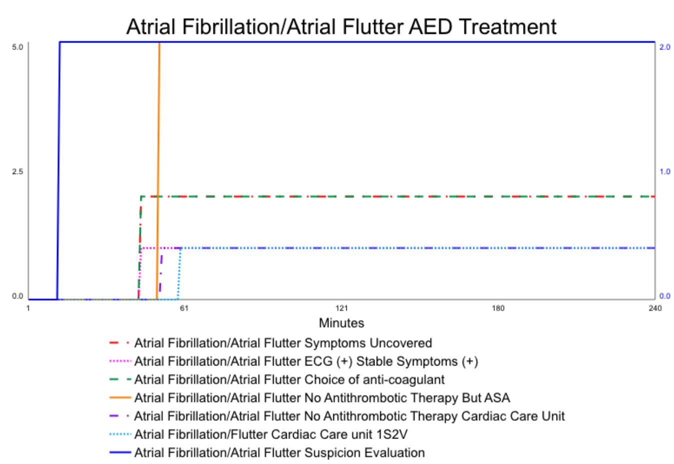

Figure 55. Graph showing risk evaluation for AFib/Atrial Flutter.

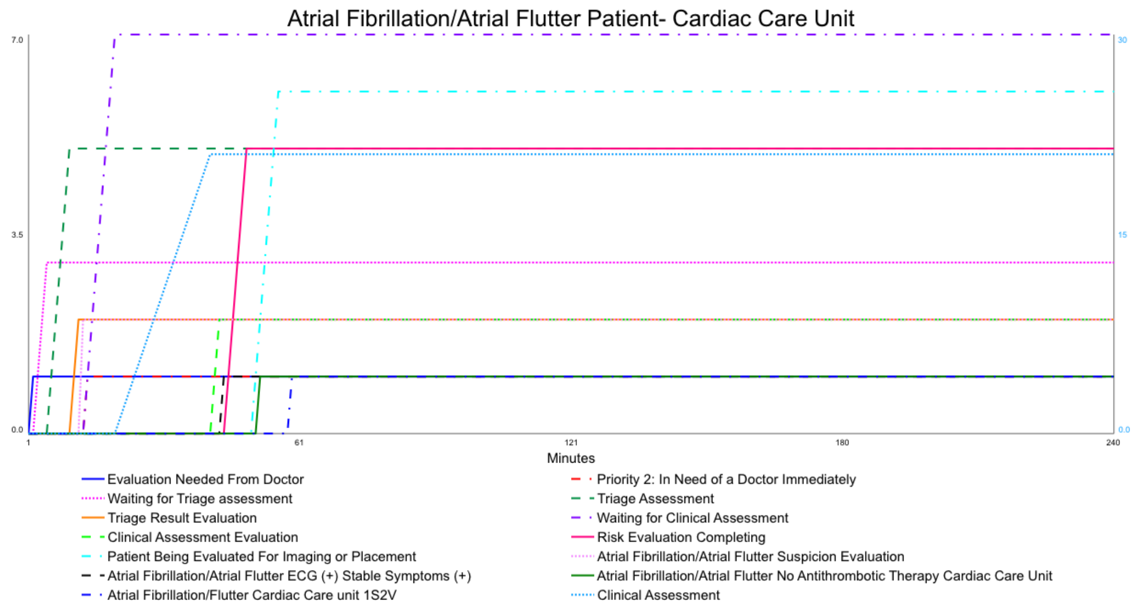

Figure 56. Graph showing Atrial Fibrillation/Flutter patient and its pathway.

In this scenario, the model assumes the patient displays a new-onset AFib/Atrial flutter during ECG and qualifies for early/immediate placement. The first scenario shows a patient that based on risk score do not require any antithrombotic therapy. The risk score takes into consideration risk factors such as possibility of stroke, length/duration of the arrhythmia, status of anticoagulation and other risk factors. The stroke risk for this scenario is low and the duration of the Afib/Flutter is more than 48 hours but the patient appears stable. The registration of risk factors and administration of possible treatments are taken into account and therefore, the AFib/Atrial Flutter evaluation in the clinical assessment sub-model is completed later.

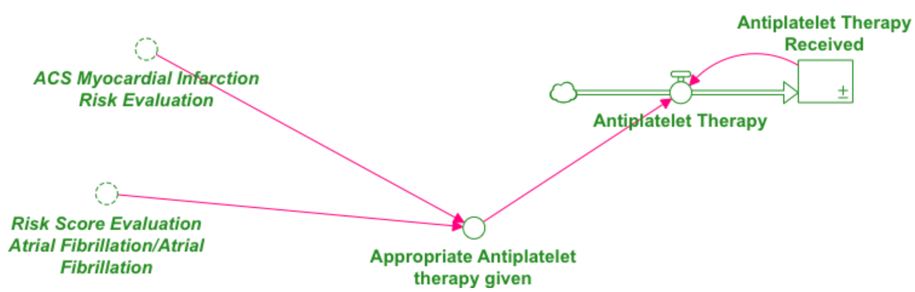

Figure 57. Antiplatelet therapy given to AFib/Atrial flutter patients.

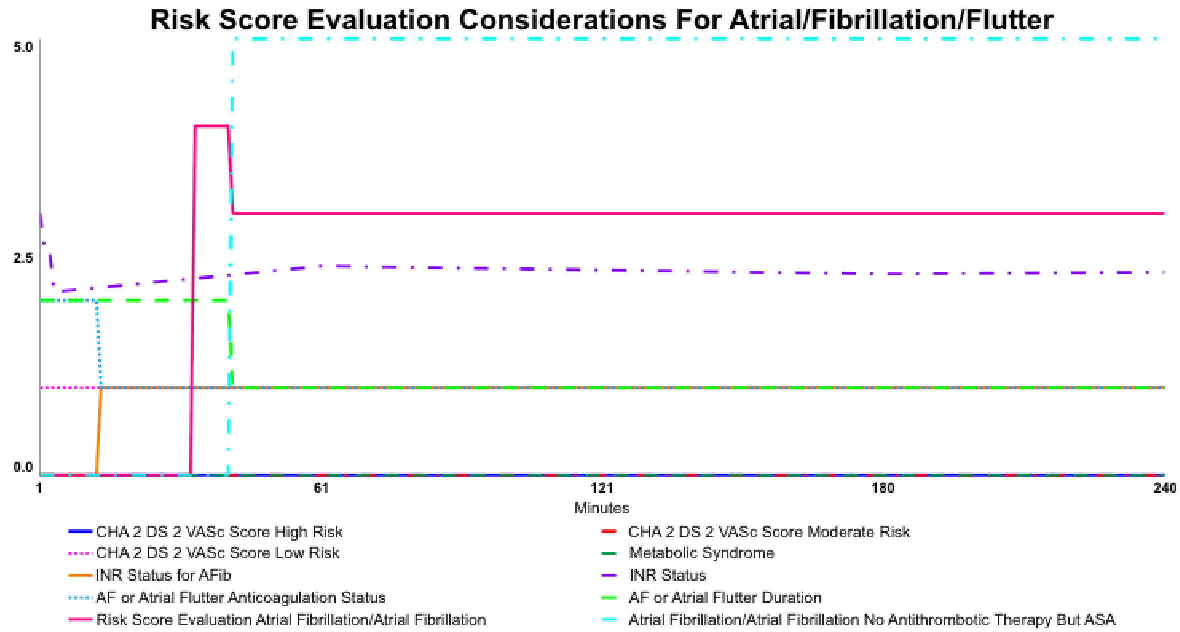

Figure 58. Graph showing risk score evaluation and treatment based on evaluation.

4.6 Scenario 13: Ventricular Fibrillation

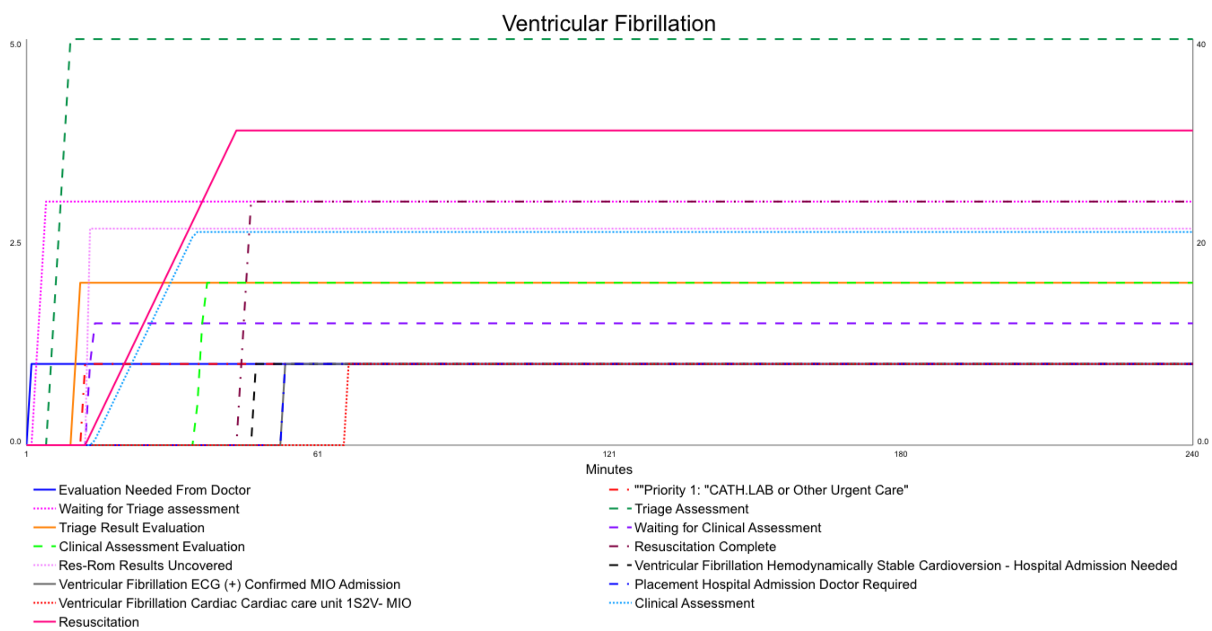

Figure 59 Graph showing Ventricular Fibrillation patient and its pathway.

Ventricular Fibrillation is a serious cardiac rhythm disturbance and is generally characterized by the hearts electrical activity being disordered and the hearts lower chamber quiver. As a result, the heart is unable to pump enough blood and causes cardiac arrest. (American Heart Association, 2016) For this scenario, symptoms observed during triage are used as indicators and any ongoing symptoms during the clinical assessment is taken into consideration. The scenario indicates a patient that is experiencing loss of consciousness and when ventricular Fibrillation is indicated on the ECG during triage, resuscitation is initiated. Like AV-Block III, the status of the resuscitation is revealed after 47 minutes. The resuscitation is successful and the patient is ready for placement in the Cardiac care unit (MIO), unit for observation and cardioversion. Figure 59, illustrates the diagnostic process of ventricular fibrillation from arrival to assigned placement decision.

4.7 Scenario 14: Ventricular Tachycardia

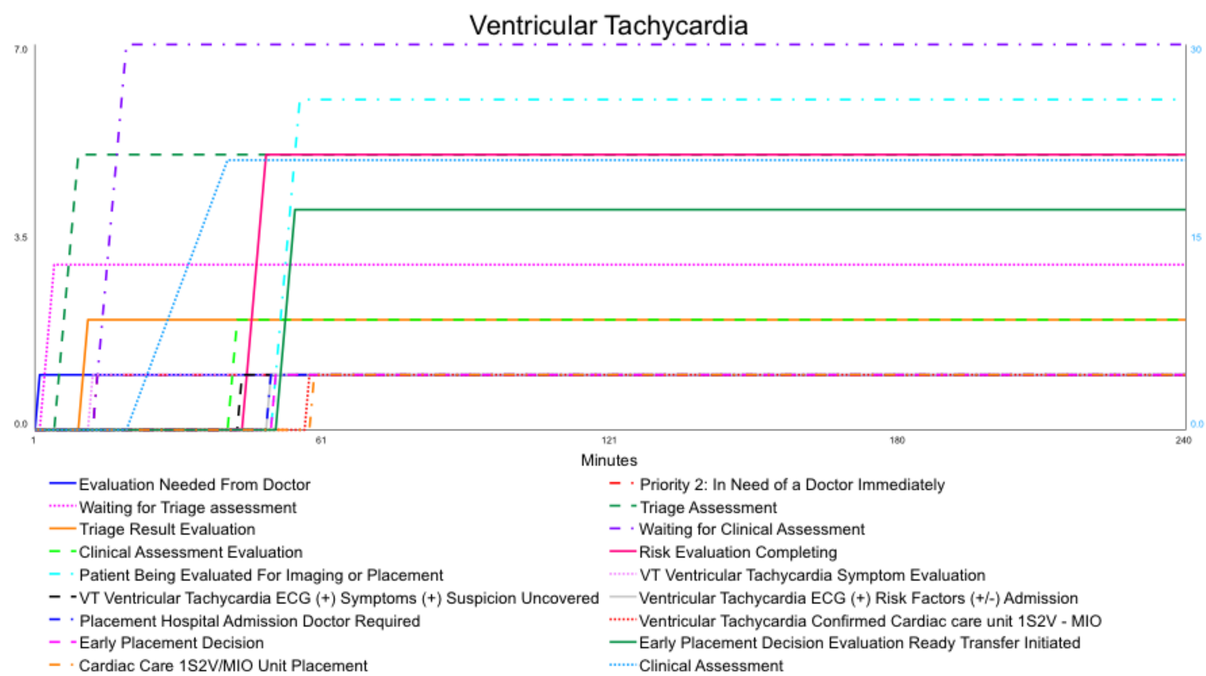

Figure 60. Graph showing ventricular tachycardia patient and its pathway.

Ventricular tachycardia (VT's) is a condition that can be revealed during the course of myocardial infarction. It can be caused by a previous heart attack, after heart surgery or it can be due to a congenital heart defect. Other possible causes were specific medications or less common causes such as blood imbalances. Rarer causes were not included in the model such as cardiomyopathy or myocarditis. Someone with established (VT's) is at risk for developing ventricular fibrillation and it is important the patient be admitted to the cardiac care unit for cardioversion. The scenario above illustrates a patient showing ventricular tachycardia on the ECG during triage. Based on triage findings, the patient is assigned an urgency level 2, this included positive ECG findings and presence of chest pain. During the clinical assessment symptoms such as pre-syncope (dizziness), sweating and dyspnea is discovered and risk factors are registered. On the basis of these findings the patient is eligible for early placement and the he or she received a placement status for the cardiac care unit after approximately 59 minutes.

CHAPTER 5

Research Outcome and Conclusion

5.1 Research Outcomes

In this study, SD has been used as a tool to understand the multifaceted processes involved in the AED from a patient oriented perspective. According to research, there are few SD that focuses on the diagnostic processes at such complex medical and diagnostic level.

The interacting objects in the accident and emergency department contribute to a dynamically changing environment accompanied by a seemingly ever increasing demand amidst limited resources (Morrison and Wear, 2011). The mix of such challenges and constraints is what makes the AED environment so complex, unpredictable yet fascinating to explore. The AED serves as a network of resources aiding the patient in the most appropriate direction in order to place him or her in the right location at the right time. The patient-oriented modeling approach has proven useful, as it has enabled a systematic observation on the emergence of various cardiovascular pathways based on patient attributes incorporated in the model. The interactions and activities involved in the AED process are intriguingly complex and a challenge to model. Despite the inherent intricacies involved, the modeling endeavor has allowed us to gain a clearer understanding of how the complex the diagnostic processes in the AED. We can see how AED processes are utilized at different times depending on the individual patient in the system. The model permitted the AED processes to be mapped out in detailed and observable segments allowing for investigation of resource allocation rules and how they influence the quality of the care delivery in the AED.

The use of discrete event and object-based modeling concepts in a system dynamic environment aligns with the goal of creating a model comprised of interacting AED entities in the form of system dynamic sub-models. The sub-models encompassed interacting AED objects in the form of activities and patient attributes.

It is clear from the simulated scenarios, that the time spent in the AED for an individual patient will be significantly longer once multiple patients enter the system at once. Once multiple patients occupy the AED, allocation strategies and rules applies. A queuing structure needs to be incorporated observations can be made on when patients are "assigned" the resources according to patient attributes and prioritization rules. Nonetheless, the scenarios investigated should be a reminder of the importance of patient-centered care, as the needs of the patient is the most vital piece of the hospital delivery system. The scenarios also highlight the key resources needed by cardiovascular patient during their general AED stay and the model captures how the patient attributes are directly linked to the procedures and tests carried out. Various placement policies were modeled and the question of whether the patient was placed at the most appropriate time was investigated.

A detailed mapping process of the AED from a patient perspective, provides a different modeling viewpoint as well as contributing to a better understanding of the complexity that lies within placing a patient in the correct location. Activities carried out in the AED requires the presence of medical staff such as nurses and physicians and the simplified structures indicating the procedures and tests carried out signaled the need for medical staff. Waiting time between doctor request and doctor availability was observed based on simplified activity time structures. The simplified activity time structures also highlighted the time spent in the AED for different patient types. Based on the structure of the model, the numerous sub-models allowed for a strategic understanding of the processes involved. The simulation results address how the degree of complexity and variability of the patient's medical composition greatly influences the resources required and utilized in the AED. The methods used in the model development, contributed to the overall goal of mimicking quintessential features of cardiovascular pathways in the AED (Morrison and Wear, 2011).

5.2 Research Limitations and Boundaries

Like most simulation models, they do not mimic all aspects of the system in question and as such, several limitations need to be acknowledged. First, a major limitation to this study was the lack of proper validation. The current model is perhaps an in between model based of the old and the new AED and though the new features of the AED is mentioned in the thesis, there is a lack of validation and communication with the hospital, which has limited the model from having a total *new AED* perspective. The lack of proper validation from sources concerning the AED layout and a confirmation on the AED process steps, the model might not accurately reflect how the AED at HUS operates. Though the intention was to represent it to the best of my abilities, some might want to add or rearrange on AED process steps once it is looked at in more detail by medical staff at HUS. Moreover, the new AED opened in May, 2016, and it was difficult to try and model a hospital I had never actually stepped foot in, but had only read about, or been briefed about by hospital staff based on their own experiences and expectations of how the new AED would turn out.

Second, a late start to the project and fewer meetings than desired with medical staff, contributed to the limitations of the research. However, points made by Sterman (2000), in his book Business Dynamics can summarize some of the limitations to the model. In the book, he presents principles for successful use of SD in which he points out one should avoid black box modeling. Black box modeling is defined as building models out of sight of your client, which never leads to change in deeply held mental models and a change in client behavior. Though several meetings over the course of the study contributed a great amount towards the completion of the model, the lack of model validation from medical and administrative staff is a major limitation. However, this particular study was not about changing mental models, but about mapping existing behavior and practices, more meetings with the hospital and more actors at the institution perhaps would have benefitted the model's outcome to a larger degree. Nonetheless, Sterman (2000) indicates, "any theory that refers to the world, relies on imperfectly measured data, abstractions, aggregations and simplifications", and therefore the model is as good as it can get with the information obtained.

Moving to limitations from a technical modeling perspective: Though the new AED now has two head physicians who take care of urgency patients' right after arrival, some waiting is expected. However, a scenario with no waiting time can be simulated and would result in an AED stay shorter than normal. However, I believe this means the SATS triage urgency level waiting-times are ignored, as patients will be treated as they arrive and not by urgency level.

Another point made referring to the model structure is that a comprehensive treatment structure could have been incorporated to show how the patient's status could have change based on the effects of the treatment provided. The current model assumes patients receive the appropriate treatments, and the attribute graphical function representing the developments are assumed to mirror the overall result including any treatment effects. The graphical functions indicating patient developments of clinical attributes are considered a result of the assumed treatment. Thought a more complex treatment structure could have been built, this was not executed mainly due to time constraints as well as the lack of validation for treatment options for all diagnoses in the model. This limited the opportunity to develop a more comprehensive treatment structure.

5.3 Ideas for Future Research

Although this study has its limitations and though there is certainly room for improvement, the outcome of the model proves that the potential for model expansion certainly exist. Though the model can only investigate one patient, one diagnosis at a time and the resources that particular patient requires during its AED stay, the model brings up questions for further model development and challenges the AED might face. Future model expansion can include the short-term unit, and the additional assessments completed here as well as the inclusion of the diagnostic unit. This unit consists of a large portion of "unsorted" patients who often have multiple suspected diagnoses who need interdisciplinary medical assistance (Helse Bergen, 2012).

Furthermore, by incorporating room allocation structures, more medical staff allocation structures as well as a comprehensive treatment structure, a more complete patient throughout model can be built. The numerous scenarios covered, only reflect one of many possible ways to structure and observe a patient-oriented SD model. A comprehensive diagnostic mapping process in the form of a SD model, might aid in the process reducing the number of patients who end up in the diagnostic unit, or facilitate and improve efficiency in the diagnostic unit in the future.

The healthcare chain is a vast and exceedingly complex system where its intricacy stems from the numerous stakeholders involved. The stakeholders might often work on different agendas with their own interests, depending on where in the healthcare chain they are. Hospital administrators and hospital staff might have different opinions about what is the most important agenda, whereas patients and families have other priorities when it comes to hospital stay. Therefore, future models might consider the viewpoint of stakeholders. Sub-models containing stakeholders such as patients and family, hospital administration, and medical staff observations can be made in terms of how peoples' goals and aspirations affect the AED efficiency and the hospital overall.

Lane et al. 2000's accident and emergency department study, discussed possible elaborations to his model where he mentioned the patient attributes in his study were aggregated for the purpose of his research. This model would be a good example of exploring patient attributes on a more detailed level and possibly incorporate it into a similar model such as Lane's (2000) and investigate how such patient attributes affects a larger system. Lane et al. (2000) focused exclusively on an emergency department but takes into account feedbacks from other areas of the hospital and studied its effect on the AED. Some of his most useful findings indicated that the time spent waiting for admission to their desired wards were one of the major causes of delay in the accident and emergency department.

In regards to the initial discussions about the development of this model, DES was the preferred method to run the model due to the more operational and tactical perspective. DES's advantage of defining individual entities and objects were one of the main reasons for considering DES over SD. In the start of the project, PowerSim was considered as a simulation tool that comprehended both DES and SD concepts because of PowerSims ability to model discrete events. However, as this was a system dynamics master's thesis and I had been trained in using iThink/STELLA and SD methods, a STELLA model was built taking on a different modeling perspective in contrast to many other traditional SD models. As the model progressed, mapping the workflow process in a smaller scope appeared to work well with SD methodology, rather than as a system consisting of controlling queues as DES is more suited for, as such it was not necessary making a transition into a DES version. The model was originally built around the concept of having several patients entering the system and then observing the flow of these patient throughout the AED. As the project progressed and model modifications were made, it was decided that an interesting way to illustrate the process of clinical pathways in the AED, was to solely display the processes in which the patient would be diagnosed depending on the patient's characteristics. As a result, a patient entering the system was not included. Throughout the model development, supplementary medical information had to be added to try and best reflect the real life processes of the AED. The model still needs proper medical validation if the purpose is to expand the model further.

Last, the shared understanding of causal relationships in the AED from the perspective of various stakeholders and their cooperative efforts enables better predictions and inferences to be made that benefits the AED and the hospital as a whole. A shared understanding of the purpose of the model leads to a more accurate and useful model. The successfulness of other similar SD-models, depend on the teamwork and communication between the modeler, the various stakeholders in the AED and the healthcare system in general. Outside influences in the community impact the daily operations of the AED including decisions made by managerial and organizational stakeholders. "The successfulness of new implementations and hospital strategies requires a collaboration and shared understanding of the system goal. This collaboration occurs across both vertical and horizontal boundaries, and a successful collaboration rests on creating a culture of shared responsibility, authority and accountability for results" (Beyerlein, Freedman, McGee & Moran,2003). For this model in particular, the communication and teamwork between medical staff and the hospital administration is especially important. Working well together depends on shared understanding of the goal and aspirations of the AED and the hospital in its entirety. In order to make intelligent decisions and coordinating with one another within a complex organization such as hospitals, it is important that the various involved staff and administrators have a shared understanding of the goal (Beyerlein et al., 2003). This type of collaboration is a key factor for successful implementation of hospital strategies aiming at improving and organization the environment and its services. Beyerlein et. al (2003) states that such a collaboration provides useful inputs from multiple perspective and generates meanings that enables coordinated action. However, too often stakeholders like hospital administrators make decisions unilaterally and sometimes with the lack of appropriate input or appropriate participation, such as input from medical staff or external influences. Therefore, it is important to include not just hospital administrators in the model developing process but collaborating with medical staff who are down in the field and take into consideration how the internal AED operations influence the surrounding communities.

5.4 Conclusion

This study focused on mapping existing AED processes in an SD environment for cardiovascular patients in the AED at Haukeland University Hospital. I chose a patient-oriented approach in with the goal was to create a SD model placing the patient in the center of the AED. In doing so the model simulated various clinical pathways for cardiovascular patients, highlighting the multiple resources linked to the care delivery of in the AED. I used various modeling concepts to facilitate model development in which the patient-centered approach was especially important. Having a patient-centered mentality to model development, I utilized concepts from other simulation method to create this patient-centered model. This include object-based modeling and discrete event concepts, resulting in a synthesis of these methods. Various AED processes were modeled and I was able to observe how AED activities carried out depended on the type of cardiovascular patient occupying the system. I offered a detailed illustration of the structure of the AED processes and resources provided for this patient group. Subsequently, a variety of cardiovascular diagnoses were incorporated into the model structure so as to observe the behavior of the model under a variety of scenarios and thus I let patient attributes dictate the various clinical pathways. By observing the clinical pathways in the AED, I was able to analyze what type of patients departed at specific times during the process, depending on the various patient attributes displayed.

The model was built to take into consideration how resources affect the rest of the hospital with regards to cardiovascular patient admission. The outcome of the model should initiate discussion with respect to clinical pathways and current and future resource allocation strategies for a variety of patient groups. How should resources be distributed when multiple patients and clinical pathways cross each other and claim the same resources. What happens when the AED functions cannot be maintained in an adequate and satisfactory manner within the framework of the available resources meant to be allocated to each individual patient? If this happens, what rules and regulations are implemented to ensure proper and fair resource allocation between patients and patient groups? Based on the anticipated rewards gained by the expansion of the AED and the associated uncertainty in patient influx, this SD model was developed to illustrate how cardiovascular patients and their resources can be characterized and modeled from a system dynamics perspective.

The AED is one small part of the hospital system and should not only be considered in isolation. The AED should be represented as part of a larger model encompassing the entire hospital. Correspondingly, it is vital to consider how the AED and the hospital are parts of a greater social system that interacts in feedback with the hospital, of which the AED is a major influential component.

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A APPENDIX

Appendix A – Clinical Findings

Electrocardiogram Screening Results
Atrial Fibrillations
Atrial Flutter
AV Block II Mobitz Type 1
AV Block II Mobitz Type 2
AV Block III
Left Bundle Branch
NSTEMI (non-ST-elevation myocardial infarction)
Right Bundle Brand Block
SA Block
Showing prior myocardial infarction
Sinustachycardia
STEMI (ST elevation myocardial infarction)
Ventricular Extra Systole (VES)
ventricular fibrillation
Ventricular Tachycardia

Cardiac Markers	**Arterial Bloodgas**	**Electrolytes**
CK	pH	Sodium (Na+)
CK-MB	BE	Potassium (K+)
Hemoglobin	PO2	
Myoglobin	pCO2	Calcium (ca+)
Troponin T (cardiac form) CTnT	HCO3	Magnesium (Mg++)

Symptoms	**Signs**	**TEWS**
Altered mental status	Asthma cardiale	Heart rate
Anxiety/Agitation	Clammy skin	Respiratory rate
chest pain	Cold extremities	SpO2
Clouding of consciousness	Cold sweat	Systolic blood pressure

Confusion or impaired thinking	Congested lungs	Temperature
Decreased physical performance	Cough	
Dizziness	Cyanosis	
Exhaustion	Diastolic blood pressure	
Feeling of weakness	Dyspnea/Shortness of breath	
Headache	Fast and/or irregular heart beat	
Heavy breathing	Jugular vein distention	
Nausea	Jugular vein pressure	
Symptoms	Signs	
Unrest shivering in the chest	Oliguria or anuria	
	Pale skin	
	Palpitations	
	Papilledema	
	Presyncope	
	Signs of infection	
	Sweating/diaphoresis	
	Syncope	
	Vomiting	

Appendix B

Cardiovascular Risk Factors	
Diagnosis of electrical instability	History of previous myocardial infarction
Congenital heart disease or heart abnormalities	History of structural heart disease
Family history of premature SCD	Peripheral artery disease
Family history or patient history of heart disease	Potential clues suggesting etiology of heart failure
History of aortic plaque	Previous experienced angina symptoms
History of coronary atherosclerosis known CAD stenosis greater or equal to 50	Previous heart surgery
History of previous heart failure	Previous TIA/thromboembolism

Risk Factors – Pharmaceutical and Drug Related
History of illegal drug use
Patient on antipsychotics or anti-arrhythmic drugs
Patient on Aspirin or Acetylsalicylics/ASA use for the past 7 days
Patient taking digitalis

General Risk Factors	
Abnormal renal and liver function/renal impairment	History of hypotension
Bleeding	History of- pre-eclampsia
Current obstructive pulmonary disease (COP)	History of respiratory infection/disase
Diabetes mellitus or high blood sugar	History of syncope
Excessive alcohol or caffeine use	Hypercholesterolemia
High stress levels	Hyper metabolism
History of chronic obstructive pulmonary disease	Hypoxemia
History of an autoimmune condition	Known asthma
History of cigarette smoking	Obesity or significant weight increase
History of gastrointestinal symptoms	Physical inactivity
History of high blood pressure	Reduced appetite
History of hypertension	Sleep problems

Appendix C

ECG	Range 1	Range 2	Range 3
STEMI	(IF ECG_Development_Options <= 15 THEN ECG_STEMI_Development_1 ELSE	IF ECG_Development_Options > 15 AND ECG_Development_Options <= 19 THEN ECG_STEMI_Development_2 ELSE	IF ECG_Development_Options > 19 AND ECG_Development_Options < 25 THEN ECG_STEMI_Development_3 ELSE 0)
NSTEMI	(IF ECG_Development_Options <=30 AND ECG_Development_Options > 26 THEN ECG_NSTEMI_UA_Or_Other_Indication_Of_MI_Development_3 ELSE	IF ECG_Development_Options > 30 AND ECG_Development_Options <= 37 THEN ECG_NSTEMI_UA_Or_Other_Indication_Of_MI_Development_1 ELSE	IF ECG_Development_Options > 40 AND ECG_Development_Options < 45 THEN ECG_NSTEMI_UA_Or_Other_Indication_Of_MI_Development_2 ELSE 0)

Ventricular Tachycardia	IF Heart_Rate_Patient_ Condition> 100 THEN (IF ECG_Development_ Options < 30 AND ECG_Development_Options > 26 THEN ECG_Ventricular_Tachycardia_Development_3 ELSE	IF ECG_Development_ Options > 30 AND ECG_Development_Options < 37 THEN ECG_Ventricular_Tachycardia_Development_1 ELSE	IF ECG_Development_ Options > 40 AND ECG_Development_Options < 45 THEN ECG_Ventricular_Tachycardia_Development_2 ELSE 0) ELSE 0
Atrial Fibrillation	IF Heart_Rate_Patient_ Condition> 100 THEN (IF ECG_Development_ Options < 30 AND ECG_Development_Options > 26 THEN ECG_Atrial_Fibrillations _Development_2 ELSE	IF ECG_Development_ Options > 30 AND ECG_Development_Options < 37 THEN ECG_Atrial_Fibrillations_Development_3 ELSE	IF ECG_Development_ Options > 40 AND ECG_Development_Options < 45 THEN ECG_Atrial_Fibrillations_Development_1 ELSE 0) ELSE 0
Sinus Tachycardia	IF Heart_Rate_Patient_ Condition> 100 THEN (IF ECG_Development_ Options < 30 AND ECG_Development_Options > 26 THEN ECG_Sinustachycardia_ Development_3 ELSE	IF ECG_Development_ Options > 30 AND ECG_Development_Options < 37 THEN ECG_Sinustachycardia_Development_1 ELSE	IF ECG_Development_ Options > 40 AND ECG_Development_Options < 45 THEN ECG_Sinustachycardia_Development_2 ELSE 0) ELSE 0
Atrial Flutter	IF Heart_Rate_Patient_ Condition> 100 AND Age_Of_Patient > 50 THEN (IF ECG_Development_ Options < 30 AND ECG_Development_Options > 26 THEN ECG_Atrial_Flutter_Development_3 ELSE	IF ECG_Development_ Options > 30 AND ECG_Development_Options < 37 THEN ECG_Atrial_Flutter_Development_1 ELSE	IF ECG_Development_ Options > 40 AND ECG_Development_Options < 45 THEN ECG_Atrial_Flutter_Development_2 ELSE 0) ELSE 0
SA- Block	IF Heart_Rate_Patient_ Condition<50 THEN (IF ECG_Development_ Options <1.4 THEN ECG_SA_Block_Development_2 ELSE	IF ECG_Development_ Options >1.4 AND ECG_Development_Options < 5 THEN ECG_SA_Block_Development_3 ELSE	IF ECG_Development_ Options > 6 AND ECG_Development_Options < 10 THEN ECG_SA_Block_Development_1 ELSE 0) ELSE 0
Ventricular Fibrillation	(IF ECG_Development_ Options < 30 AND ECG_Development_Options > 26 THEN ECG_Ventricular_Fibrillation_Development_2 ELSE	IF ECG_Development_ Options > 30 AND ECG_Development_Options < 37 THEN ECG_Ventricular_Fibrillation_Development_1 ELSE	IF ECG_Development_ Options > 40 AND ECG_Development_Options < 45 THEN ECG_Ventricular_Fibrillation_Development_3 ELSE 0)
Right Bundle Branch Block	(IF ECG_Development_ Options <1.4 THEN ECG_Right_Bundle_Branch_Block_Development _1 ELSE	IF ECG_Development_ Options >1.4 AND ECG_Development_Options < 2.4 THEN ECG_Right_Bundle_Branc	IF ECG_Development_ Options > 2.4 AND ECG_Development_Options < 4 THEN ECG_Right_Bundle_Branc

		h_Block_Development_2 ELSE	h_Block_Development_3 ELSE 0)
Left Bundle Branch Block	(IF ECG_Development_ Options <1.4 THEN ECG_Left_Bundle_Bran ch_Block_1 ELSE	IF ECG_Development_ Options >1.4 AND ECG_Development_Option s < 2.4 THEN ECG_Left_Bundle_Branch_ Block_2 ELSE	IF ECG_Development_ Options > 2.4 AND ECG_Development_Option s < 7 THEN ECG_Left_Bundle_Branch_ Block_3 ELSE 0)
Extra Systole VES	(IF ECG_Development_ Options < 30 AND ECG_Development_Opti ons > 26 THEN ECGr_Extra_Systole_V ES_Development_1 ELSE	IF ECG_Development_ Options > 30 AND ECG_Development_Option s < 37 THEN ECG_Extra_Systole_VES_ Development_2 ELSE	IF ECG_Development_ Options > 40 AND ECG_Development_Option s < 45 THEN ECG_Extra_Systole_VES_ Development_3 ELSE 0)
AV-Block III	(IF ECG_Development_ Options < 50 AND ECG_Development_Opti ons > 40 THEN ECG_AV_Block_III_Dev elopment_2 ELSE	IF ECG_Development_ Options > 23 AND ECG_Development_Option s < 35 THEN ECG_AV_Block_III_Develo pment_1 ELSE	IF ECG_Development_ Options > 0 AND ECG_Development_Option s < 10 THEN ECG_AV_Block_III_Develo pment_3 ELSE 0)
AV-Block II Type 2	(IF ECG_Development_ Options < 50 AND ECG_Development_Opti ons > 45 THEN ECG_AV_Block_II_Mobi tz_Type_1_Developmen t_1 ELSE	IF ECG_Development_ Options > 23 AND ECG_Development_Option s < 35 THEN ECG_AV_Block_II_Mobitz_ Type_1_Development_2 ELSE	IF ECG_Development_ Options > 0 AND ECG_Development_Option s < 10 THEN ECG_AV_Block_II_Mobitz_ Type_1_Development_3 ELSE 0)
AV-Block II Type 1	(IF ECG_Development_ Options < 50 AND ECG_Development_Opti ons > 45 THEN ECG_AV_Block_II_Mobi tz_Type_2_Developmen t_1 ELSE	IF ECG_Development_ Options > 23 AND ECG_Development_Option s < 35 THEN ECG_AV_Block_II_Mobitz_ Type_2_Development_2 ELSE	IF ECG_Development_ Options > 0 AND ECG_Development_Option s < 10 THEN ECG_AV_Block_II_Mobitz_ Type_2_Development_3 ELSE 0)