Performance Improvement of ED at VGH Using Simulation and Optimization

By

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Abstract

Emergency department(ED) is one of the busiest clinical units in Winnipeg Victoria General Hospital (VGH) which faces the challenge of patients' long waiting-time as increasing healthcare demand and limited resources. This research investigates the critical factors of the ED operation to enhance the operational efficiency using simulation modeling and optimization. The contribution of this research is the integration of simulation and optimization for the performance improvement of ED operations. Discrete-events simulation (DES) methodology provides a cost-effective tool to analyse the performance of the ED operations and evaluates the potential alternatives. Design of experiments (DOE) and Scatter search (SS) of model optimization are proposed to search the ED potential capacity for waiting-time reduction. The patient-flow is accelerated along with the waiting-time reduction, which results in better efficient patient throughput in the ED. A specific strategy is suggested to improve the ED operation based on the simulation model.

Acknowledgments

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List of Abbreviations

ABSM: Agent-based Modeling and Simulation

CTAS: Canadian Triage and Acuity Scale

Cycle T&L: Cycle Times and the Patient Acuity Level

DES: Discrete-event Simulation

DOE: Design of Experiments

ED: Emergency Department

ER: Emergency Room

ERH: Emergency Room Holding

GA: Genetic Algorithm

LOS: Length of Stay

MTA: Minor Treatment Area

OR: Operations Research

PA: Physician Assistant

PD: Pending Discharge

QA: Queuing Analytic

RefSet: Reference Set

SD: System Dynamics

SS: Scatter Search

SOGH: Seven Oaks General Hospital

TBADM: To be Admitted

TIP: Treatment in Progress

TSG: Trail Solution Generator

VGH: Victoria General Hospital

V&V: Model Verification and Validation

WTBS: Waiting to Be Seen

WRHA: Winnipeg Regional Health Authority

Chapter 1

Introduction

1.1 Thesis Background

Healthcare systems today face challenges such as increasing operation cost, a shortage of qualified medical staff, and limited hospital facilities. The imbalance between limited healthcare resources and increasing demands is a possible reason leading to overcrowding that becomes a common phenomenon in many units of a hospital. The overcrowding in emergency departments (EDs) contributes to waiting-time increasing which causes patients' dissatisfaction and can even put a patient's life at risk. Winnipeg Regional Health Authority (WRHA) started a project in 2011 to investigate patient flows of the emergency department to design possible alternatives for performance improvement. Based on the understanding of the current ED operation, the potential bottlenecks are identified in this research. Feasible solutions are then proposed to improve efficiency for the current ED operation.

1.2 Research Objective

This research investigates possible ways to improve the performance of the ED at Victoria General Hospital (VGH), Winnipeg, MB. The objective of this research is to develop potential methods to reduce patients' waiting-time and further enhance the efficiency of the ED operation. To effectively analyse the ED performance and effects of ED improvement methods, the ED patient-flow is represented by a simulation model. Selection of a proper simulation method is the initial step of model development. It also requires clear understanding of the ED operation. Since ED is a complex system with many factors to affect the performance, identifying factors for the significant impact of the waiting-time will reveal problems and bottlenecks of daily ED operations. The optimal combination of selected factors changing will maximize the positive effect of waiting-time reduction. The developed methods and suggested solutions will be verified in a simulation model using the optimization evaluation to match conditions of the ED operation.

1.3 Thesis Overview

The thesis consists of three parts. One is the performance analysis of the ED operation based on a designed baseline. The second part is simulation modeling for the target system. The last part is the performance evaluation and model optimization. An alternative is proposed based on the current ED condition to reduce patients' waiting-time in this part. The thesis structure is organized as follows:

Chapter 1 introduces the thesis background and research objectives. Chapter 2 is a literature review for simulation and related analysis methods. Chapter 3 describes the patient flow in the ED of VGH, and functions of the related treatment units. The critical factors of the target system are discussed for developing the model. Chapter 4 compares the performance of VGH with Seven Oaks General Hospital (SOGH) in order to identify the delay location among the general treatment procedures. Chapter 5 illustrates general procedures of the model development, and shows the details applied in the ED modeling for the data analysing and converting, simulation modeling, and model testing. As one of the most important parts of model development, the method of model verification and validation is introduced in this chapter. Chapter 6 introduces using design of experiments (DOE) methods to identify the treatment procedure with the significant impact for the patient waiting-time. To minimize patients' waiting-time, the optimal combination of the available reduction ranges of the treatment procedures is identified by using scatter search (SS), a model optimization method. A modified improvement strategy for waiting-time reduction is introduced in Chapter 7, the solution is evaluated using the built model. Chapter 8 concludes this research and suggests further work.

Chapter 2

Literature Review

Emergency Department (ED) overcrowding has become a significant public healthcare problem (Fatovich 2005). The main reason is that available ED resources cannot meet the increasing healthcare demand. Simulation technology has been widely applied in many fields such as management, control engineering and industrial engineering. In the last decade, the publication about using simulation in the healthcare has been dramatically increased (Günal 2010). Combined with operations research (OR), simulation technology provides healthcare administrators a method to make the decision-making using proper strategy to enhance the system performance (Niu 2009). Representing system operation using a simulation model is the initial phase of OR application. Simulation modeling is an important tool for understanding resource allocation and utilization, as well as estimating the current and proposed system workflows (Barrick 2009). Considering that not all decision variables are of equal importance, sensitivity analysis is necessary for the simulation model to select variables which have the maximum effects for the system performance (Montevechi 2012). Design of Experiments (DOE) is one of the sensitivity analysis methods, which can be used to determine the significance of the resources of system's behaviour. Changing the values of critical factors identified by DOE method is to select the optimum combination which has the most positive effect to enhance system performance. It makes DOE application usually cooperate with the model optimization method to identify the optimum combination.

2.1 Simulation Approaches

There are mainly three simulation approaches that can be selected for the healthcare system modeling: discrete-event simulation (DES), system dynamics (SD), and agent-based simulation modeling (ABSM) (Borshchev 2004). Both of discrete-event simulation and system dynamics are the traditional ways for target system modeling. DES is an essential tool designed for system optimization at a medium level. On the other hand, SD is a strategic tool to represent the system's behaviour at a much higher description level (Brailsford 2010). In contrast, ABSM methodology is used at a very detailed level to understand the impact of human factor in system operation (Borshchev 2004).

In the discrete-event simulation (DES) model, the entities are described as passive objectives (Borshchev 2004). These objectives are driven by the conceptual model description which is gathered from the target system. The simulation approach of DES provides a flexible way to investigate the interaction between entities and related characteristics selected from the target system. The challenge of DES application is that the model development is based on massive exercises of data collection.

System Dynamics (SD) model is represented by differential equations. This mathematical model consists of several state variables and various algebraic equations with the appropriate numerical inputs (Borshchev 2004). The integrated variables represent the actual components of the target system such as location, pressure, concentration, etc. The qualitative aspect of SD makes the simulation modeling enable to cast light on the unintended consequences of actions (Brailsford 2008). SD model can run very fast because it does not require multiple replications. However, SD has the potential risk to mislead the conclusion caused by ignoring system stochasticity.

Agent-based modeling and simulation (ABMS) is a relatively new approach using autonomous, and interacting agents (Macal 2008).It does not have universal agreement on the definition of the term “agent”, but the essential capacity of an agent is to make independent decisions (Jennings 2000). Unlike purely passive components, agents should be able to response the external requests and even make simple plan in the system.

2.2 Design of Experiment (DOE)

One research study used simulation modeling implanted with DOE method to improve the performance of a sawmill in Chile (Baesler 2004). The bottleneck analysis indicates that the procedure of wood extractions has the most important individual effect which should be considered seriously in the process of alternatives design. DOE can also be integrated with the simulation model to understand detailed operations and system interaction in the industrial field. As an example of a steelmaking workshop, the decision making parameters were defined as the number of machine and operators (Azadeh 2006). A complete 3^k factorial design was used to estimate effects of four fixed factors in this case. The research result indicates that the number of blast furnaces have the significant impact on the response variable.

Although DOE is recognized as an initial phase of alternative design and is being widely applied in manufacturing modeling, there are few research publications using it for healthcare simulation modeling. There is one used DOE to serve the increasing healthcare demand. The method was proposed to investigate the potential capacity for an ED in Chile (Baesler 2003). The research results of the system study were obtained based on the operation of the DES model. The author indicated that the ED could serve the demand increasing 30% as well as maintaining treatment time in the acceptable range. Here the design of experiments was applied to determine the minimum number of human and physical resources required to meet treatment demand.

2.3 Model Optimization

The optimum search of factors' combination brings additional complication because the performance of a particular system cannot be estimated comprehensively using a single replication (Banks 2005). The determination of a better solution requires experimentation with multiple replications or long-time model running to reduce noisy of model output. Exploring a few but important alternatives is an effective searching strategy to identify optimal ones in limited time, which makes the simulation optimization recognized as one of the most significant aspects of simulation technology development (Wurbs 1993).

DES method in this research is selected for ED modeling. As lacking optimization functions in DES (Law 2002), DES modeling always implants an add-on package of simulation optimization to meet optimal demand. The simulation optimization here can be defined as a process to test various combinations of controllable variables in the target system. The aim is to identify the combination which provides the most desirable output results for simulation models (Harrell 1992).

The classical approaches of deterministic optimization include: gradient search, random search, and math programming adaption. However, these approaches are not available to be implanted in the DES model for optimum identification. Meta-heuristics is a popular method of solving complex optimization problems in the DES model, which guides the searching process to avoid trapping by local optimality (Gendreau 2010). It is an iterative generation process to guide exploring and exploiting in the search space, the learning strategies of subordinate heuristic are used to structure information to find efficiently near-optimal solutions (Osman 1996).

2.4 Summary

This chapter reviews potential methods for the ED model development, system factors and model optimization. Simulation model can be used to represent dynamic characteristics of healthcare systems for the various patient treatment strategies (Brailsford 2007). In order to analyze the impact of the system factors, design of experiments (DOE) method can be used to estimate the factor significances. Model optimization based on OR methodology can be applied to accelerate the searching process of the optimal configuration. Reasons of the method selection and related applications will be introduced in following chapters.

Chapter 3

ED System Description

Victoria General Hospital（VGH）is a 231 bed community hospital located in south Winnipeg. There are more than 1,200 staff and 350 volunteers working in the hospital for healthcare services to thousands of Manitobans each year. To better understand the ED system operation, the first impression was obtained through a close observation for three weeks. The flowchart of a patient pathway is simplified from the actual treatment process. The function of each ED treatment unit is concluded from the conversation with the medical staff and the close observation of their daily work.

3.1 ED Treatment Units

The ED layout is shown in Figure 3-1**,** which mainly contains five distinct zones with specific functions: Registration and Triage Area, Resuscitation Area, Monitor Area and

Treatment Area, Minor Treatment Area (MTA), and Reassessment Area. The function of these care areas and related terminologies are illustrated in the following sections. Since the ED is sharing the examination room with other departments, the places for laboratory tests (X-Ray, blood test, and scanners.) are not shown in the layout.

Figure 3-1: ED Layout

Registration & Triage Area: Registration Area is the first place facing arrival patients. Patient's information and conditions are gathered in this area. Patients are brought to the triage area to be assed for their acuity level. The purpose of triage is to prioritize the medical care for incoming patients based on the severity of their conditions. Multiple patients are sorted into several categories through the triage process. It greatly enhances the survival opportunity for patients requiring emergency care. The triage process is also responsible to decide which medical care area is suitable for patients identifying where patients will receive further assessment and treatment.

Resuscitation Area: Resuscitation Area is a key area of ED to provide immediate medical care for the patient with life threatening condition. An arrival patient of Resuscitation Area should receive emergent treatment preferentially. The operation of Resuscitation Area usually requires one physician and two nurses. Once a patient arrives, one physician will stop his current work to see the patient. At the same time, two nurses will come to help from Monitor Area.

Monitor Area & Treatment Area: Monitor Area and Treatment Area compose the main Emergency Room (ER) where most patients receive treatment. The equipment of Monitor Area provides real-time reports for the patient requiring close observation. For other ER arrivals, the patients will be moved to the Treatment Area.

Minor Treatment Area (MTA): MTA is the place providing a fast-track treatment for less injured patients. It is performed by a nurse practitioner who works together with a nurse. The patients in this area are non-critical patients who do not need the long-time medical care.

Reassessment Area: Reassessment Area is also called “Observation Area” or “Holding Area”. The function of this area is taking care of patients who have received the necessary treatment from other care areas. In some cases, patients cannot be discharged home or admitted immediately. The common motivation making patients stay here is because the patients can be discharged only if their conditions have been verified safe. It means some patients will have a long-time observation. On the other hand, an admitted patient has to stay here waiting for available stretcher in the transfer direction.

3.2 Patient Flow Description

Based on the information obtained from the charge nurse, physician and other medical staff involved in the care process, a flow chart was constructed to represent a general patient pathway. The developed flow chart describes patients crossing three phases: Triage, Distribution Location Decision and Treatment Throughout. The traditional flow chart of patient flow contains input, throughput, and output. To contain more detail information, the flow chart of ED patient flow at VGH is drawn as Figure 3-2 showing. The patient flow begins at a patient entering the ED and ends at a patient who is either discharged or admitted into the hospital. Starting from this flowchart, patients arrived by ambulance are ambulance patients, the others are recognized as walk-in patients who arrive by themselves. The “Acuity Level Identification” and “Distribution Location Deciding” are the two main steps that patients pass through before they enter the Emergency Room (ER) to receive treatment.

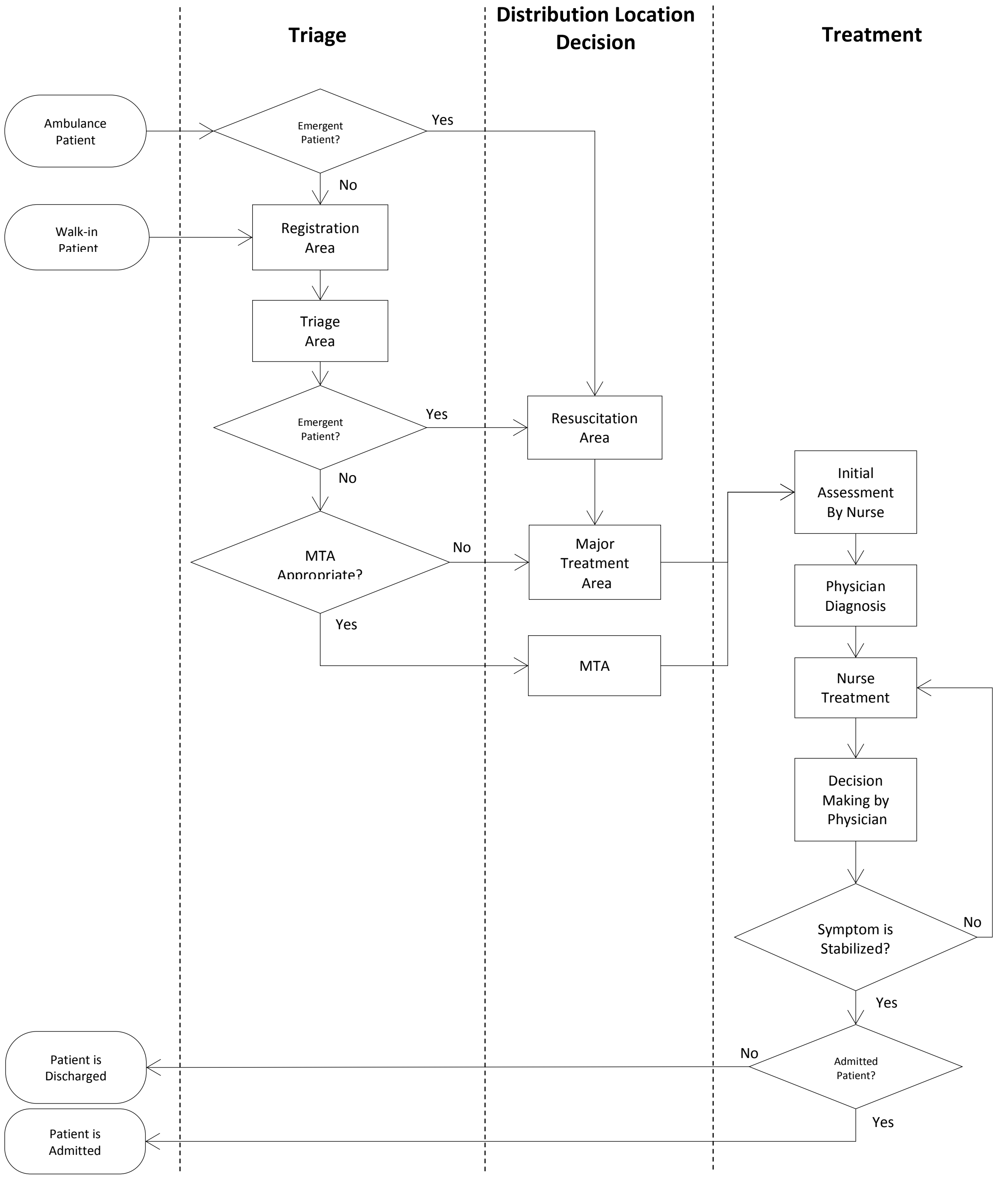

Figure 3-2: Flowchart of Patient Pathway

3.2.1 Triage

In the procedure of acuity level identification, the information of walk-in patient is gathered by a registration clerk in Registration Area. Then the patients are seen by a triage nurse to decide their CTAS levels through the triage assessment. CTAS is the abbreviation of "Canadian Triage and Acuity Scale". To represent the acuity of incoming patients, EDs in different countries use the similar strategies to sort patients based on the severity condition. The Canadian Healthcare service uses the CTAS level to represent patients' acuity levels. Depending on several criteria, patients are assigned one of CTAS levels from 1 to 5 in the triage process. CTAS 5 is the least acuity level and CTAS 1 means real emergency which is threatening patient's life. The arrival of patients by ambulance may bypass the processes of registration and triage, because it can be done on the way to the hospital. The ambulance patient with life threatening will be sent to the Resuscitation Area immediately; the others will wait in a special area for entering ER.

3.2.2 Treatment Location Decision

Triage nurses also assign eligible patients to proper treatment locations. Each patient is assigned to a room with stretcher where the patient will receive completed treatment. The patient who needs emergency treatment will be brought into Resuscitation Area. Patients who are seriously ill but without life threatening will be sent to Monitor Area or Treatment. Non-critical patients will be moved to MTA (Minor Treatment Area) where they will have the quick treatment mainly by a nurse practitioner.

3.2.3 Treatment Throughput

The process of medical care includes several treatment procedures to make sure the patient can safely leave the ED. The treatment services in emergency room are mainly provided by nurses and physicians. When a patient lies in a stretcher, the nurse on duty in the corresponding area will come for the initial assessment first. Based on the gathered information, physician in the initial diagnosis decides whether the further test (like X-rays or Blood test) is required, or immediate treatment should take place. Nurses will follow the physician to do the lab test and treatment decision. The physician will go back to check the result and give the further treatment direction. This recycling process keeps operating until the patient reaches the stabilized condition. Then most patients will be discharged home. Some of acuity patients may stay at the ED for a while to have further observation. It may take time to decide whether a patient can be released or admitted.

Based on the understanding of the ED operation process, following Chapter discusses the ED performance analysis.

Chapter 4

Patient Flow Analysis

For the performance analysis of ED operation, the WTBS (waiting to be seen) is always used as a measurement to reflect the operation efficiency (Duguay 2007). However, there is no clearly measurement to show the efficiency of treatment steps. For this reason, a concept called "benchmarking" is implanted into the research. The result indicates the potential bottleneck location of the treatment process. The data obtained from Seven Oaks General Hospital (SOGH) are used as baseline for comparison. Here patients' condition is marked by several statuses along with the treatment progress including: Treatment in Progress (TIP), Emergency Room Holding (ERH), Pending Discharge (PD), and To Be Admitted (TBADM). These treatment statuses are recognized as general treatment procedures in a simplified case. To identify the bottleneck of the ED operation in Victoria General Hospital (VGH), the performance of each treatment procedure is analyzed individually.

4.1 Treatment Process Simplification

As the ED is a complex system, the first work of this research is to capture important factors in the patient treatment process. It is necessary to represent the ED using a general simplified process. To monitor patients' conditions in the ED, an individual patient is marked by several statuses along with the treatment progress (Figure 4-1).These statuses are recognized as general treatment procedures for an individual patient in this research.

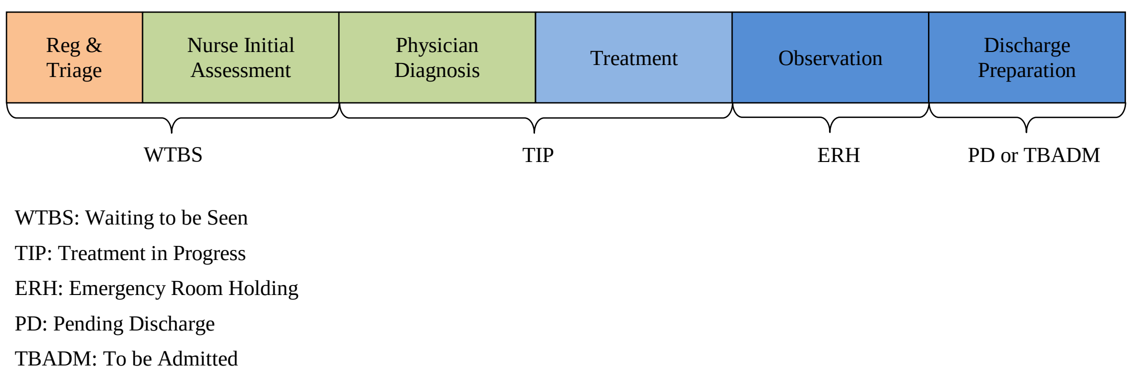

Figure 4-1: Treatment Timeline

WTBS (Waiting to be Seen) starts status recording when a patient enters Registration Area, and ends recording when the patient is seen by a physician. This status represents the time that a patient waits for physician diagnosis, in addition to the triage time and the time of the initial assessment.

The status of a patient receiving emergency treatment is defined as Treatment in Progress (TIP). The physician diagnosis and following medical cares mainly take place in this period. Patient will not enter the next step until the necessary treatment has done. The actual treatment procedures of the TIP process are in a loop process rather than linear steps (Figure 4-2). Once the initial assessment and physician diagnosis have completed, nurses follow the physician's decision in the following treatment such as lab tests. The physician later checks the result for the further process. This recycling process keeps operating until a patient reaches the stabilized condition. Then the patient will enter the next phase of treatment. Some of acuity patients may stay at the ED for a while to have further observation in the Emergency Room Holding (ERH) process. PD and TBADM represent the period that the patient cannot be discharged due to the transfer delay.

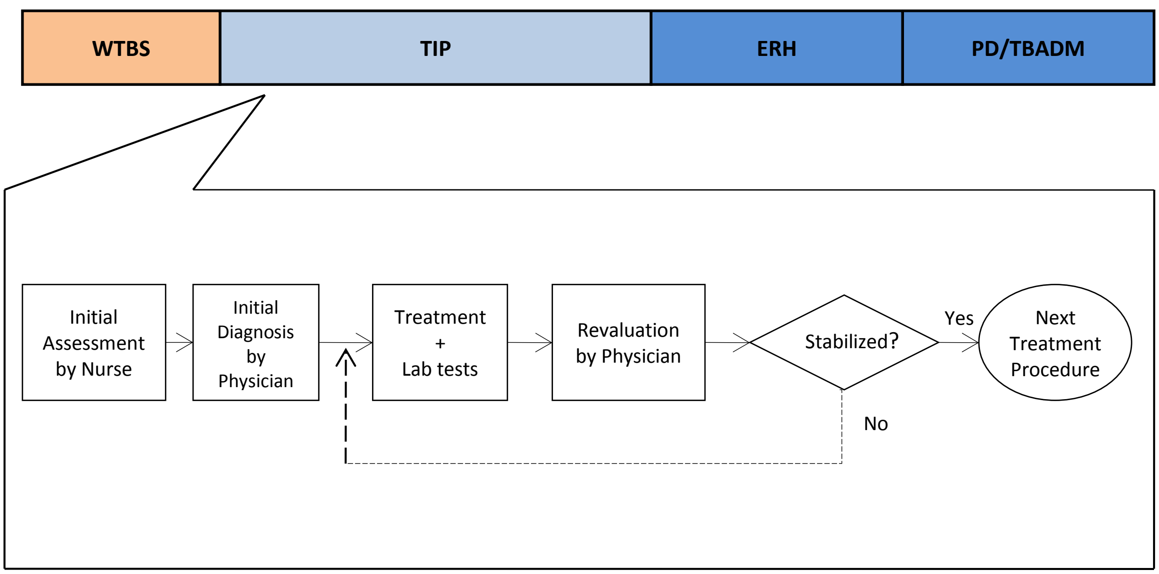

Figure 4-2: Flow Chart of TIP Process

Some patents may need to stay in the ED for a while to check if their conditions are stabilized. Before a patient is discharged home, it is necessary to confirm that the patient is safe, which is especially important for elderly patients. The potential risk caused by undetected disease is minimized through the ERH process. Additionally, the order of patient admission is not only determined by a physician, a special team will check the patient's condition to confirm physician's admission order.

The terms of "To Be Admitted (TBADM)" and "Pending Discharge (PD)" are used to describe the discharge disposition. TBADM describes the status that holding admitted patients in ED due to transfer inability. Admitted patients have to stay in ED waiting for available bed in the transfer direction. It still requires basically medical care while patient's waiting, although emergency treatment has been completed. PD represents the status that patients stay in the ED when the discharged order has been submitted. It does not last very long for ordinary patients to change cloth or clean up. But the elderly patient may take much more time to wait for picking up home.

4.2 Benchmarking Application

The concept of "Benchmarking" was firstly applied in the industrial field, it is a method for comparing the performance of a target organization to the "best-in-class organization" (APICS Dictionary 1998). The application of benchmarking mainly contains three steps (Amold 2011): 1) select factors to benchmark; 2) identify an organization with the "best-in-class" performance of studying process; 3) understand differences between target organization and benchmark organization to find potential bottleneck for improvement.

For the comparison, the ED of Seven Oaks General Hospital (SOGH) is selected as a baseline. ED in SOGH has the better performance in the local hospital, which provides emergency medicine with the second busiest Emergency Department. The comparison of arrival patients is shown in Figure 4-3. The ratios of the arrival patient in the age range of 20-70 (74% of arrival patients) are similar. The SOGH ED has the similar training backgrounds of hired medical staff with the VGH ED. The actual treatment time in the two EDs is similar, which does not affect patients' Length of Stay (LOS).

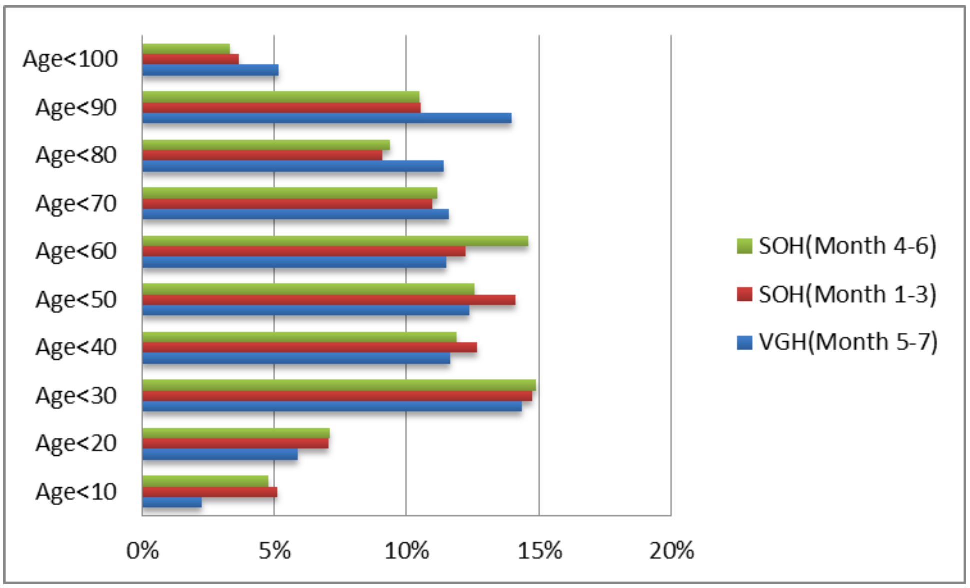

Figure 4-3: Patient Constitution Comparison

4.3 Treatment Procedure Comparison

To identify potential bottlenecks in the treatment process, the comparison of each treatment procedure is analyzed individually. Since WTBS is the result of medical resource limitation, it can be used as a measurement to represent the efficiency of ED operations. Although the layout is different between the two EDs that causes arrival patients spend different waiting-time to enter Emergency Room (ER), this factor does not influence the process-time of following treatment procedures. As TIP, ERH, PD and TBADM are treatment procedures after a patient is assigned a stretcher, comparisons of the statuses of TIP, ERH, TBADM and PD are representative

The TIP comparison in Figure 4-4 clearly shows that the TIP process-time increases gradually for the elderly patient's treatment. Since ED treatment can be recognized as a cycling process which consists of several treatment cycles, the delay is accumulated along with cycle times increasing, which enlarges the process-time of TIP in Figure 4-5. It explains that the slope of the TIP process-time is more sharp along with patient age increasing, because elderly patients often require longer process-time, which means more cycle times as well as more delay accumulated.

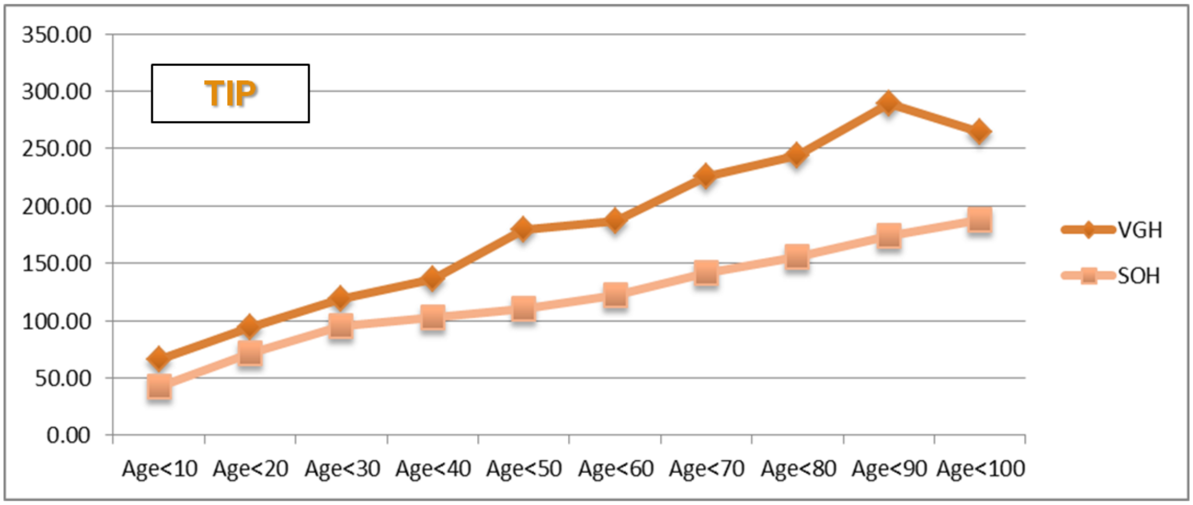

Figure 4-4: TIP Comparison

Unlike the stable ERH time in SOGH, the ERH time increases dramatically for the patients older than 40 in VGH (Figure 4-5). The gradient of ERH time increasing is similar with that of the total process-time in VGH. It means the ERH status in VGH contains some critical factors affecting the efficiency of patient flow. For the ED itself, status comparison clearly shows that the delay in the period of ERH (Emergency Room Holding) is the main reason that leads to process-time increasing sharply in VGH.

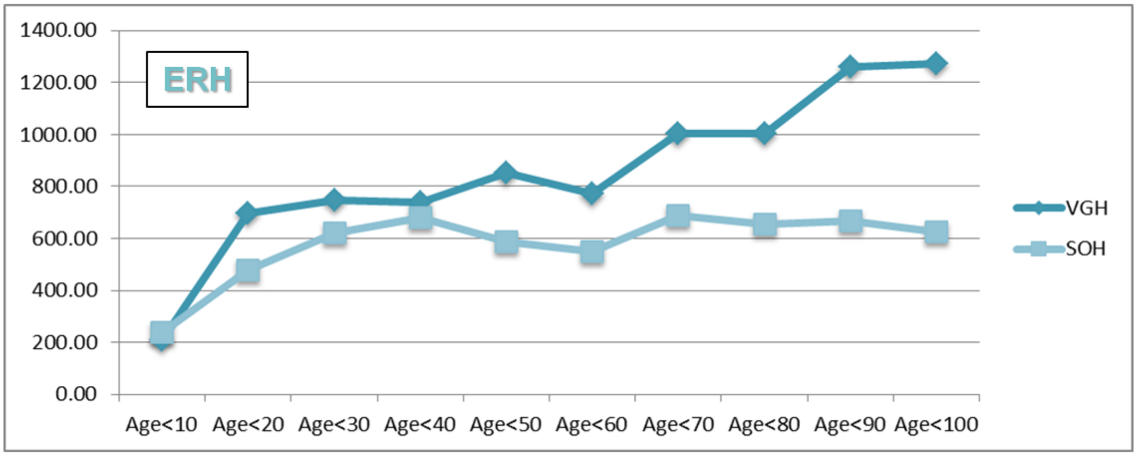

Figure 4-5: ERH Comparison

Transfer delay for the admitted patients is always recognized as a main problem that enlarges patient's stay-time in the ED. It is a common problem existed in both of VGH and SOGH. Although the TBADM range in VGH is larger than that of SOGH, the comparison (Figure 4-6) still indicates that the transfer delay is not a main reason resulted in the tendency of process-time becoming sharp in VGH. Admitted patients in VGH do not take much time waiting for available bed compared to the TBADM baseline.

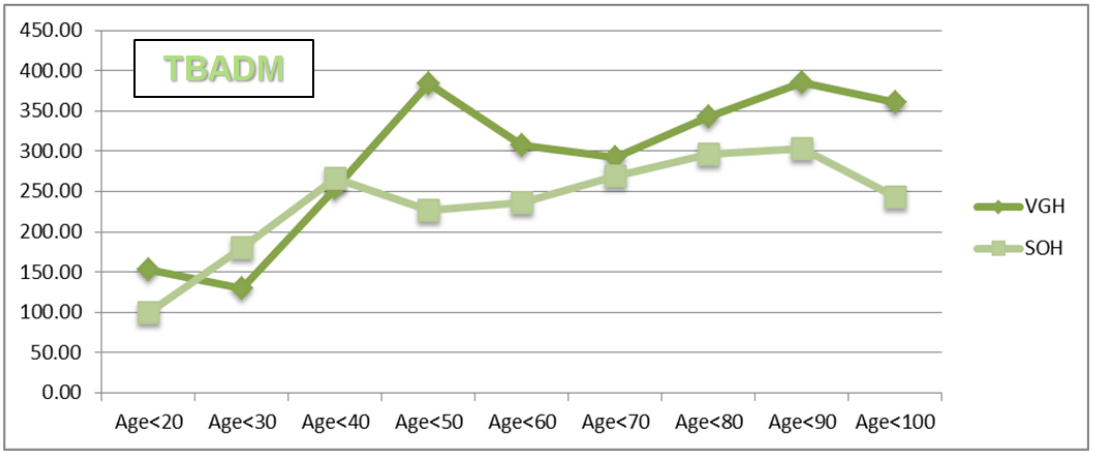

Figure 4-6: TBADM Comparison

The PD time of VGH is significant larger than that of SOGH as shown in Figure 4-7. It is not just for a particular age group of arrival patients, but also covers every age region. Although the delay in the PD period is obvious, it does not have much influence for the total treatment time because the ratio of PD time is very low compared to the process-time of the other treatment procedures.

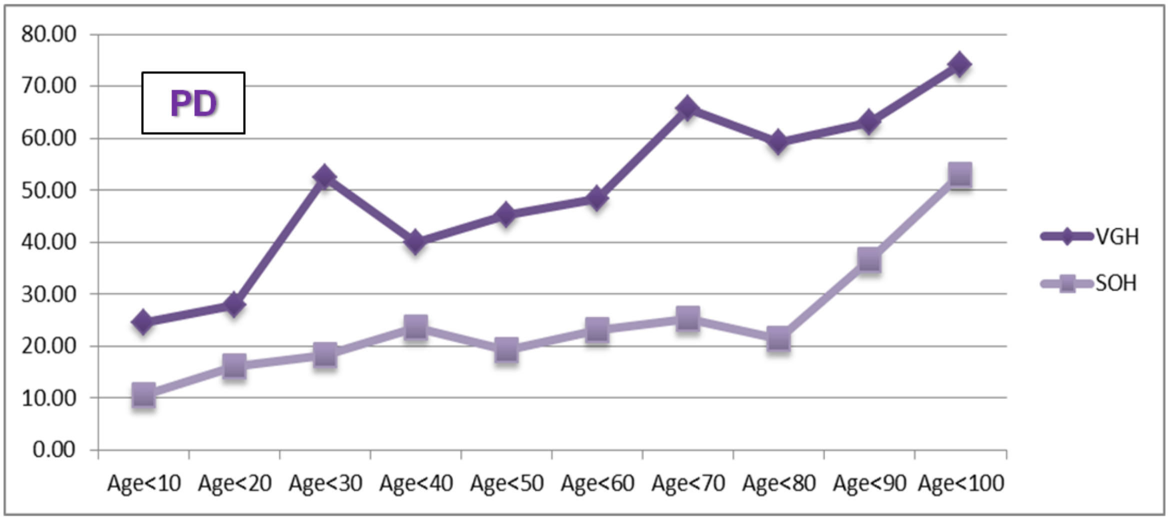

Figure 4-7: PD Comparison

4.4 Discussion

The TIP procedure is the process that patient receives emergency treatment. The simple alternatives for time saving are hard to apply because the treatment strategies are difference depending on patients' symptoms.

Emergency Department is one of the few hospital units opening for 24-hours, it has the interaction with other departments which only open in the daytime typically (from 8:00AM to 4:00PM). Some ED arrivals have to wait for available medical care from other departments. For example, if a patient requires consult from other department but arrives at night, the patient has to stay in the ED for the whole night. It is because the consult doctor works only in the daytime shift. The similar condition is that the team for evaluating ERH patients also works in the daytime.

Transfer delay is another reason that affects the efficiency of ED patient flow. It causes unnecessary stay-time in addition to the required treatment time. It causes that the admitted patient has to stay in the ED even the necessary treatment has done. The reason is that there is no available stretcher in their transferred departments. In this case, the patient will still occupy ED resources. For this reason, the delay in TBADM can be recognized as a functional problem of ED operation. This problem is not caused by improper treatment procedures. Capacity strain of the inpatient unit is the main reason makes admitted patients be blocked in the ED. The improved efforts in this part require systematic thinking to take both of ED and inpatient units under consideration.

The reason for the longer process-time of PD is that patients cannot be discharged immediately. Some elderly patients need picking up home because they are too weak to go by themselves. The other possibility is caused by improper recording in the database of VGH. Through observing the ED operation in VGH, the discharged time is not always recorded in time when the patient left ED.

4.5 Summary

The comparison result indicates that the delay in TIP process accumulates along with the treatment time increasing. Long ERH time in VGH is the main reason enlarges patients' Length of Stay (LOS). Although the discharge delay exists in the PD procedure, it is not the main reason that enlarges the patient stay-time. It is because that the ratio of PD time is very low in the total treatment time. TBADM is always considered as a main reason which blocks the patient flow, but the TBADM comparison shows that the delay in TBADM is a common problem existing in both of the hospitals. It means the delay in the TBADM period is hard to avoid. Benchmarking method is used to analyse the performance differences between VGH and SOGH. The initial performance analysis is to establish a basic understanding about the ED performance of VGH. The research for the impact of each treatment procedures will be introduced in the chapter of DOE (Design of Experiments) application.

Chapter 5

Simulation Modeling

Simulation provides an experimental environment to evaluate the performance of a target system. The ability of tracking the element performance makes the simulation be a proper tool to investigate the daily operation of the Emergency Department (ED). The simulation feedbacks are used to identify problems in the patient flow.

5.1 Simulation Application in Healthcare

Simulation has been widely used in the healthcare field for the performance improvement which mainly involves: hospital scheduling and organization, infection and communicable disease investigation, and costs of illness and economic evaluation (Günal 2010). Depending on research objectives, appropriate simulation approach can be chosen to represent the behaviour of a target healthcare system.

The Discrete-event Simulation (DES) application for the healthcare system modeling has been rapidly growing in the past decades (Komashie 2008). Since hospital is a system with complexity activities, the attempt of whole hospital modeling is rare (Fone 2003). The most effective way is to simulate one part of the hospital, like emergency room, clinic and operating theatre. As one of the busiest units of a hospital, ED modeling is an important part of the simulation applications in the healthcare field. Ferrin (2007) demonstrates a DES model used to increase ED throughput in the USA. The DES model also can be used to estimate the impact of key resources (Komashie 2005).

System Dynamics (SD) modeling has been successfully applied for the disease epidemiology study such as heart failure (Homer 2004). It is also used for the research about the patient flow in emergency and extended care. For example, mathematical programming approach was used to schedule doctors in the emergency room (Beaylieu 2000). Implanted with operations research, SD model could reveal the optical allocation of healthcare resources by using linear programming (Flessa 2000). Queuing analytic (QA) theory is referred to solve many hospital problems related to releasing overcrowd of patient flow. The queuing analytic model consists of a set of queuing formulas to describe the conflicts between the healthcare demand and service. The form of closed mathematical formulas makes that the queuing analytic model can be recognized as one kind of SD model. Here the most widely used queuing model is specified as M/M/s type (Hall 1990). It can be used to solve hospital problems through calculating needed medical staffs, stretchers and operating rooms.

The capability of modeling human behaviours makes Agent-based Modeling and Simulation (ABSM) fit the requirements to predict disease spread (Miller 2012). Taking a mode of flu spreading as an example, the pre-decided rules govern the agent (the people in the model) interaction in the simulated environment (O'NEIL 2010). The healthy people behaviour will change when the disease happens. A susceptible agent may potentially become infected decided by the probability of infection parameter, when he/she contacts with an infectious patient. All the events of agent's behaviour occurring are controlled by the probability.

5.2 Simulation Method Selection

There is a question for the queuing analytic theory of SD modeling in the application of some healthcare problems (Kolker 2008). Kolker mentioned that the pre-condition of the queue analytic application requires the flow of events in the system with a steady-state Poisson processes. The model requires several assumptions for applying the queue analytic theory, which results in queuing formulas invalid in some healthcare processes (Koler 2012).The other trend is to apply ABSM in the ED simulation. Agent-based modeling provides insight into the behaviour without offering a complete representation of the behaviour (Heath 2009). For this reason, the agent-based method becomes an appealing approach to evaluate the ED performance in recent years. However, there is still at the phase of rhetorical analysis because several challenges have not been solved. Due to the complex patient constitution and uncertainty, hardly understanding the whole ED operation is always the first problem that the model developer meets. In this research, the discrete-event simulation (DES) is chosen to build the ED simulation model. DES is an appropriate tool to learn the complexity of the system and designing valid model for training and decision-making (Duguay 2007). It has been proved as an effective tool for process improvement (Khurma 2008).

5.3 General Procedures of Model Development

General procedures of model development are shown in Figure 5-1. The objective of modeling is the ED performance evaluation and improvement for the utilization of medical resources and the process time of patients' treatment. The conceptual model is abstracted from the operation of the target system. For the healthcare system, a conceptual model represents the pathway of patient flows in the treatment process. Data analysis provides the foundation of model developing. Gathered data are converted into the form of distribution functions for the simulation modeling. Some characteristics of the system operation are revealed at this step. In this research, the model of the ED model is built using the simulation software called Flexsim. With a 3D interface, the software shows the model operating from multi-views to track the performance of each element in the simulation. The developed model requires verification and validation before the application. Verification process makes sure that the model operation follows the flowchart of the conceptual model. The chart of the patient flow in the ED is confirmed by medical staffs. The validation process tests if the simulation model represents the reality. Only the verified and validated model can be used as an experimental environment for the solution research of the ED improvement.

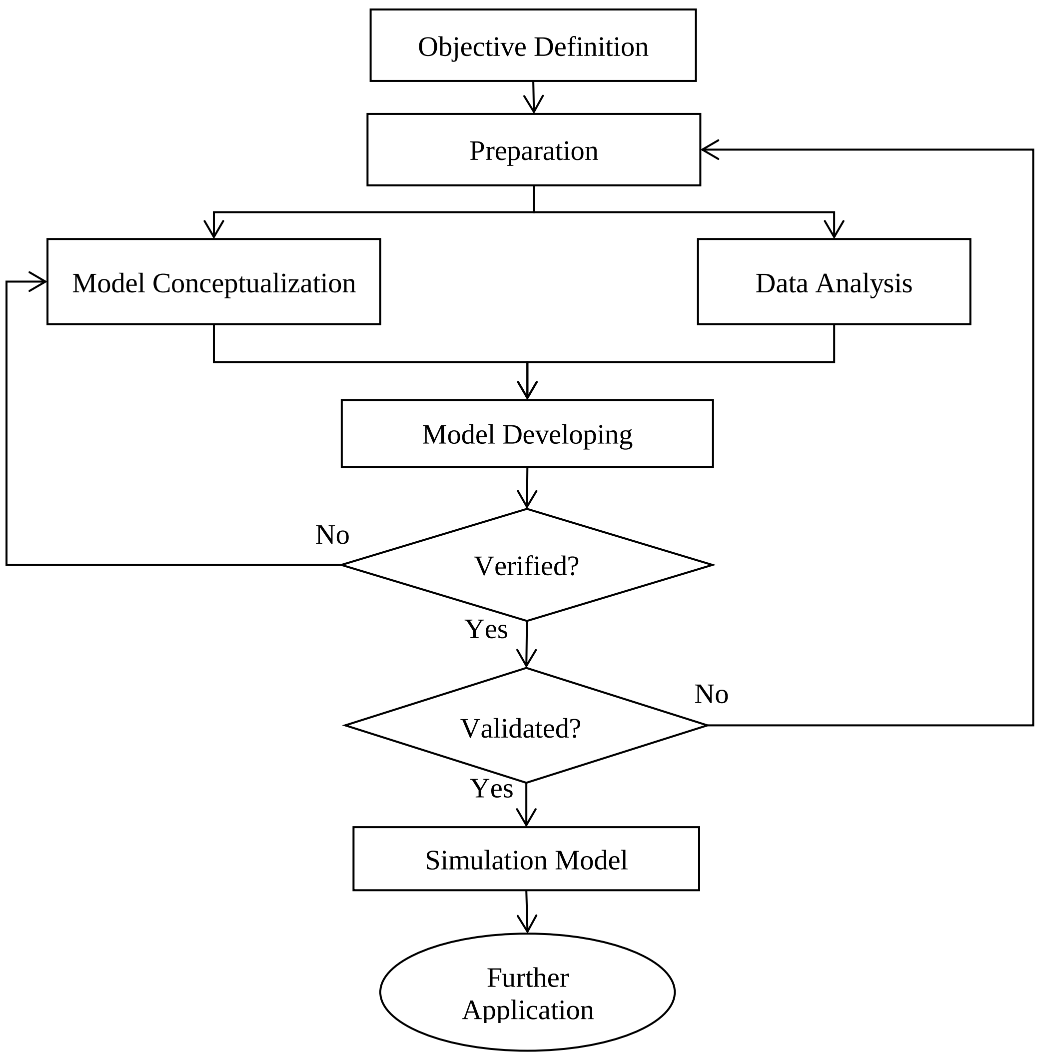

Figure 5-1: Model Development Procedures

5.4 Data Analysis

5.4.1 Arrival Pattern

Patients' arrival pattern is for the arrival tendency representation in the simulation model. Depending on the way that patients enter the ED, the arrival patients are classified into two categories: ambulance patients (18%) and walk-in patients (82%). Expect patients arrival with ambulance, all the other patients are recognized as walk-in patients. Patterns of the two arrival modes are different. Figure 5-2 shows the proportion of the hourly arrival patients in a 24-hour period. The fluctuation of walk-in patients reaches its peak at 10 am, and keeps at high level from 10 am to 8 pm, then the level of arrival frequency reduces gradually at night. The ambulance arrivals do not have much fluctuation in a day like walk-in patients do.

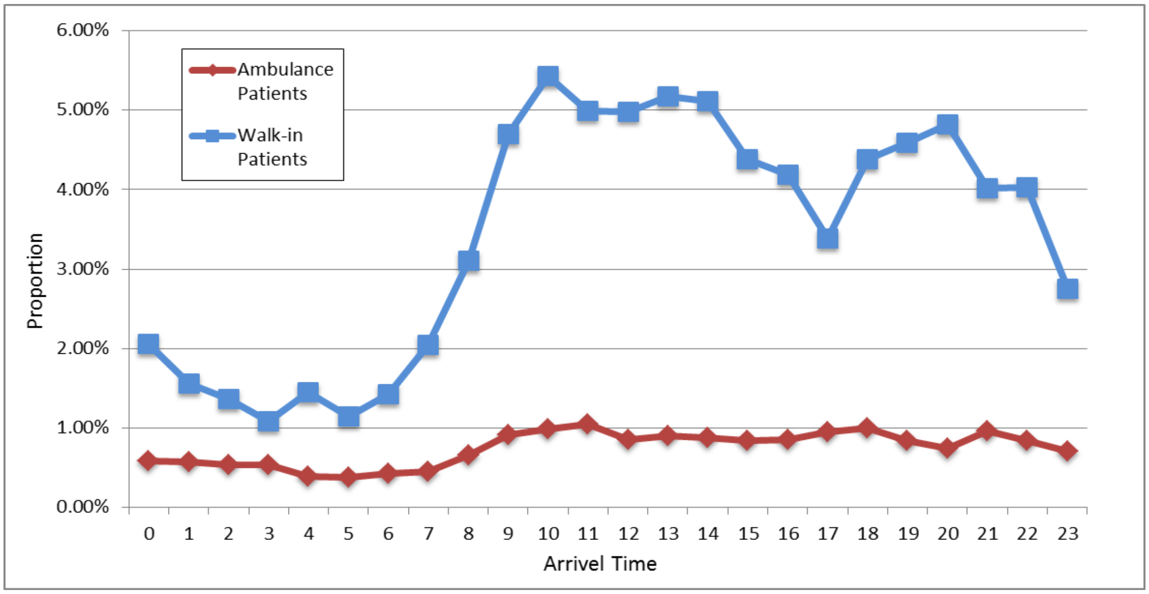

Figure 5-2: Patient Arrival Pattern of a 24h Period

The arrival pattern of each month is repeatable and consistent through analyzing three month data. It means that monthly changing is not a critical factor affecting the patient arrival pattern. Also there is no obvious variation of the CTAS constitution along with the daily changing. The proportion of five CTAS levels fluctuates in a small range of a seven-day period. It can be assumed that the patient arrival is stable in the simulation model. Based on the data diverted from the ED database, the acuity level of arrival patients is dispatched as: 0.94% of CTAS 1, 12.38% of CTAS 2, 30.25% of CTAS 3, 43.35% of CTAS 4, 11.86% of CTAS5 and 1.22% patients marked as “UNKNOWN”.

5.4.2 Patient Distribution

The patient distribution of 7,884 patients in the 3-month study period is shown in Figure 5-3. The ratio of CTAS levels is correlated with the treatment locations. In the table, the constitution of the patients in Resuscitation Area contains a big part of CTAS 1 and CTAS 2patients.On the other hand, most patients with lower acuity level (mainly CTAS 4 and CTAS 5) are brought to MTA. In some cases, patients were placed in MTA due to the lack of available stretchers in other care areas. Only patients specially labelled as “MTA Appropriate” of the ED database are recognized as true MTA patients shown in the figure. The locations with small distribution proportions (less than 2%) are omitted for simplicity.

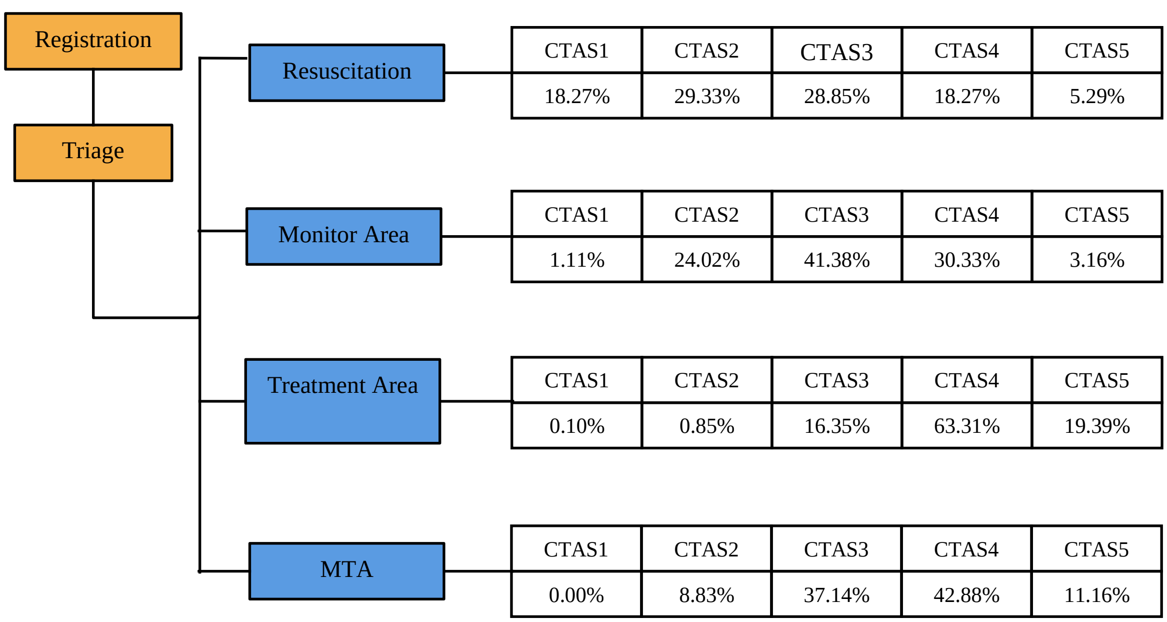

Figure 5-3: Patient Distribution

5.4.3 Process-time of Treatment

The treatment units of Resuscitation Area, Monitor Area and Treatment Area provide the treatment service for the major part of arrival patients (66%). The patients marked as "MTA appropriate" mean they are minor injured to require a quick treatment process. The statistical result shows that the major patients always spend more time in ED compared with MTA patients (Figure 5-4). Nearly 75% of the MTA patients spent less than 250 minutes staying in the ED for treatment, only 35% of the major patients' treatment time is less than that number. Representations of the treatment procedures for the major patients and MTA patients are therefore be considered separately in model developing.

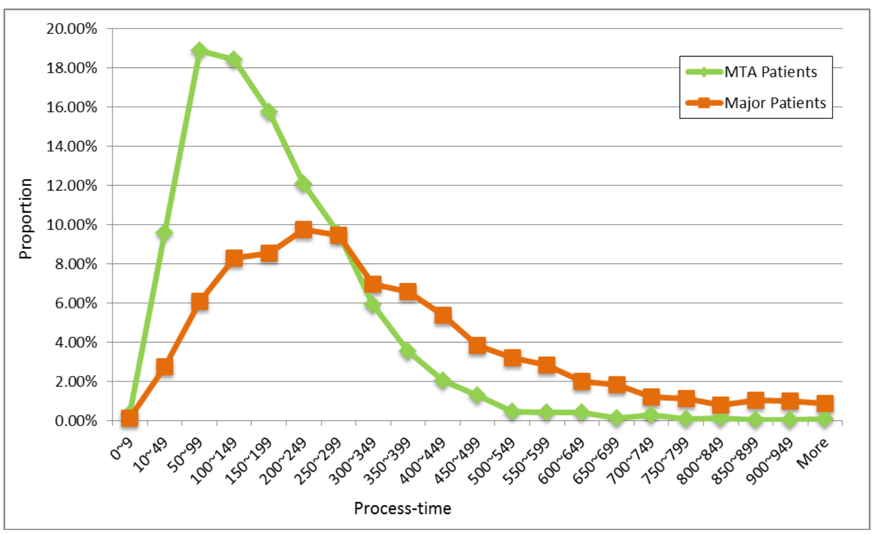

Figure 5-4: Total Process-time Comparison between Major Patients and MTA Patients

5.4.4 Relationship between Age and Process-time

As an important element of patient information, patient age is associated with patients' stay length. Figure 5-5 shows that the treatment time of older patients often takes more time. The treatment for elderly patients requires not only emergency treatment but also long-time observation to minimize risks caused by chronic disease. It is a complex process with the serious care to make sure that elderly patients are safe to be discharged. Additionally, the comparison of SOGH patients in different seasons indicates that the arrival patients' age is repeatable, which is not affected by the seasonal changing. Analyzing one seasonal period data is able to represent the fact of ED operation.

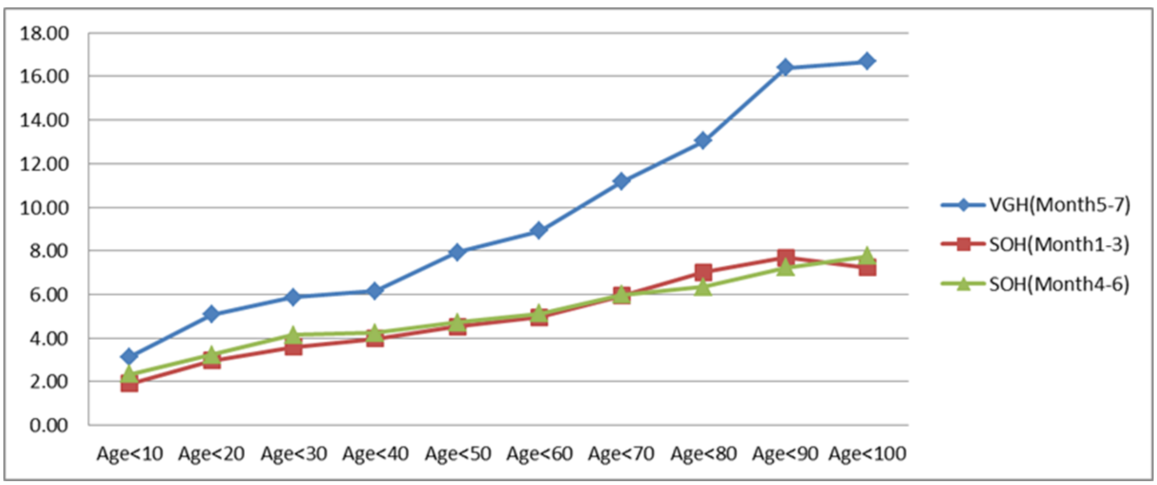

Figure 5-5: Stay Length Comparison (Hour)

5.5 Modeling Preparation

The model is used to mainly simulate three aspects of the ED system (Figure 5-6): patients data, the treatment procedures of individual patient, and the process-time of each treatment procedure. The data define the identification of patients in the model. The treatment procedures and corresponding process-time of the patients are decided based on these data. The treatment procedures are simplified into four steps based on the treatment status of the gathered data. The type of required treatment procedures for an individual patient depends on the pre-determined probabilities. Patients' process-time in the treatment procedures is generated from the corresponding distribution functions. The distribution functions are converted from the statistical results of the real data.

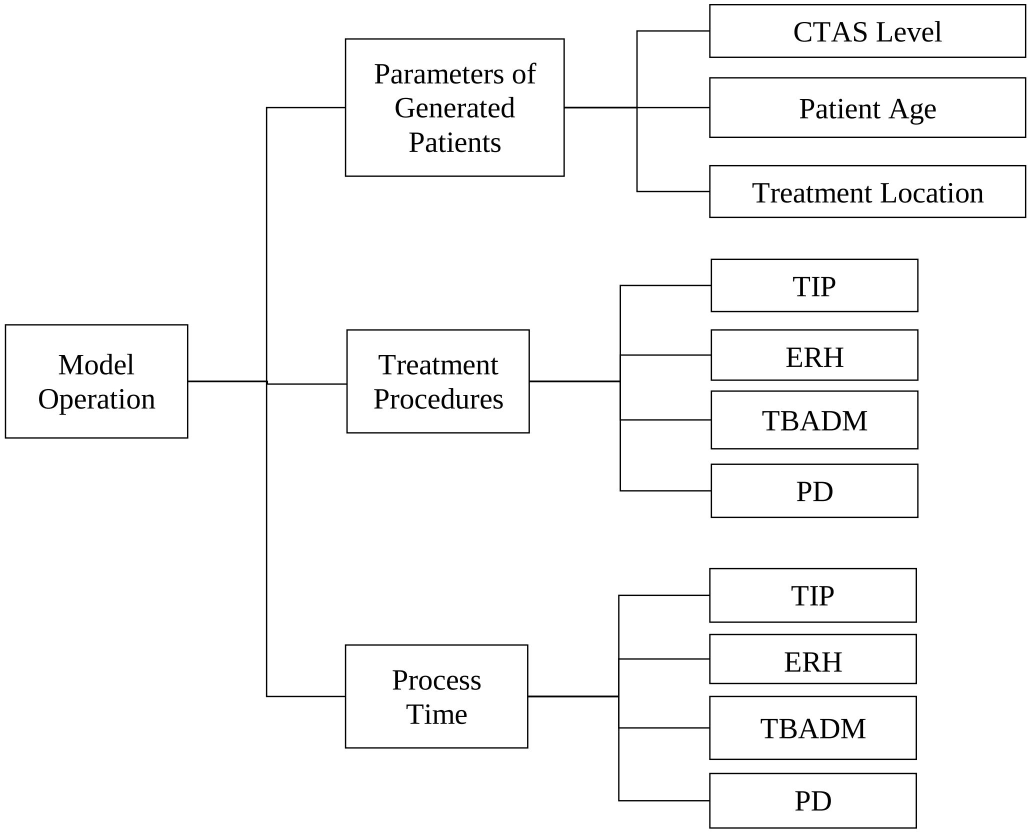

Figure 5-6: Required Data for Model Operation

The ED model belongs to a non-terminating system, the model keeps running until the pre-determined criteria are reached. The discrete data in the database have to be converted into distribution functions to provide random data for the model operating. To guarantee the accuracy, an analysis tool in the simulation software is used to generate distribution functions based on the gathered data. The parameter definition of the generated distribution functions is listed in Table 9-1 of Appendix A. Figure 5-7 is a sample of the graphic comparison between gathered data and the generated distribution functions. The horizontal axis of the blue histogram lists the cell range of the data and data bins; the vertical axis represents the proportion of each data set. The red curve of the generated distribution function fits the blue histogram of the real data.

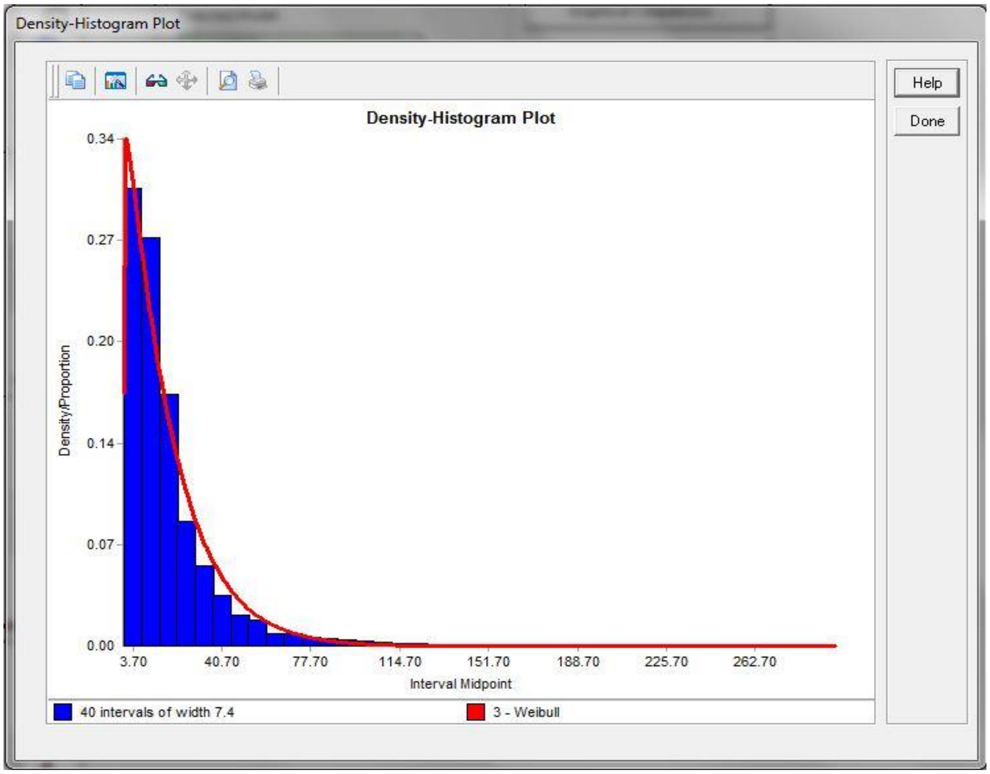

Figure 5-7: Distribution Function Generated from Discrete Data

5.5.1 Arrival Frequency Representation

To represent the frequency of arrival patients in a 24h period, a concept of inter-arrival time is implanted in the process of model developing. The inter-arrival time is time between consecutive patients arriving at the ED. For example, assuming that the arrival time of the first patient is 12:15, and the consecutive patient arrives at 12:32. The inter-arrival time between these two patients is 17 min. Since the arrival frequency of walk-in patient fluctuates significantly in the 24h period, the walk-in arrivals in the 24h period are separated into 12 parts to represent the fluctuation of arrivals in the model. The time duration of each individual part is 2 hours (Figure 5-8).The inter-arrival time of ambulance patients is recognized as an entirety, which is generated from one distribution function. The corresponding distribution functions are shown in Table 9-2 of Appendix A.

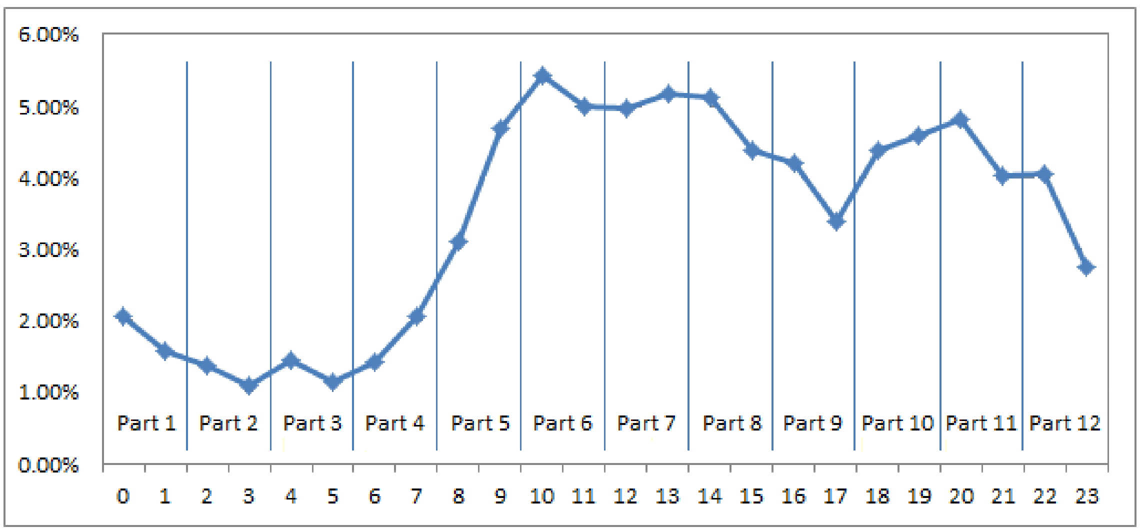

Figure 5-8: Representing the Arrival Frequency of Walk-in Patients with 12 durations

5.5.2 Patient Parameter Setting

Through analyzing the gathered data and closely observing the ED operation, the treatment time and required procedures are associated with three parameters: patient's CTAS level, treatment location, and the patient age. Table 5-1 lists functions of theses parameters in the treatment process. The CTAS level is decided based on patient's symptoms in the triage process. CTAS 1 means the patient is in the highest acuity condition, with the priority to enter the ER immediately. CTAS 5 is the least acuity level, which means the patients are safe to wait longer time. On the other hand, the different treatment locations in ED can provide a proper medical service for specific treatment requirement. For example, the reason why some patients are bought to the Monitor Area is that the equipment here can show patients' condition in real-time; and MTA provides a quick treatment for patients marked as "MTA appropriate". Therefore the treatment location is an important parameter for the definition of patients. The last parameter is patient's age. It has been verified that patient's age is associated with the process-time of each treatment status in the previous discussion.

Parameter	Function
CTAS Level	Representing patient's acuity level, which is associated with the priority of entering the ED.
Treatment Location	Providing proper treatment environment for patients with differently medical requirements.
Patient Age	The process-time of treatment is correlated with patient's age; elderly patients always require more complex medical service and process-time.

Table 5-1: Patient Basic Parameters

To represent these parameters in the simulation model, the first challenge is to decide the relationship among these parameters to set them one by one along with the model running. The sequence of parameter setting follows three steps shown in Figure 5-9:

Step 1: Setting the constitution of CTAS levels separately for patients with different arrival modes.

Step 2: Setting the distribution of patients' ages which is decided by both of arrival modes and CTAS levels.

Step 3: Setting the treatment location for the patient distribution, which is associated with patient age and the CTAS level.

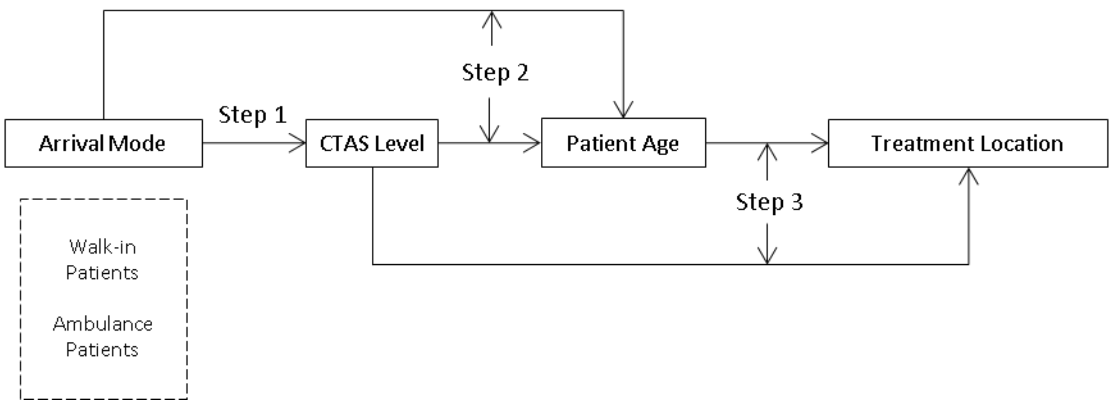

Figure 5-9: Sequence of Parameter Setting

CTAS is an isolated parameter only associate with the arrival mode, it is decided firstly. The CTAS level influences the sequence of ER entering in the simulation model, higher CTAS level means that the patient has the priority to enter the ER. Depending on the way that patients arrive at the ED, arrival modes of patients are classified into two arrival modes: walk-in, or arrived with ambulance. Since the ambulance is for patients with serious illness or patients without the ability to come, the rates of CTAS 1 and CTAS 2 are higher than that of walk-in patients. Patients' number at each CTAS level is set separately for two different arrival modes (Table 5-2).

	Walk-in Patient	Ambulance Patient
CTAS 1	0.46%	3.13%
CTAS 2	10.56%	20.74%
CTAS 3	30.16%	37.50%
CTAS 4	44.98%	35.87%
CTAS 5	13.84%	2.77%
Total	100.00%	100.00%

Table 5-2: CTAS Rates of Two Arrival Modes

The age distribution in the model is decided by both of arrival mode and CTAS level. Since the probability of getting serious illness is increasing along with the age growth, the rate of elderly patients is at a high level of patients with acuity conditions. Hence there are more elderly patients with CTAS 1 or CTAS 2 levels compared to the other patients such as young or adult patients. Moving inability of elderly patients makes them generally require ambulance transfer to arrive the ED. The age setting also considers two arrival modes. Table 5-3 is the part of the matrix for the age distribution, the full table of the age distribution is shown in Table 9-3 in Appendix A.

Walk-in Patients					
	CTAS 1	CTAS 2	CTAS 3	CTAS 4	CTAS 5
Age 0~9	10.00%	2.63%	3.17%	7.21%	8.26%
Age 10~19	0.00%	5.12%	7.32%	12.46%	11.05%
Age 20~29	6.67%	14.91%	18.54%	20.32%	19.20%
Age 30~39	6.67%	14.47%	12.95%	14.07%	13.39%
Age 40~49	6.67%	17.25%	13.16%	12.98%	14.73%
Age 50~59	10.00%	15.06%	12.39%	10.54%	11.38%
Age 60~69	20.00%	12.13%	11.47%	8.10%	9.15%
Age 70~79	30.00%	8.77%	10.19%	6.69%	6.58%
Age 80~89	10.00%	8.19%	8.29%	5.77%	4.58%
Age 90~100+	0.00%	1.46%	2.51%	1.85%	1.67%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

Table 5-3: The Sample of Age Distribution

Both of the patient age and CTAS level influence the transfer direction of the treatment locations. For patients with different CTAS levels, they are further classified into 4 age categories: Category 1 (age 0~ 9), Category 2 (age 10~49), Category 3 (age 50~79), and Category 4 (80~100). The probability of the patient distribution is shown in Table 5-4. A full table is shown in Table 9-4 in Appendix A.

CTAS 1				
	Age Category 1	Age Category 2	Age Category 3	Age Category 4
Resuscitation Area	33.33%	52.63%	52.38%	40.00%
Monitor Area	66.67%	36.84%	40.48%	50.00%
Treatment Area	0.00%	5.26%	2.38%	0.00%
MTA	0.00%	5.26%	4.76%	10.00%
Total	100.00%	100.00%	100.00%	100.00%

Table 5-4: The Sample of Location Distribution

5.5.3 ERH, PD and TBADM Probabilities

The treatment procedures in the model are decided based on the statistical result of the gathered data. Table 5-5 lists the deciding criteria for the probability calculation. The statistical analysis shows that the patient marked as "MTA appropriate" barely requires ERH and TBADM service. Most patients are set with a probability to require ERH and TBADM. The calculation of PD probability includes major patients and MTA patients. The elderly patients always require an ERH evaluation. ERH tests patient's safety for discharging home or admission. The age growth makes elderly patients easily get serious illness; their admission probability is higher than other patients. Admission probability is represented by the status of TBADM in the model. As elderly patients always require picking up home, the factor of patient age also affects the PD probability. The related probability matrixes are shown in Table 9-5 and Table 9-6 in Appendix A.

	Deciding Condition
ERH Probability	Depending on patient age (Non MTA patients)
TBADM Probability	Depending on patient age (Non MTA patients)
PD Probability	Depending on patient age (Non admitted patients)

Table 5-5: Deciding Condition of ERH, TBADM, and PD

5.5.4 Process-time Representation

Process-time Representation (TIP)

To represent this cycling process in the model, many research publications have been reviewed. However, there are barely papers noticed this case in the research. The only paper found is the one published in 2011; the author investigated the relationship between the cycle times and the patient acuity level (Weng 2011). Table 5-6 is the research result, which is used in my model to represent the treatment in the TIP procedure. The service time involves the treatment time of one cycle time and the related lab tests. In the Table, 23% of CTAS2 patients requires one cycle of lab tests and treatment. 49% of CTAS 2 patients need to have two cycles of the treatment which may contain further lab tests. The required cycle number is decided following the same logic for patients in different CTAS levels. The distribution function of physician diagnosis is Triangle (4,12,8), and the distribution function of nurse assessment is Exponential (0,5). In Table 5-6, Exp is the abbreviation of exponential distribution which is a non-negative continuous probability distribution in form of exp (α, β). Here α is a location parameter, and β is a scale parameter. The exp (0,5) means that an exponential distribution with a location of 0 and a scale of 10.

Cycles L&T	Service Time	CTAS 1	CTAS 2	CTAS 3	CTAS 4	CTAS 5
1	Exp(0,80)	15%	23%	32%	50%	50%
2	Exp(0,150)	37%	49%	42%	50%	50%
3	Exp(0,150)	15%	18%	17%	0%	0%
4	Exp(0,170)	11%	7%	6%	0%	0%
5	Exp(0,170)	10%	2%	1%	0%	0%
6	Exp(0,170)	6%	0%	0%	0%	0%
7	Exp(0,170)	5%	0%	0%	0%	0%
Total		100%	100%	100%	100%	100%

*Exp: Exponential distribution

Table 5-6: Lab and Treatment (L&T) Cycles and Distribution of CTAS Levels (Weng 2011)

Process-time Representation (ERH, PD and TBADM)

Formula 5-1 is proposed to calculate the actual process-time for an individual patient in the model. Since the process-time is correlated with patient's age, the formula uses the coefficient called age weight to represent the time difference. The patient's process-time for one treatment procedure is generated by the corresponding distribution function at first (Table 9-7 in Appendix A). Then the model checks the patient's age to multiply the value of the process-time with the corresponding age weight. The age weight is based on the average process-time for the patient in different age groups. Patients are classified into 10 categories depending on their ages. The age category and the type of treatment procedure construct the matrix of the average process-time. The values of Age Category 5 are used as the baseline for the average weight calculation. The average process-time of the other categories is divided by that of Age Category 5 shown in Formula 5-2.The final matrix about the Age Weight is shown in Table 5-7.

$$\text{Actual Process-time} = \text{Distribution Function of Each Procedure} \times \text{Age Weight} \quad (5\text{-}1)$$

$$\text{Age Weight} = \frac{\text{Average Process Time of Each Age Category}}{\text{Average Process Time of Age Category 5}} \quad (5\text{-}2)$$

Age Category	Age Range	ERH	PD	TBADM
1	Age<10	0.25	0.54	0.00
2	Age<20	0.82	0.62	0.40
3	Age<30	0.88	1.16	0.34
4	Age<40	0.87	0.88	0.66
5	Age<50	1.00	1.00	1.00
6	Age<60	0.91	1.07	0.80
7	Age<70	1.18	1.45	0.76
8	Age<80	1.18	1.31	0.89
9	Age<90	1.48	1.39	1.01
10	Age<100	1.50	1.64	0.94

Table 5-7: Age Weight Matrix

5.6 Model Verification and Validation

Model verification and validation (V&V) is the approach to evaluate built model. It investigates if the simulation model accurately represents the reality for the given goals (Kleijnen, 1999). Successful simulation modeling should involve the process of V&V investigation (Rable, 2009). Only the model with certain credibility can be utilized to support the decision making for the target system. It should not progress to the next stage until the model has satisfied the requirements of verification and validation (Sargent, 2010). Verification concerns that if the necessary input parameters and logical structure of the conceptual model are implemented in the simulation model**.** In verification process, the potential errors caused by in-proper code or mathematical analysis are identified and corrected. On the other hand, validation is the process determining the quantified confidence of the model compared to the reality. The aim is to guarantee that the model's accuracy is sufficient for the intended application (AIAA, 1998). Validation is a significant element of any simulation study (Chung, 2003). The confidence of the model's correctness and accuracy increases along with the positive evidences accumulated in the validation process (Law 2009). It should be noticed that the aim of the validation is to make sure the model is sufficient accuracy for the study purpose, but it does not require 100% representation. Simulation model is built to represent the behavior of the real system with the study intent (Centeno, 1998). The validation includes two key concepts: ideally sufficient accuracy and successfully built model for a specific purpose. It concerns the qualified accuracy of a simulation model by comparing the model outcomes with the experimental data gathered from the reality. If the comparison result is in the acceptable range, the simulation model is recognized as having certain predictive ability for the further application; otherwise it requires further work to revise the model for the error identification and elimination.

5.6.1 Model Verification

Model verification is achieved from two aspects: Code Verification and Calculation Verification (Thacker 2004). Here the code verification is to find and remove mistakes in the code-driving model. It makes sure that model operates as the description of the conceptual model. Calculation verification assures the appropriateness of results of the mathematical analysis and corresponding behaviors of the model output (Sargent, 2010). For the ED model, the code verification repeats along with the model development. All the code errors are corrected from the notices of the program editor of the simulation software. The operation logic is verified by tracing the animation of the simulation model to test if it follows the conceptual model. The calculation verification is performed by using sensitivity analysis to study the model responses with input alteration. It tests that if the model's output value changes correspondingly. The verification method modifies the arrival frequency of patients by increasing or decreasing 10%of the interval-arrival time. Results from the input modification are then compared to the real system. The interval-arrival time from the statistical analysis of ED database is used as basis, the amounts of increasing 10% and decreasing 10% is taken to adjust the patient's arrival frequency of entering the ED. The initially arrival frequency generated by the model is compared with that of the reality shown in Figure 5-10.

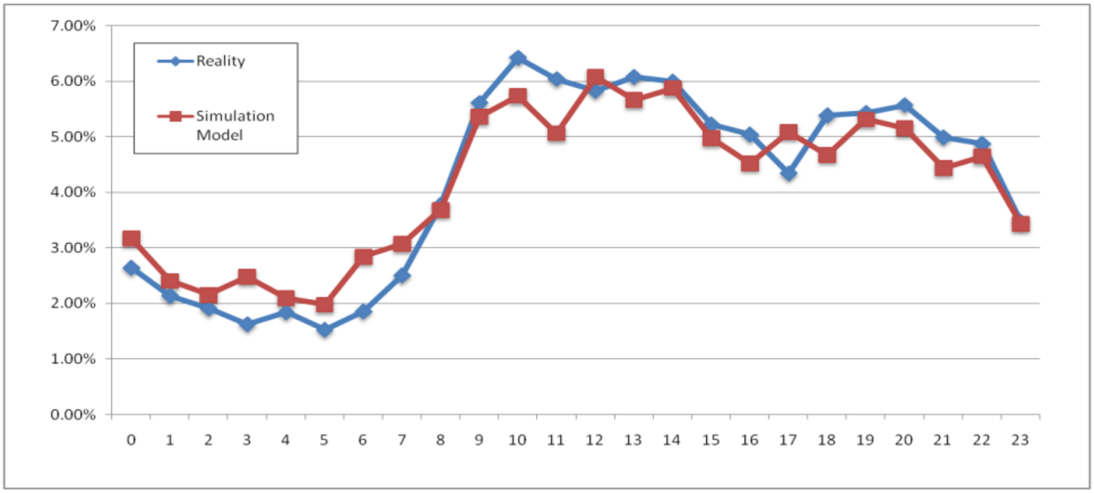

Figure 5-10: Arrival Frequency Comparison

The result of arrival frequency alternation is shown in Table 5-8. It illustrates that the WTBS and throughput are increased along with the arrival rate increasing. The reverse condition happens similarly for arrival rate decreasing.

	Original arrival rate mean (stdev)	90% arrival rate mean (stdev)	110% arrival rate mean (stdev)
Throughput	7593 (82.63)	6884 (81.47)	8482 (81.47)
WTBS	132.78 (68.11)	61.99 (14.74)	525.52 (165.13)
LOS	462.00	385.74 (21.34)	879.28 (281.37)

Table 5-8: Sensitivity Analysis (min)

5.6.2 Model Validation

Steady State Analysis

Simulation model can be classified into two types: terminating model and non-terminating model (it is also called steady-state simulation model). The natural termination time is the inherent character of a terminating system. For example, the model representing a bank system only runs for 8 hours like the reality which opens in the daytime from 8 am to 4 pm. Conversely, non-terminating model has no nature termination time. The model will continuously run if there is no default stop condition. The non-terminating model has no input at the beginning of running. The model requires a warm-up period to reach steady state (Centeno 1998). Since the bias of this initial period will influence the results analysis, the simulation length should sufficiently cover the warm-up period. The data generated during the warm-up period is discarded to get rid of the bias of the simulation.

The ED model belongs to the non-terminating system. Welch's method is a general technique to decide the length of warm-up period (Mahajan 2004). It requires multiple replications to obtain time-series of the output data. Through adjusting the window size, the data of moving average will reach a smooth condition. Initially, the model implements for 10 replications for the necessary data collection. The run-length for each replication is

90 days. In Figure 5-11, the moving average of WTBS reaches a stable condition after the model running for 17 days, and the corresponding window size is 30.

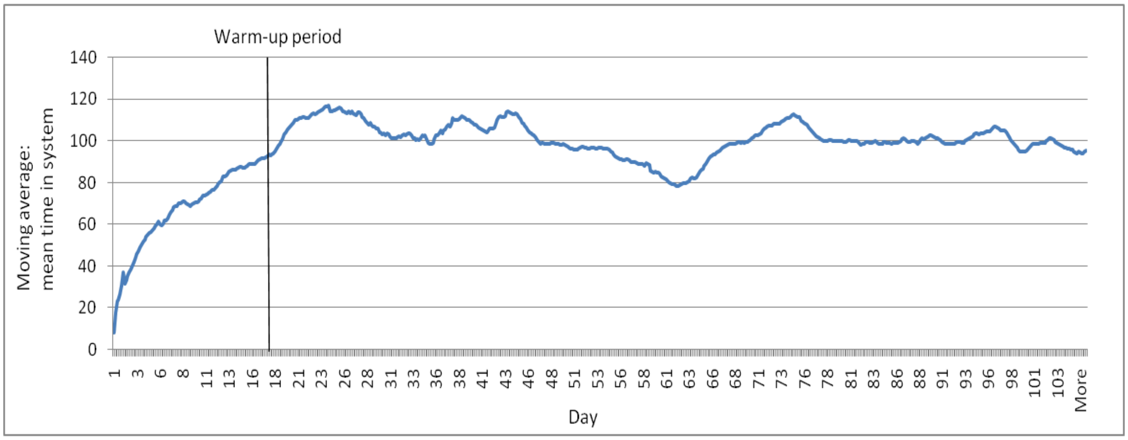

Figure 5-11: Welch's Method: Plot of Moving Average

Data Comparison

Validation process is performed with the modeling phase (Rable, 2009). Black-box validation with statistical analysis is the common validation form for the model test. A typical way concentrates on the patients' average throughput time, hence "the time from arrival to discharge" (Rouohonen 2006). Another alternative approach compares waiting durations of the treatment procedure (Duguay 2007).Thus, the critical variables of WTBS (waiting to be seen) and LOS (length of stay) are chosen to estimate the acuity level of the simulation model.

Confidence Interval indicates the reliability of an estimate in the validation process. It contains a range of values where the mean value is at the center. The 95% confidence level (ą=0.05) is used for the calculation of model output in this research. The model was run for 3 month plus 17 initial days that were deleted as the warm-up period. Thirty replications of model running were performed, and the system was always reset between replications. First two months of data were used for simulation modeling, and the validation was based on the statistical result of the third month data. The comparison results are summarized in Table 5-9. At the 95% of confidence level, it does not have significant difference between the reality and the model.

Waiting to be Seen (WTBS)			
Patient Type	Actual Mean	Simulation Model	
		Mean	Confidence Interval
CTAS 1	50	28.92	[27.30, 30.54]
CTAS 2	116.65	110.59	[91.43, 129.75]
CTAS 3	151.61	154.38	[126.18, 182.59]
CTAS 4	140.56	132.12	[113.51, 150.73]
CTAS 5	122.81	113.26	[98.08, 128.44]
Length of Stay (LOS)			
Patient Type	Actual Mean	Simulation Model	
		Mean	Confidence Interval
CTAS 1	626.58	672.35	[631.20, 713.30]
CTAS 2	653.54	629.07	[599.83, 658.31]
CTAS 3	553.68	563.13	[531.16, 595.10]
CTAS 4	382.90	383.01	[363.26, 402.77]
CTAS 5	216.00	241.52	[226.18, 256.86]

Table 5-9: Comparison based on the Interval Confidence

Since TIP procedure is a cycling process, the TIP process-time is mainly decided by three factors: nurse assessment, physician diagnosis, and actual treatment time. The TIP comparison in Figure 5-12 indicates that the fluctuation of model output and reality are similar. It means the data gathered from published paper (Table 5-6) can be used to represent the TIP process of VGH.

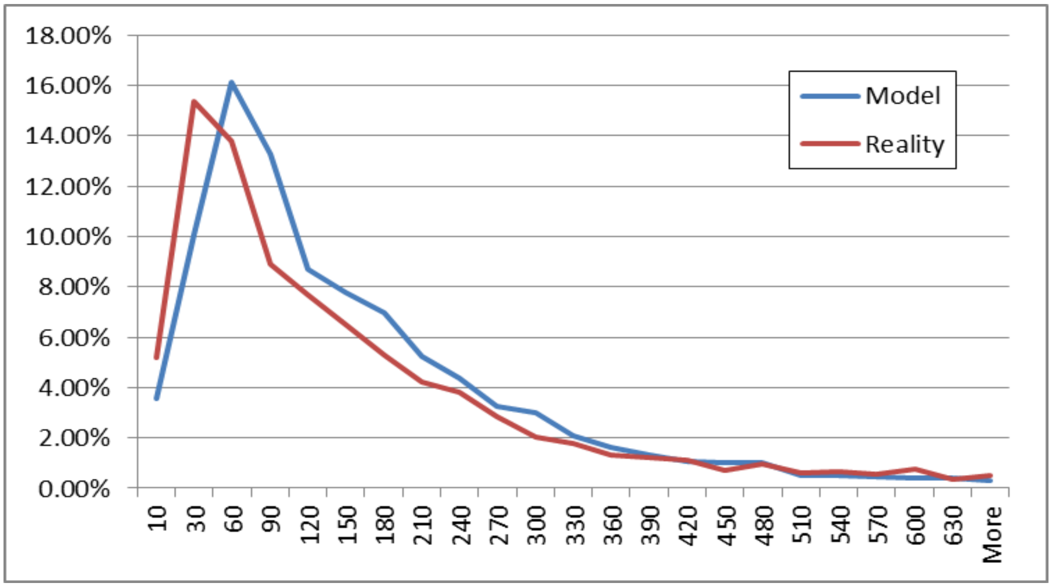

Figure 5-12: TIP Process-time Comparison

In order to illustrate visually, the element of Length of Stay (LOS) in Figure 5-13 is a sample for the comparison between the model and reality. It shows the statistic result of the counted LOS proportions in several time ranges. The model output is gathered from one replication. The comparison indicates that the fluctuation of wave generated from the model approximately matches that of the reality.

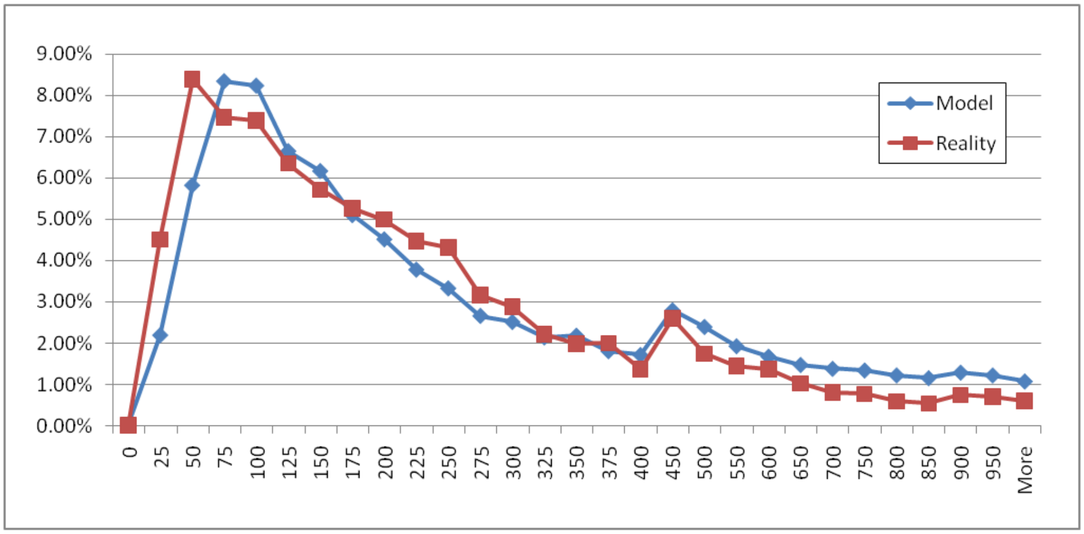

Figure 5-13: LOS in ED Histogram

5.7 Summary

The built simulation model provides an experimental environment for the ED performance analysis. Both of model verification and validation are the necessary steps to determine the model's accurate level to match the reality. Model verification is to determine the model operation following the description of the conceptual model. The validation process investigates if the model has the sufficient accuracy level to represent the target system. As a non-terminating system, the warm-up period of the ED model is set as 17 days. The WTBS and LOS from the model and reality are utilized as the measurements for the validation test. The positive result indicates that the model is accurate sufficiently for the further application.

Chapter 6

Simulation Model Optimization

Simulation is a proper tool to examine "what-if" scenarios for the modification of target systems. Discrete-event simulation (DES) is recognized as an important research technique to support decision-making due to its versatility, flexibility and analysis potential (Jahangirian 2010). The DES model implanted with design of experiment (DOE) analysis reveals the significance of each treatment procedure in the investigation of the waiting-time reduction. However, DOE methodology cannot provide an optimal configuration to maximize the positive effect. It is also hard to simply find a way to reduce the process-time of one treatment procedure for the waiting-time reduction in the reality. The challenge is to look for an optimal solution to minimize the waiting-time. The optimization result will indicate the direction of ED improvement.

Although most commercial simulation software has integrated optimization package based on meta-heuristic optimization search techniques, customized search strategy can accelerate the process for a particular case of the model optimization. In this research, a meta-heuristic method of model optimization is proposed to investigate the potential capacity of the Emergency Department (ED) at Victoria General Hospital (VGH). With the precondition of maintaining certain utilization level of treatment areas, the research result indicates the optimal and realizable time-saving range of treatment procedures to minimize waiting-time

6.1 Literature Review

6.1.1 Design of Experiments (DOE)

Design of experiments (DOE) is a method of systematically applying statistics to experimentation (Lye 2005), which is used to identify factors with the significant impact for design alternatives. A traditional application is to understand the factor impacts from the analysis of response variables, which is realized by factor screening and characterization.

DOE is a technique that has been applied for many years in the field of engineering and manufacturing for the quality improvement. The initial application could date back to 1975 (Bisgaard 1992). One of the initial introductions about the combination between the computer simulation and design of experiments (DOE) was published in 1984 (Smith 1984). The author briefly discusses the required elements for applying design of experiments in the simulation model. In an article by Boning (1994), design of experiment methods are illustrated using in response surface modeling (RSM). Since the variables are unknown in most problems, the initial step of RSM is to find an accurate approximation for the true relation between the response and variables. Using an appropriate experimental design, inputs are classified into several blocks and systematically imported into the model. A response surface model can be constructed and kept modifying based on the output. The identified additional design points from DOE process could enhance the accuracy of the built model. A general approach of meta-modeling was proposed to replace the usual modeling strategy for an "ad hoc" problem (Kleijnen 2000). A meta-model is an approximation of the input/out-put (I/O) transformation implied by the simulation model. The methodology consists of ten steps within DOE in the meta-modeling process (Kleijnen 2000). The classic DOE can be extended to the stage-wise DOE used to identify inputs and their characteristics. One of the typical applications of DOE approach in meta-modeling was used for the regression model construction with the input-output behaviour from an underlying simulation model (Cheng 2000). The model is represented by nearly saturated queues of M/M/1 type. In particular, D-optimal designs of experiment are considered.

The proposed DOE uses the response surface methodology (RSM) to understand the process behaviour and to construct the optimal configuration (Ilzarbe 2008). It is to implant DOE in the discrete-event simulation (DES) to deal with complex operation systems to replace the traditional implantation with a mathematical model.

Factorial design is the most effective strategy for the study involving two or more factors altered at the same time, instead of using one at a time (Montgomery 2005). The investigation for the possible combination leads to a valid discovery about the interaction between factors (Montgomery 2010). Here the analysis of variance (ANOVA) is an important aspect in the common experimental design. The statistical test of ANOVA is utilized to accept or reject hypotheses that a factor alteration or interaction is significant.

The design with two levels (2^k) and three levels (3^k) are both the typical ways for factor testing, in which the "levels" means the variations possible for each factor (Chung 2003). Since 2^k factorial design requires the smallest number of runs, it is widely used in factor screening experiments (Montgomery 2005). The number of experiments (N) for k factors evaluation is given by $N=2^k$. For the 3^k factorial design, the number of experiments changes to $N= 3^k$. The 2^k factorial design is a useful design for preliminary analysis, which can narrow down the select range to important factors. On the other hand, 3^k factorial design is used to estimate the effects of each factor and their two-way interactions. In this research, 3^k factorial design is utilized to estimate the significant levels of each treatment procedure.

6.1.2 Meta-heuristic Methods

Simulation Optimization is an important tool for system improvement, which has been widely used in many fields, such as manufacturing systems, supply chains, call centers, financial, and inventory control systems. Four meta-heuristics methods have primarily been applied with some success to the simulation optimization: Simulated Annealing, Genetic Algorithms, Tabu Search and Scatter Search (Gendreau, 2010).

Simulated Annealing (SA) is a random-search technique which locates a good approximation to the optimal solution. It mimics the annealing process of mental cooling and reaching the minimum energy crystalline structure (Kirkpatrick 1983). The goal of SA is to find an accentually good solution in the statistic aspect. It is more efficient than exhaustive search which focuses on the best possible solution. Since SA search includes random search procedures, it might take long computational time to identify a high quality solution (April 2003).

Tabu search was initially created as a local search method (Glover 1986). The word "Tabu" comes from Polynesia language, which means the things that cannot be touched. In difference from SA method, Tabu search has deterministic behaviour (D. Werra 1989). It starts from one potential solution and then searches the better solution from the neighbourhood. If the best solution of the neighbourhood is accessible, the best one replaces the current solution. Then it repeats the checking process. In order to avoid being trapped by the locally optimal solution, Tabu search explores the other regions of the search space, in which the point leaving the current region is depending on the Tabu length. The searching process will be done once some stopping criteria are satisfied.

Genetic Algorithm (GA) is a heuristic method inspired from the natural evolution to search the optimal solution of a global problem. The properties of one solution are generally represented in a form of binary string. Based on the estimating result of a fitness function, the existing solutions are selected to breed a new generation of solutions. In other words, randomly initial solutions will evolve to better region after several iterations. The iteration process follows the roles of evolution theory such as inheritance, mutation, selection, and crossover. This method is useful to solve the optimization problem with complex fitness landscape (Bies 2006).

Scatter Search (SS) is another evolutionary method based on the generalized form of path re-linking, which is applied for solving optimization problems (Gendreau, 2010). It initially operates on a small set of trail solutions, and explores enlarged solution space by evolving a set of reference points. The original concept was develops in 1960s (Glover 1963), and the method was proposed in 1970s (Glover 1977). It is proved effective for a variety of applications in a meta-heuristic context, such as scheduling, routing, financial system design, neural network training, and optimizing simulation. The native advantages of Scatter Search are concluded as follows:

- Solution diversification is at a high level to construct initial population, which is helpful to avoid trapping by locally optimal solution.
- SS algorithm allows the condition that there are several optimal solutions for the target system, which provide variety choices rather than single optimum.

- Clearly stopping criteria of the SS algorithm decided by the elements of Reference Set.

6.2 Problem Formulation

As mentioned in the previous sections, a patient is marked by several statuses (TIP, ERH, TBADM and PD) along with treatment progress. These four statues can be recognized as the general treatment procedures for each arrival patient. Depending on the model outcomes, the procedure with a higher effect will be identified, which provides a direction for the future work of the ED improvement. Since the process time of treatment procedures is the factor that directly impact process time, the waiting time will be minimized if the process time of four treatment procedures changes in feasible range. To represent the decreasing scope for the treatment procedures, four test coefficients (TIP Coefficient, ERH Coefficient, TBADM Coefficient and PD Coefficient) are implanted into the model when generating the process time for an individual patient. The formula is shown as follows:

$$\text{Experimental Process Time} = \text{Status Coefficient} \times \text{Actual Process Time} \quad (6\text{-}1)$$

The investigation for the reduction range of treatment procedures is realized by changing the value of the corresponding coefficient. Scopes of the four procedures are considered integrally. Taking the ERH time as an example, assuming the actual process time generated from the corresponding distribution function, which is 100 minutes for a specific patient. If the ERH coefficient equals 0.9, the experimental process time of ERH is 90 minutes. With the same logic, the experimental process time of ERH is 80 minutes when the ERH coefficient equals 0.8. The variations of the model outputs, such as WTBS and LOS, are associated with the coefficient changing. Since overcrowding caused by long waiting-time is the main reason to block the patient flow, the objective function is set to minimize the average waiting-time before patients seen by physician (WTBS).

The objective function is defined as:

$$Minimize\ SC(y) = E[f(y)] \qquad (6\text{-}2)$$

Subject to:

$$VTIP_{min} \le y_1 \le VTIP_{max} \qquad (6\text{-}3)$$

$$VERH_{min} \le y_2 \le VERH_{max} \qquad (6\text{-}4)$$

$$VTBA_{min} \le y_3 \le VTBA_{max} \qquad (6\text{-}5)$$

$$VPD_{min} \le y_4 \le VPD_{max} \qquad (6\text{-}6)$$

$$\text{UCMonitor} \ge \text{UMonitor} \qquad (6\text{-}7)$$

$$\text{UCTreat} \ge \text{UTreat} \qquad (6\text{-}8)$$

$$\text{UCMTA} \ge \text{UMTA} \qquad (6\text{-}9)$$

Where

$VTIP_{min}$ is the minimal value of TIP coefficient;

$VTIP_{max}$ is the maximal value of TIP coefficient;

$VERH_{min}$is the minimal value of ERH coefficient;

$VERH_{max}$ is the maximal value of ERH coefficient;

$VTBA_{min}$is the minimal value of TBADM coefficient;

$VTBA_{max}$ is the maximal value of TBADM coefficient;

$VPD_{min}$is the minimal value of PD coefficient;

$VPD_{max}$is the maximal value of PD coefficient;

UMonitor is the bed utilization of Monitor Area in the original model;

UTreat is the bed utilization of Treatment Area in the original model;

UMTA is the bed utilization of Minor Treatment Area in the original model;

UCMonitor is the bed utilization of Monitor Area in the current model;

UCTreat is the bed utilization of Treatment Area in the current model;

UCMTA is the bed utilization of Minor Treatment Area in the current model;

SC(y) of Function (6-2) is the objective function. *E[f(y)]*is the evaluation function with critical variables from the model. *y* is an array with four elements, $y_1 \sim y_4$ are used as the input parameters of the simulation model. The lower bound of the coefficient constrains are gathered from the corresponding process time of the treatment procedures in Seven Oaks General Hospital (SOGH), and the upper bound of the coefficient constrains equal 1 as the initial condition of the current ED at VGH.

The minimum coefficients gathered from SOGH guarantee that the reduction range for VGH case is achievable in the reality. It is based on the assumption that if both of the two departments applying the similar treatment procedures, the process-time should be similar. Otherwise, it is obviously clear that the average WTBS will reach the minimum value if the variables from y1 to y4 equal 0. Moreover, the bed utilization of each treatment unit should maintain at the certain level which is set as the 80% of the original condition. It also guarantees that the coefficient of each treatment procedure will not infinitely reduce to the corresponding lower bound. The trial solution will be discarded if it leads to the bed utilization less than the utilization constrains.

Depending on the comparison result between VGH and SOGH, Table 6-1 lists the coefficient element which could constitute 7,140 combinations (12*7*17*5= 7,140). Each combination can be recognized as a potential solution for the optimal combination identification. It will take at least 550 hours to finish an exhaustive search if all the solutions are imported into the model. Therefore, the choosing proper optimization method is necessary to accelerate the process of identifying the optimal solution.

Col.	TIP	ERH	PD	TBADM
1	1.00	1.00	1.00	1.00
2	0.95	0.95	0.95	0.95
3	0.90	0.90	0.90	0.90
4	0.85	0.85	0.85	0.85
5	0.80	0.80	0.80	0.80
6	0.75	0.75	0.75	
7	0.70	0.70	0.70	
8	0.65		0.65	
9	0.60		0.60	
10	0.55		0.55	
11	0.50		0.50	
12	0.45		0.45	
13			0.40	
14			0.35	
15			0.30	
16			0.25	
17			0.20	

Table 6-1: Coefficient Selection List

6.3 Design of Experiments Application

In order to have a deep insight of the relationship between the process-time of each treatment procedure and WTBS, Design of experiments (DOE) method is applied in this research to investigate the significant levels of treatment procedures for WTBS reduction. The decision-making parameters are defined as the coefficient of each treatment procedures. The aim is to investigate which procedure has the most significant level to impact the WTBS. The parameters are defined as:

- Factor A: The value of TIP coefficient
- Factor B: The value of ERH coefficient
- Factor C: The value of PD coefficient
- Factor D: The value of TBADM coefficient

To estimate the effects of each factor A, B, C, and their interactions, a complete 3k factorial design is considered. The four factors and their characteristics are shown in Table 6-2. The 3^k factorial design with four factors means it requires $N=3^4=81$ experiments. Therefore, there are 81simulation runs with each run representative of a particular experiment. The simulation time of each run is 107 days within 17 days as the warm-up period. The variables of WTBS and LOS are chosen as respond variables to estimate the impact of the four coefficients of treatment procedures.

Factor	Low	Median	High	Number of levels
A	0.5	0.7	0.9	3
B	0.5	0.7	0.9	3
C	0.5	0.7	0.9	3
D	0.5	0.7	0.9	3

Table 6-2: Characteristics of the Design of Experiments

6.3.1 Result Analysis

Minitab commercial software is widely applied in the field of quality improvement. In this research, the configurations followed 3k design is imported into the software Minitab for the DOE analysis. The software output is shown in Table 6-3. The f-value is referred to the result of ANOVA analysis, which implies the significant level of actors in the model. The large value means the factor or the interaction is more significant. P-value is the probability representing the test statistic of the null hypothesis being true, in which the hypothesis is that factor alteration or interaction is significant. It means the factor is significant when P-value is at the small level a (a<0.05 in the research). P-value indicates that if factors of the model involving are significant, and F-value shows the level of significance for the certain factor. By referring to the ANOVA table, A, B, and D have the significant impact to the waiting-time.

Effect	Seq SS	Adj SS	Adj MS	F Ratio	P Value
A	4	254088.1	254088.1	507.05	0.000
B	2	218794.1	218794.1	1056.62	0.000
C	7	10900.8	10900.8	10.90	0.000
D	1	8956.4	8956.4	142.92	0.000
A*B	8	19472.0	19472.0	77.830	0.000
A*C	28	4254.0	4254.0	1.490	0.203
A*D	4	866.1	866.1	5.480	0.000
B*C	14	1138.5	1138.5	2.370	0.051
B*D	2	463.6	463.6	12.810	0.000
C*D	7	1441.8	1441.8	1.590	0.174

Table 6-3: Results of ANOVA for Main and Interaction Effects

The process-time of the four treatment procedures occupies the main part of the whole treatment time. The corresponding P-values approach to zero. Using the F ratio to represent the significance of the chosen factors, the Pareto Chart shows how the time of treatment procedures affecting the waiting-time (WTBS). In Figure 6-1, the process time of

ERH procedure has the significant effect compared to other factors. The process-time of TIP also affects patients' waiting-time. The result also indicates that the interaction between two factors (such as TIP*ERH) does not play important roles for the WTBS. The following research will concentrate on the reduction of individual factor.

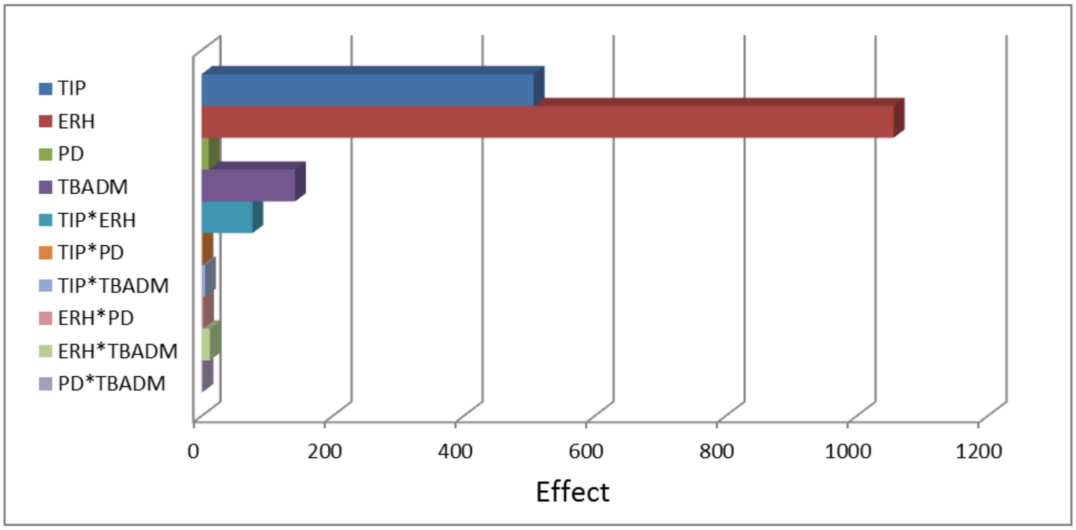

Figure 6-1: Pareto Chart for WTBS in ED System

6.4 Meta-heuristic Optimization

6.4.1 Meta-heuristic Method Selection

Meta-heuristic methods include three basic design parameters (Laguna 2002): (1) the use of adaptive memory, (2) strategy of neighbourhood exploration, and (3) number of chosen solutions maintained to the next after every iteration. The features of each meta-heuristic method are concluded in the form of “a/b/c”, which are shown in Table 6-4. The comparison table shows that the dynamic updating process of Scatter Search relies on the static memory to maintain the balance between intensification and diversification for solution convergence. The incorporate strategic principles are pretty similar with the certain components of Tabu Search methods (Rego 2005). The method is flexible to implement variety ways in its elements (Fu 2005), like employing some procedures from Tabu Search or Genetic Algorithm. Scatter search is an effective method to solve the problem of non-linear multi-objective optimization (Molina 2007).

Meta-heuristic	Parameters
Simulated Annealing	M/R/1
Tabu Search	A/N/1
Genetic Algorithms	M/R/P
Scatter Search	M/N/P

A: Adaptive memory Requiring
M: Memory-less
N: A method relying on systematic neighbourhood search
R: Methods employ random sampling
1: One solution is maintained from one iteration to the next
P: A population of trail solutions are maintained

Table 6-4: Meta-heuristic Method Classification

For the ED model, the aim of model optimization is to find the optimal combinations of reduction scopes of treatment procedure to minimize the waiting-time. Applying the feasible combinations in the reality is an important aspect should be considered. It means the number of potentially optimal combinations is not specified as one combination. The methods of simulated annealing and Tabu search do not fit the requirements of the ED model optimization, although the result of these two methods can provide an optimal solution in global searching. Compared to other typical evolutionary methods like Genetic Algorithms, the process of creating new solutions in Scatter Search orients its explorations rather than deriving randomization (Gendreau 2010). Therefore, the scatter search method is chosen for the optimal combination identification in this research.

6.4.2 Scatter Search for the ED Model

Required elements in the meta-heuristic approach are similar to a general optimization problem which contains the objective function, variables, and constrains. Instead of using an approximated mathematical model, the model of a target system is represented by using Discrete-event Simulation. In this research, an optimization subroutine based on Scatter Search is used to guide the searching process, while the model of ED operation is viewed as a black box function evaluator (Figure 6-2). The optimization subroutine of Scatter Search chooses a set of trial solutions as the input parameters and uses the responses of the model to make decisions regarding the selection of the next trial solutions.

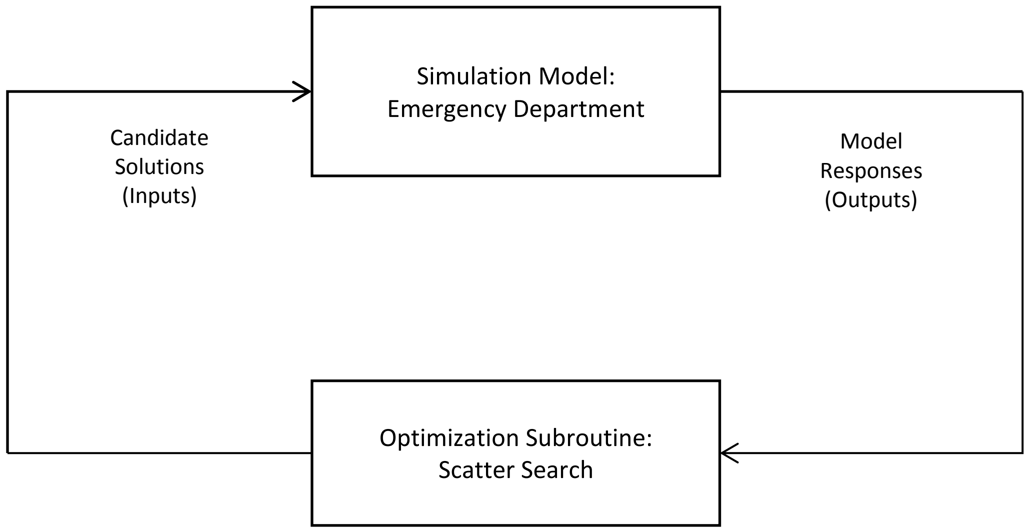

Figure 6-2: Black-box Approach of Simulation Optimization

6.4.3 Scatter Components

Scatter Search performs iterations to enlarge the search space followed the orientation of the previous explorations from a Reference Set. Reference Set consists of a set of good solutions where the definition of good is not only restricted for the evaluation of objective function, but also considering the diversity as the other criterion of selecting candidate solutions. Collecting reference points is a cycling process which updates new good solutions to Reference Set. The template of Scatter Search contains five methods (Arti 2006): 1) Diversification Generation Method, 2) Improvement Method, 3) Reference Set Update Method, 4) Subset Generation Method, and 5) Solution Combination Method. The interaction of the methods and the searching procedure is shown in Figure 6-3.

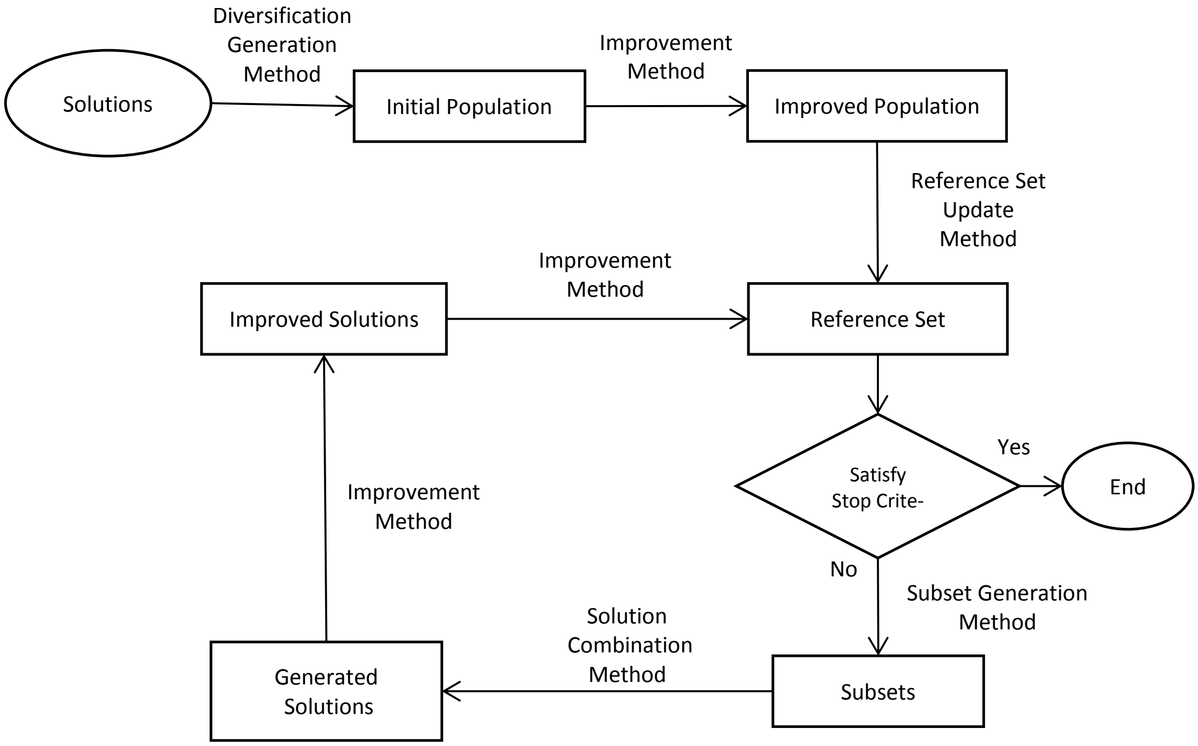

Figure 6-3: Search Components of Scatter Search Algorithms

Initial population of trial solutions is created from candidate solutions by using Diversification Generation Method. The chosen solutions should contain certain diversification, which are recognized as seed solutions (or arbitrary solutions) to be utilized as inputs of the Scatter Search algorithm. Positive attributes of trial solutions will be enhanced by using Improvement Method. If the input trial solution is not improved as a result of the application of this method, the "enhanced" solution is considered to be the same as the input solutions (Marti 2006). As the core of Scatter Search, a set called Reference Set is created and controlled by Reference Set Update Method. Initially, the "best" solutions of the first iteration are added to the empty Reference Set. It keeps updating "best" solutions of iterations into the Reference Set but the solution quantity is still maintained at a typically small level (i.e. less than 20). In the next step, solutions of Reference Set are distributed into several subsets by using Subset Generation Method. Such subsets are used as a basis for creating combined solutions following Solution Combination Method. The new rated solutions will be estimated by the objective function and then best ones are added to Reference Set. This cycling process keeps operating until default stop criteria are reached.

6.4.4 Initial Population Generation

The first step of ***P*** set generation should guarantee that the initial population of ***P*** contains enough diverse solutions. A large set *P* of trail solutions is built by using Diversification Generation Method, which is typically at least 10 times seize of the reference set. In this research, all the solutions are listed following lexicographical order (Table 6-5). The solutions with 35 intervals are abstracted to construct the initial population. The size of P (Psize) is set as 10 times of Reference Set, which equals 200.

No.	TIP	ERH	TBADM	PD
817	0.95	0.90	0.50	0.95
818	0.95	0.90	0.50	0.90
819	0.95	0.90	0.50	0.85
820	0.95	0.90	0.50	0.80
821	0.95	0.90	0.45	0.95
822	0.95	0.90	0.45	0.90

Table 6-5: Sample of the List of Candidate Solutions

6.4.5 Reference Set Generation

According to the quality of diversity, b solutions of Reference Set (*RefSet*) are collected from P. In this research, the number of solutions included in the *RefSet* is that b= 20. Reference Set contains a pair of elements, which is denoted by $b= b_1 + b_2 = |RefSet|$ and b_1= 1/2 *b. Here b_1 means the quantity of high quality solutions which are evaluated by the objective function. The solution with the highest quality will place as the first one in the list.b_2 are the quantity of the solutions with high diversity. When b_1 solutions are added in *RefSet*, these solutions will be deleted from P at the same time. Choosing solutions for b_2 set is based on the corresponding minimum distance between solutions in *P-RefSet* and b_1 solutions. b_2 set consists of the solutions with the maximum value of the minimum distances. For the ED model, one solution is recognized with four elements of TIP, ERH, TBADM, and PD. The form is like solution # [element (TIP), element (ERH), element (TBADM), element (PD)]. Using e^k to donate each element of one solution, the distance $d(e^1, e^2, e^3, e^4)$ between two solutions a_i and a_j, is calculated as:

$$d(a_i, a_j) = \sum_{k=1,\ldots,4} |e_j^k - e_i^k| \qquad \text{(6-10)}$$

Assuming a solution No.5617 (0.55, 0.85, 0.95, 0.95) is in the current *RefSet*. Using the formula (6-3) to respectively calculate the distance with other two solutions No.2500 (0.80, 0.95, 0.70, 0.80) and No. 2501 (0.80, 0.95, 0.65, 1.00) in the *P-RefSet* Set. The calculation process is shown as follows:

$$d(a_{5617}, a_{2500}) = |0.80-0.55|+|0.95-0.85|+|0.70-0.95|+|0.80-0.95|= 0.75$$

$$d(a_{5617}, a_{2501}) = |0.80-0.55|+|0.95-0.85|+|0.65-0.95|+|1.00-0.95|= 0.70$$

The calculation results indicate that the distance from the solution No.5617 to solution No.2500 is much further than the distance reaching the solution No.2501. If the distance between solution No.5617 and solution No.2500 is the maximum one, solution No.2500 will be added to the corresponding place in the b_2 set of the *RefSet.*

6.4.6 Subset Generation based on Reference Set

As a typical character of Scatter Search, using Solution Combination Method for new solution generation allows combining two or more solutions of subsets of the current *RefSet*. Scatter Search methodology could guarantee that all the combined solutions of one subset are produced at once. Depending on selecting approaches, four types of subsets are constructed to avoid the subset duplication among iterations as follows:

- Subset Type1: Choosing one solution from b1 set and one from b2 set to construct a subset.
- Subset Type2: Add another high quality solution of b1 in to the current subset of Subset Type 1. The additional solution should be different from the solutions of the current subset.

- Subset Type3: Each subset of Type3 is augmented by adding the third high quality solution of b1 which is different from the solutions of current subset.
- Subset Type4: Based on the subsets of Type3, the subsets of Type4 contain additional high quality solutions of b_1-3.

6.4.7 Combination Method with GA Implantation

Combination Method of Scatter Search is a problem-dependent element. It means that combination methods are customized by a relative problem and the solution representation. In particular, a probabilistic method is validated to solve the problem with the solutions represented by binary vectors, such as the knapsack problem (Campos 2001). For the problem that solutions are presented by real vectors, linear combinations have been widely applied (Mautor 1997). Alternatively, the voting method is proper to solve an order problem in which solutions are represented as permutations (Pantrigo 2005).

Since the objective function of this research is represented by the built ED model, it is unavailable to use the traditional Linear Combination Method. There is no coefficient of the objective function to generate surrogate constraints from the constrain equations of the mathematical model. In order to realize the aim of Combination Method that accumulating positive attributes of iteration operations, the GA crossover operator is implemented to generate new trail solutions. Scatter Search and Genetic Algorithm both belong to the family of population-based meta-heuristics. The similarities of SS and GA make GA concept can be used to solve the SS problem. Laguna (2003) concluded the similarity in his book as: 1) Building, maintaining and working with a population of vectors; 2) Creating new elements by combining existing elements; and 3) Determining elements retained based on a measure of quality.

The combination method in this research uses the concept of the element swap in the GA application (Laguna 2003). The aim is to maintain the positive attributes as well as keeping variation. Since b_1 solutions of the *RefSet* are ordered by the objective function, the first position means the solution is with the highest quality currently. Using number 10~1 to represent the scores of b_1 solutions, which can be converted into the chosen probability for generating new trail solution (Table 6-6). The solution with higher quality has more probability to be selected.

b1 Solutions of Ref-Set	Score	Chosen Probability
X1	10	18.18%
X2	9	16.36%
X3	8	14.55%
X4	7	12.73%
X5	6	10.91%
X6	5	9.09%
X7	4	7.27%
X8	3	5.45%
X9	2	3.64%
X10	1	1.82%

Table 6-6: Chosen Probabilities of the b1 Solutions in RefSet

Once a b_1 solution is selected, the pairs in the corresponding subsets are used to constitute a new trial solution. The element position of the solution vector is recognized as a crossing point. Marti (2005) introduces a strategy of Combination Method with GA implantation which is called mutation operator referred to the GA literature. It selects two random elements in chosen solutions to exchange the partial number between them. The remaining elements are directly copied from original solutions to preserve their relative attributes.

The application of Combination Method is a cycling process, which is shown in Figure 6-4. Using one time of iteration as an example, The solution (0.55, 0.85, 0.95, 0.95) is chosen from the b1 set of the current *RefSet*, and the choosing process follows the default probability. In the next step, the other solution (0.45, 0.95, 0.60, 0.80) is selected from left solutions of the current *RefSet*. Randomly choosing two elements of the two solutions, and let them swap respectively. The combined solution is (0.45, 0.85, 0.95, 0.80).

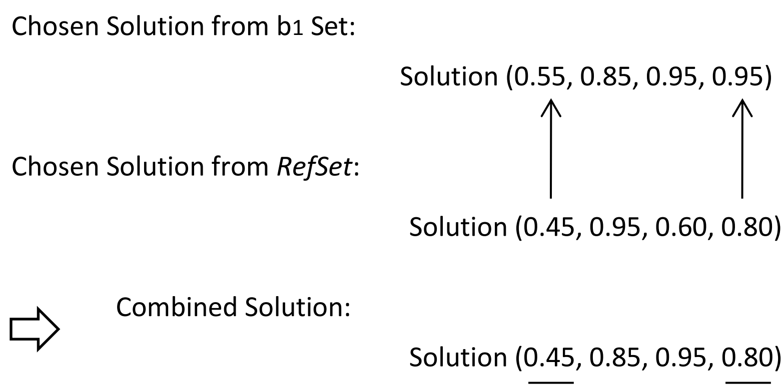

Figure 6-4: Combination Method Application

6.4.8 Improvement Method Application

Glove (1998) introduces one Improvement Method with the feature of 1-moves. The moves provide feasible diversification of trail solutions by adjacent changing for elements of solution vectors. For example, one random element of a binary solution will "flip" moves from 1 to 0 by using Improvement Method. The moving of chosen element is recognized as level 1 move, or 1-moves. It is possible that 1-move may produce an infeasible solution, but successful 1-moves will accumulate feasibility and direct iteration to optimum.

In this research, 1-moves concept is realized by making four elements of a solution vector minus 0.05, respectively. Assuming one trail solution (0.70, 0.95, 0.80, 0.90) is generated by the combination method. One solution on the subject to 1-moves will construct four new trial solutions (Figure 6-5). These new trial solutions will be estimated using the objective function. Since applying Improvement Method on the initial population will extremely enlarge P size, this method is only active to generate new trail solutions following the combination method.

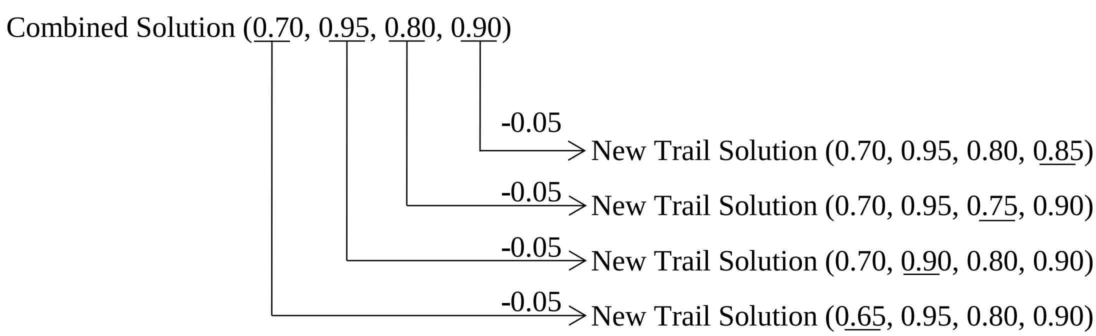

Figure 6-5: Improvement Method Application

6.4.9 Dynamic Reference Set Update Method

The Reference Set is the heart of a Scatter Search procedure, choosing a proper strategy of Reference Set update will enhance the efficiency of searching process. Instead of waiting all combined solutions from subsets estimated by the objective function, a dynamic updating strategy allows admitted solution to be added to *RefSet* directly (Marti 2000). It means that the solution with the inferior quality will be quickly replaced, and future combinations are constituted with improved solutions. Figure 6-6 illustrates the mechanism of Dynamic Updating in the b_1 set of the Reference Set. Using X1 ~X10 to donate solutions in the current *RefSet*, which have been ordered from best to worst according to the objective function F(X). Y is a new trial solution generated by Improvement Method. If the estimation result shows that F(X1) < F(Y) < F(X3), solution Y will directly be inserted into the position of the Reference Set to replace the X3 position. The solutions from X4~X9 respectively replace the solution after the current one. For example, solution X9 replaces the original X10 in the 10^{th} position.

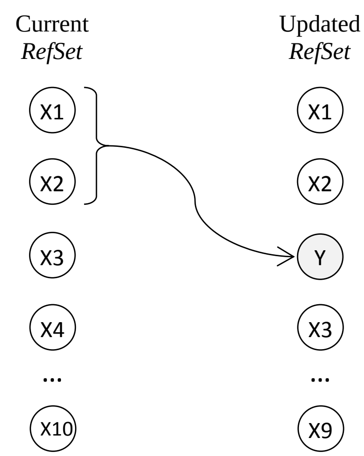

Figure 6-6: Dynamic Reference Set Update

6.4.10 Stop Criteria Setting

Scatter Search is designed to operate on solutions of Reference Set which will be continued maintaining and updating until it reaches a stable condition (Hag 2007). A simple way to set the stop criteria is at the moment when there is no new trial solutions added in Reference Set

6.4.11 Scatter Search Programming

In this research the built ED model is used for the objective function to search optimal solutions. The search results are imported to Trail Solution Generator (TSG) to prepare the next set of trail solutions. The user interface of Trail Solution Generator (Figure 6-7) is developed using C# language, which realizes the function of Scatter Search. The section 1 of TSG shows the solutions of b1 set in the current reference set. Click the button of "Load Top 10 Solutions" in the user interface window, some new solutions will replace solutions in the current b_1 set. In the meanwhile, the solutions with the maximum value and the minimum distance will refresh in the section 2 of TSG. In order to avoid the replicated solution generation, all the generated solutions are saved in a solution pool. All the new trail solutions will be checked with solutions in the solution pool before importing to the ED model. The validated trail solutions are listed in the section 3 marked.

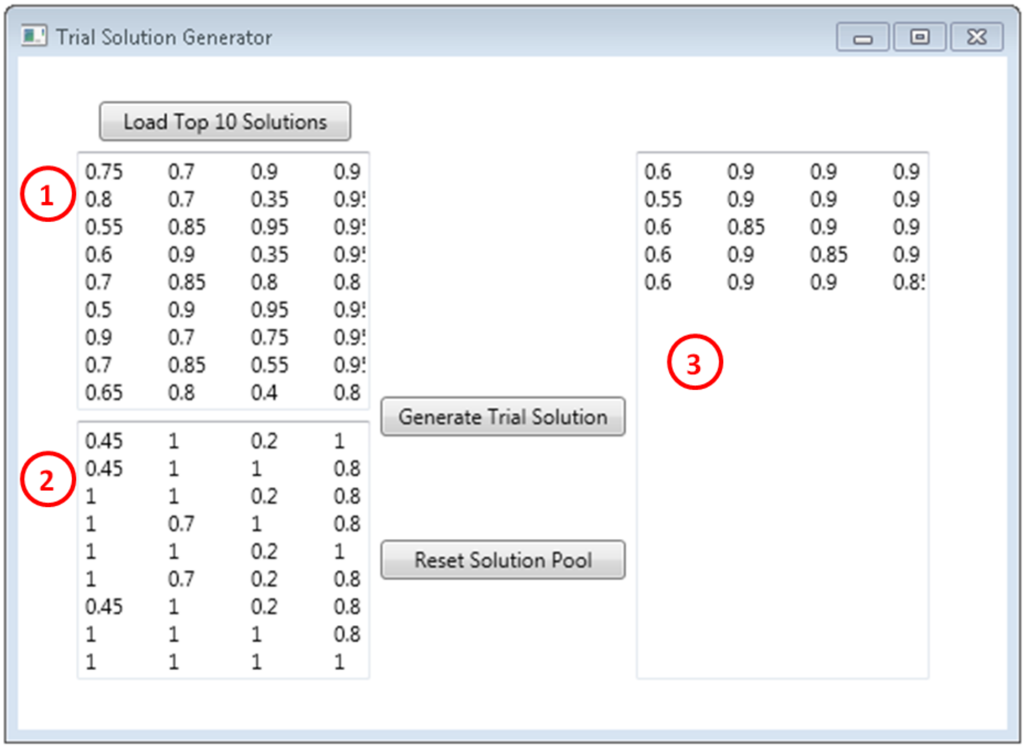

Figure 6-7: Trail Solution Generator

6.4.12 TSG Operation Mechanism

Estimating solutions in the P set is the pre-work before using Trail Solution Generator. The solutions of the initial reference set will be uploaded into TSG when a search starts working. A cycling function launches by assigning the value of *TRUE* to the variable *NewSolutions*. In step 3, *NewSubsets* are generated from Subset Generation Method. The variable *NewSolutions* switches to *FALSE*. The generation of new trial solution subjects to Solution Combination Method based on solutions in subsets. The trial solutions will be enhanced by using Improvement Method if available. In step 7, if new “best” solutions are identified by the objective function; Reference Set Up method is active again to import the solutions into the current *RefSet*. If *RefSet* changes with at least one new solution inserted, the *NewSolutions* flag is switched to *TRUE* in step 7. Otherwise the stop criteria is satisfied and searching process ends.

The pseudo code of TSG operation mechanism is as follows:

Step 1: Start with P = 200, selected candidate solutions of P set are estimated by using the built ED model.

Step 2: Upload solutions of the Reference Set into the TSG. *RefSet* = $\{b_1^1, b_1^2, \ldots b_1^{10}, b_2^1, b_2^2, \ldots, b_2^{10}\}$

Make *NewSolutions* = TURE.

while (*NewSolutions*) **do**

Step 3: Generate *NewSubsets* with the Subset Generation Method.

Make *NewSolutions* = FALSE.

while (*NewSubsets* $\neq \emptyset$) **do**

Step 4: Apply Combination Method to generate new trial solutions.

Step 5: Use Improvement Method to create enhance trial solutions.

while (NewTrailSolutions = TRUE) **do**

Step 6: Output the generated new trail solutions.

end while

Step 7: Apply the Reference Set Update Method to renew Reference Set.

if (*RefSet* has changed) **then**

Step 8: Make *NewSolutions* = TRUE.

end if

end while

end while

A flow chart for operation procedures of TSG is shown in Figure 6-8.

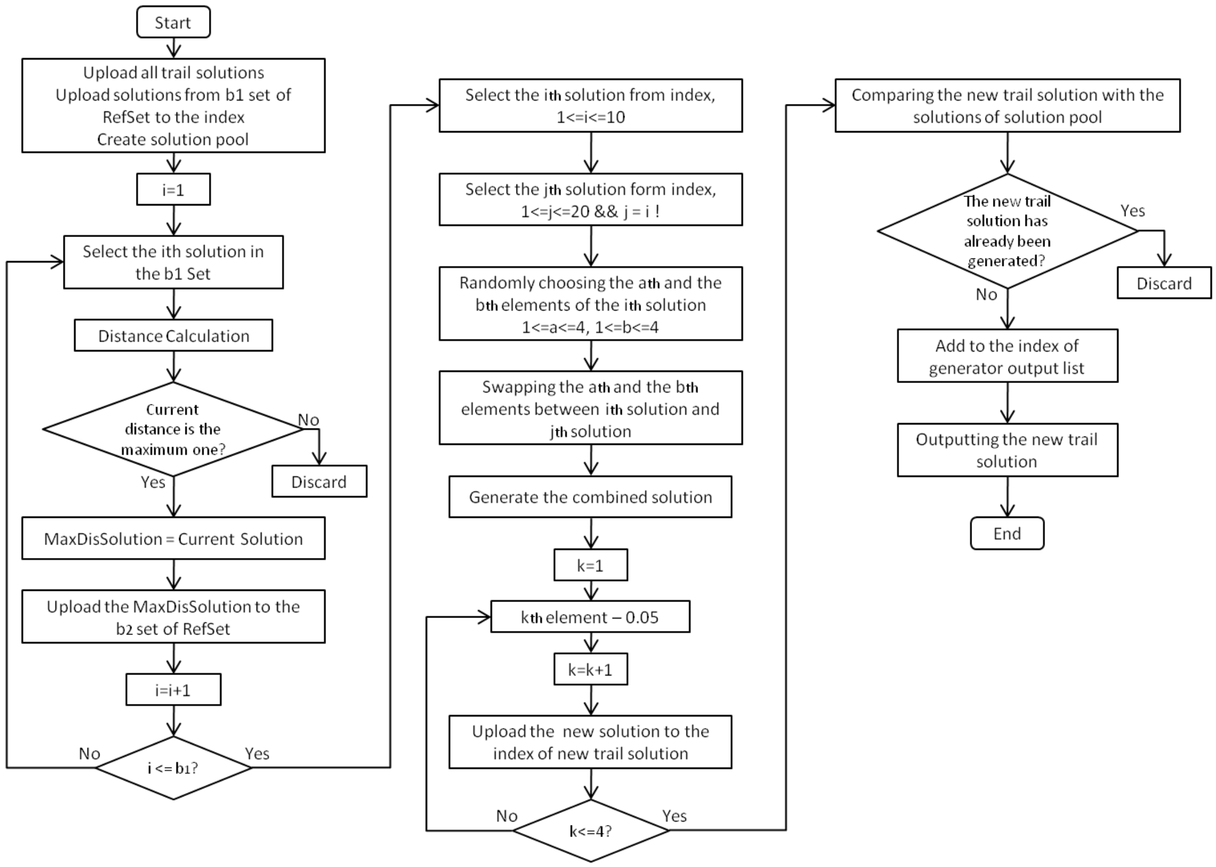

Figure 6-8: Flow chart of the developed SS

6.5 Results and Analysis

Solutions in the reference set keeps updating along with new trail solutions generated from the trail solution generator (TSG). To clearly illustrate the solution changing in the reference set, the corresponding waiting-time from the model output is used to represent the certain solution (Figure 6-9). X1 to X10 are 10 positions of the reference set which is introduced in the paragraph of Dynamic Reference Set Update Method. The TSG application starts from generation 1, which describes solutions of the initial reference set after estimating 200 trail solutions of the initial population. Once four new trail solutions are generated from the trail solution generator, the generation number increases one. If the performance of some generated trail solutions is better than the solutions in the current reference set, the new trail solution is updated into the reference set by using the reference set update method. It makes the value in the corresponding position (X1~X10) change. Figure 6-9 shows that solutions of reference set reaches the stabilized condition after 39 generations.

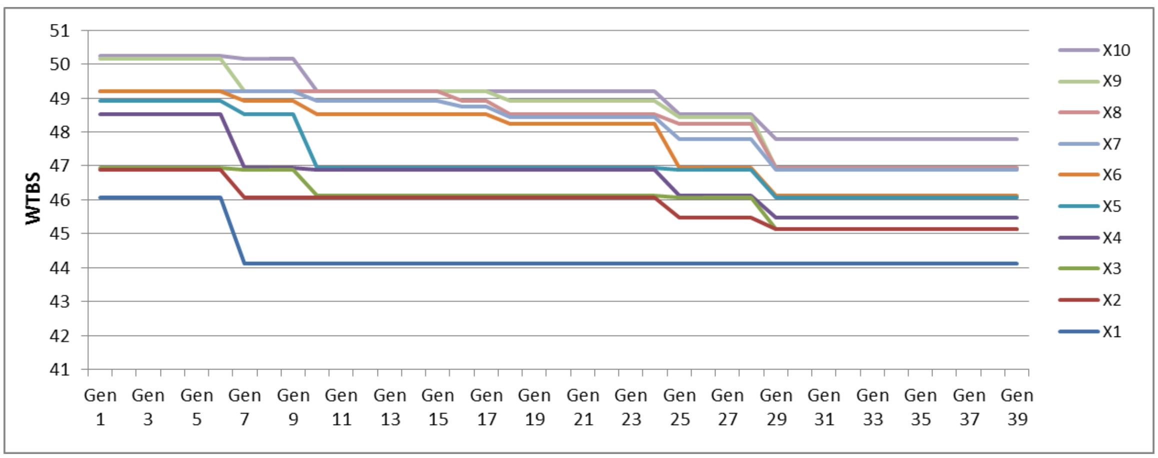

Figure 6-9: Components of Reference Set

Table 6-7 lists the elements of the reference set when the set reaches stable condition. Each element means a potential combination for waiting-time minimizing. These ten combinations are in order of the reduction range of the waiting-time. For example, the first combination with No. 2870 means the best result of waiting-time reduction with the reduction range of 72.04%, if the process-time of TIP, ERH, PD and TBADM could be reduced by 20%, 25%, 60%, and 20% respectively.

It should be noticed that the order of combinations in the reference set is considered from the mathematical analysis. The result indicates the required process-time saving of each treatment procedure, but the feasibility is the other factor that should be taken into account. As mentioned in the previous paragraph, TIP represents the period when arrival patients receive emergency treatment. Delay is accumulated among the treatment activities in this period. These activities follow several rules to complete the treatment, the delay reasons are complex. Hasty process changing may put patient life at risk. The reduction range of TIP should be set as a very low level considering the realization probability. Combinations of Column 1, Column 7 and Column 10 better match the requirement of the less TIP reduction range (marked by blue color).

Considering the similar reason of feasibility, the distance calculated by Formula (6-10) is used as the other measurement of comparisons. The distance is recognized as a realizable level of the process-time reduction, there are three solutions with a minimum distance, which are in Columns 3, Columns 5 and Columns 7 (marked by red color in Table 6-7). No.2340 solution is the optimal one which has less processing-time reduction in the TIP procedure. The WTBS minimizing is realized by mainly reducing the process-time of other treatment procedure when the process time of TIP, ERH, PD and TBADM could be reduced by 15%, 30%, 40%, and 20% respectively.

Col.	No.	TIP	ERH	PD	TBADM	WTBS	Reduction Range(%)	Distance
1	2870	0.80	0.75	0.40	0.80	44.31	72.04%	1.25
2	4983	0.60	0.90	0.50	0.90	45.13	71.52%	1.10
3	5560	0.55	0.90	0.70	0.80	45.14	71.51%	1.05
4	5064	0.60	0.85	0.55	0.85	45.48	71.30%	1.15
5	4974	0.60	0.90	0.60	0.85	46.07	70.93%	1.05
6	3380	0.75	0.80	0.40	0.80	46.12	70.90%	1.25
7	2340	0.85	0.70	0.60	0.80	46.9	70.40%	1.05
8	4984	0.60	0.90	0.50	0.85	46.93	70.38%	1.15
9	4995	0.60	0.90	0.40	0.80	46.95	70.37%	1.30
10	2790	0.80	0.80	0.35	0.80	47.8	69.84%	1.25

Table 6-7: Final Elements of Reference Set

6.6 Summary

Considering complex factors of the patient flow, the ED process is simplified into four general treatment procedures (TIP, ERH, PD, and TBADM). The DOE result indicates that the ERH process-time has the most significant impact to the waiting-time (WTBS). It means that any improvement for the ERH time reduction will dramatically benefit the waiting-time reduction. The later part of this chapter investigated the feasible combination of the procedure reduction ranges for the waiting-time minimizing. Since simulation cannot automatically provide an optimal configuration, the model is implanted with an optimization method called Scatter Search (SS) to accelerate the searching process. To realize it in the reality, it requires a deep cooperation with the medical staff to design improvement strategies. The improvement strategies considered using lean thinking is a validated way to avoid the time waste in the ED process and to achieve the aim of reducing process time. In the next chapter, strategies of the ED improvement are discussed. The effect of a modified improvement method is introduced through using physician to replace triage nurse for the initial diagnosis.

Chapter 7

Improvement Strategy Design

The built simulation model can be used to estimate a specific improvement strategy. A strategy for the treatment procedure alternative is suggested in this chapter based on reviews of research on the ED improvement. Although the reviewed strategies are valuable in the field of theoretic research, applications of these methods do not match the condition of the ED at VGH. Based on the gathered information, a strategy for the treatment procedure alternative is proposed. The simulation output indicates the performance of the proposed method. To maximize the positive impact of the improvement strategy, the proper application period is identified with various scenarios.

7.1 Improvement Strategy Review

To determine factors that account for patient waiting-time, the previous investigation indicates that ED patients spend the majority of their time waiting for treatment which is caused by limitations of treatment resources including stretchers, physicians, and nurses (Takakuwa 2004). Therefore, the foundation of ED improvement is to minimize the influence of such shortages. The available methods can be classified into four general categories: ED layout modification (beds, test equipment), human resource adjustment, inner role adjustment, and treatment procedure changing.

7.1.1 ED Layout Modification

An essential reason causing overcrowding is the ED resources without enough capacity for the treatment in time. Using additional resources is a common way to release the corresponding bottleneck in the treatment process, such as increasing the stretcher number of treatment units. More stretchers makes arrival patients could enter the emergency room (ER) earlier without waiting for available stretcher. The challenge is to identify the number changing to maximize the ED performance. In addition to add stretchers in the treatment units, the other alternative is to set an additional short-stay unit for the stabilized ED patients who are requiring further observations (Shim 2010). The benefit of this method is to “off-load” stable patients from the acute-care ED and to reduce the number of unnecessary hospital admissions (Konnyu 2012). If there is no available resource for the ED, one of the eclectic ways is to share treatment units with other departments in different time periods (Ross 2001).

7.1.2 Human Resources Adjustment

The other direct way is to hire more medical staffs and increase stretcher number. Although hiring more medical staffs can enhance the efficiency of the ED service, it is hard to realize in most cases due to the budget limitation. Alternative methods are to maximize the staff utilization. The design of improvement for the medical staff scheduling are mainly considered from two aspects: 1) adjusting the time of working for daily shifts, 2) modifying the schedule in a longer period (such as in a month). The research of daily staff rescheduling makes the manpower better match the fluctuation of arrival patients. The observed result shows that the pattern of daily demand persistently is at a low level during the night, and grows to a peak at noon (McCaig 2002). Through adjusting the time of physician's working shift, the overlap part of the periods of physician diagnosis will better match the patient arrival rate, and further reduce the waiting-time for physician seeing. Another method for medical staff rescheduling is to consider a longer period of arrangement with staff preferences (Carter 2001). The application of this method is initially designed for physician scheduling and then extended to set monthly nurse roster. Based on the collected information about rules of the nurse roster, the research result indicates the optimal roster arrangement to maximize the nurse utilization in a monthly period.

7.1.3 Inner Role Adjustment

The third way is to adjust the inner role of medical staff's activities in the treatment (Hay 2006). It is suggested that each medical staff should firstly be considered for the work only they can do. Hence the medical staff is assigned the job to match their abilities. Thresholds can be used to activise the relative medical staff. Only if the operating priority exceeds the threshold value, the corresponding tasks will be activated. Even for the same task, it has different priority for the medical staff with different training background. For example, the priority list makes a senior physician mainly focuses on the diagnosis rather than the basic treatment. This method is validated in a simulation model with two scenarios for throughout-time. However, the model in the reviewed paper was developed based on assumed data, which affects the result accuracy.

7.1.4 Treatment Procedure Changing

A concept called the fast-tracking strategy was initially introduced by McGuire in 1994. The aim of this strategy was to accelerate the ED process for the patient with low acuity level. The author tested five alternative scenarios using a simulation model. The result shows that the application of fast-tracking areas for patients required minor care could notably reduce overall length of stay (LOS). The following research indicated that 85 percent of emergency demands are due to patients with minor or non-urgent illnesses (Wally 2003). The patient flow could be accelerated if the low-acuity patients can be discharged quickly. Adding a fast-tracking system requires setting a specific separate area that exclusively serves those ED patients with minor illness or injury (Yoom 2003). The minimally ill or injured patients are assessed and treated in a parallel fashion within one geographic department (Rodi 2006). To further enhance the impact of fast-tracking system, an improvement strategy called “see-and-treat” method was developed to accelerate the patient flow of minimally ill or injured patients. The aim of applying “see-and-treat” method is to reduce the waiting-time before patients receiving physician diagnosis, and further release patients’ dissatisfaction caused by long waiting-time (Green 2006). Davies (2007) concluded features of a full implementation of “See and Treat” method as: 1) the triage nurse is replaced by receptionists who direct arrival patients to the appropriate queue; 2) a team of physician and nurse practitioner assesses and treats patients seamlessly in the Minor Treatment Area. This strategy has the potential risk to intensify the physician shortage because physician in triage team cannot take care of the patients requiring reassessment after the emergency treatment.

7.2 ED Improvement Strategy at VGH

Through interviewing with ED medical staff and the close observation at VGH, it is found that some methods mentioned in previous sections do not fit requirements of the current ED case. For example, the current ED layout has been decided followed the ED development plans. The alternatives of stretcher number changing are infeasible. The nurse number is not the bottleneck affecting the patient flow based on the analysis of the model output. On the other hand, there are two ED physicians working in the daytime, one is for initial diagnosis and the other is for patient's condition reassessment. There is no need for a large scale of medical staff rescheduling. Compared to other improvement methods, the fast-tracking strategy is the proper one for the current ED case. It is, therefore, proposed using the treatment procedure change for a possible solution to reduce patients' waiting-time.

7.2.1 Modified "See-and-treat" Method

For see-and-treat method, the potential risk is that waiting time maybe enlarged because physicians have to move between major treatment unit and MTA when some treatment activities require physician's instruction. It divides physician's time between these two areas. The modified "see and treat" method requires only one physician staying at MTA and the other physician staying at major treatment unit. The physician in major treatment unit is only on duty for patients in the certain area to make decisions on the required treatments and tests. The physician at MTA does initial assessment preferentially for arrival patients and goes to major unit to do further treatment if time is spare. In this research, one physician stays at a room of MTA with a nurse practitioner (NP) in the daytime. All walk-in patients are brought to MTA in the period of the strategy application (Figure 7-1). Through this way, low acuity patients will be treated and discharged quickly. Nearly 20% of non-acuity patients with CTAS 3 to CTAS 5 can be identified and treated by a nurse based on the statistical result. The other walk-in patients will be brought into the main treatment area to have further treatment as original treatment process. The acuity patients may stay at the ED to have further observation and then being discharged or admitted to the hospital for further treatment.

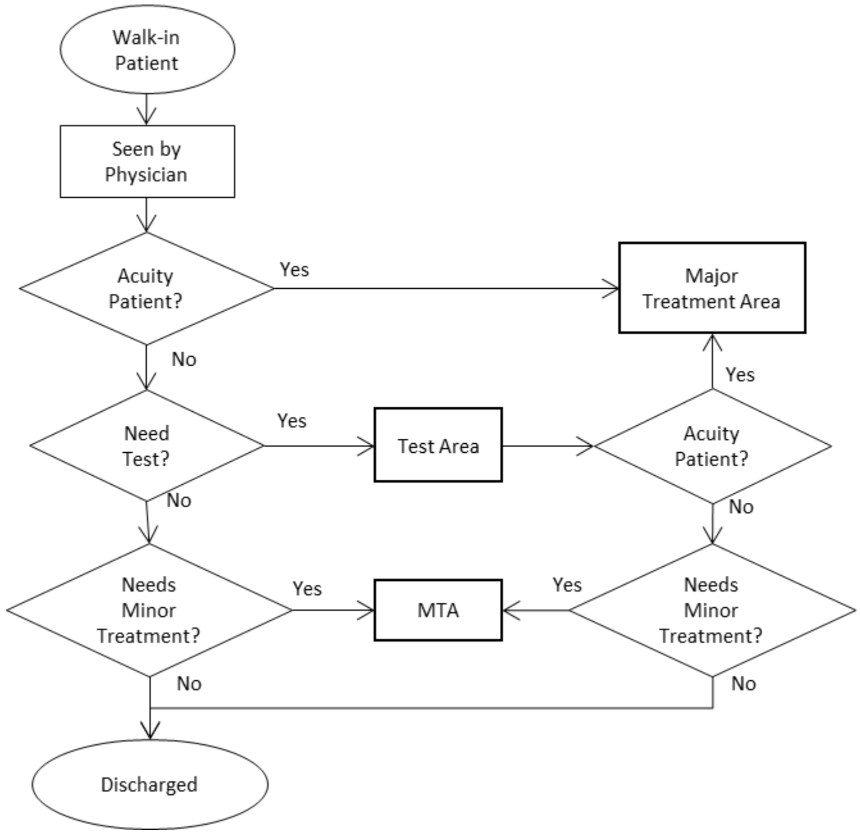

Figure 7-1: New Patient Flow of Walk-in Patient

7.2.2 Experiments Design

The application of the modified see-and-treat method is initially applied in the daytime from 8:00 am to 8:00 pm, and the result indicates that this method could dramatically reduce the waiting-time. To maximize the positive effect of waiting-time reduction, scenarios for further experiments are designed in two aspects: 1) duration of the daily strategy application, 2) the corresponding start time and end time. The upper bound of the start time of the strategy application is set at 8:00 am, and the lower bound of the end time is at 8:00 pm. Table 5 lists all potential configurations of the application periods, which involves 78 scenarios. In the table, the rows shows the scenarios classified based on the daily application duration, and the column is based on the start time of the strategy application. Taking scenario 1 (S1) as an example, its duration is 1 hour, and starts at 8: 00 am, and ends at 9:00 am.

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
1 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
	End Time:	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
		S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S23	
2 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	
	End Time:	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	
		S24	S25	S26	S27	S28	S29	S30	S31	S32	S33		
3 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00		
	End Time:	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00		
		S34	S35	S36	S37	S38	S39	S40	S41	S42			
4 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00			
	End Time:	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00			
		S43	S44	S45	S46	S47	S48	S49	S50				
5 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00				
	End Time:	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00				
		S51	S52	S53	S54	S55	S56	S57					
6 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00	14:00					
	End Time:	14:00	15:00	16:00	17:00	18:00	19:00	20:00					
		S58	S59	S60	S61	S62	S63						
7 hour	Start Time:	8:00	9:00	10:00	11:00	12:00	13:00						
	End Time:	15:00	16:00	17:00	18:00	19:00	20:00						
		S64	S65	S66	S67	S68							
8 hour	Start Time:	8:00	9:00	10:00	11:00	12:00							
	End Time:	16:00	17:00	18:00	19:00	20:00							
		S69	S70	S71	S72								
9 hour	Start Time:	8:00	9:00	10:00	11:00								
	End Time:	17:00	18:00	19:00	20:00								
		S73	S74	S75									
10 hour	Start Time:	8:00	9:00	10:00									
	End Time:	18:00	19:00	20:00									
		S76	S77										
11 hour	Start Time:	8:00	9:00										
	End Time:	19:00	20:00										
		S78											
12 hour	Start Time:	8:00											
	End Time:	20:00											

Table 7-1: Periods of Improvement Strategy Application

7.3 Result Analysis

The effect of each scenario is simulated in the built model. The time of model running is set as 108 days plus 18 days for a warm-up period. Each scenario runs with 30 replications to guarantee the result accuracy. The time waiting to be seen by physician (WTBS) is used as a measurement. With 95% of the confidence, the model output of 78 scenarios is shown in Figure 7-2. The minimum and maximum values respectively indicate the lower bound and the upper bound of corresponding fluctuation ranges of the average WTBS in each scenario. The comparison result shows that the average WTBS is minimized within the scenario 76. It means that the proper period of the fast-tracking strategy applying should start at 8:00 am and last for 11 hours until 7:00 pm to minimize the waiting-time.

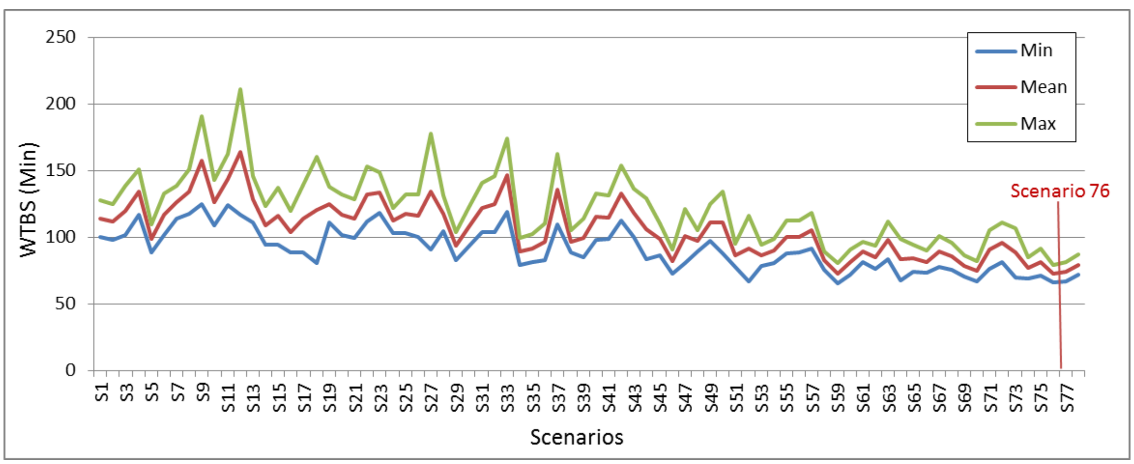

Figure 7-2: WTBS of 78 Scenarios Comparison

Since all the walk-in patients will be seen by a physician directly in the application period using the improvement method, the waiting-time is significantly reduced as shown in Figure 7-3. Since most CTAS 1 patients have the priority for the initial assessment, the corresponding waiting-time does not reduce very much. The fast-tracking method has more impact for patients with lower acuity levels. The reason of the delightful change is that low acuity patients will be seen and discharge quickly, which will reduce the waiting-time and release stretchers for new arrival patients. The length of stay (LOS) does not have a similar reduction range as the waiting-time reduction, it because patients still need to wait for available stretchers in the emergency room even the initial diagnosis has been done.

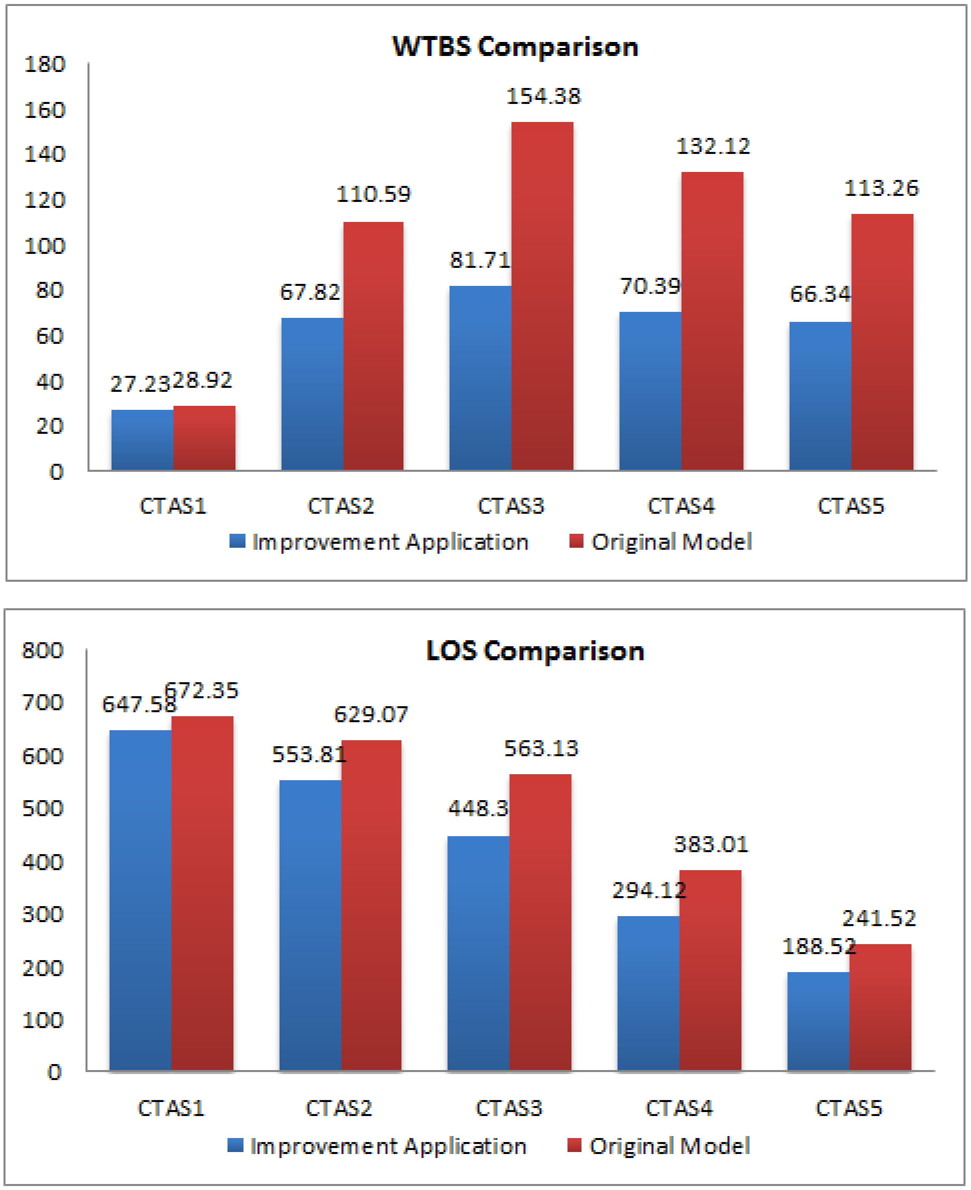

Figure 7-3: Improvement Strategy Estimation (Min)

7.4 Discussion

The application of “see-and-treat” method only changes the triage process to realize waiting-time reduction. Figure 7-4 indicates that the process-time of each treatment procedures does not have much change in the period of improvement strategy application. The comparison is based on the model outputs with 30 replications to guarantee the result accuracy.

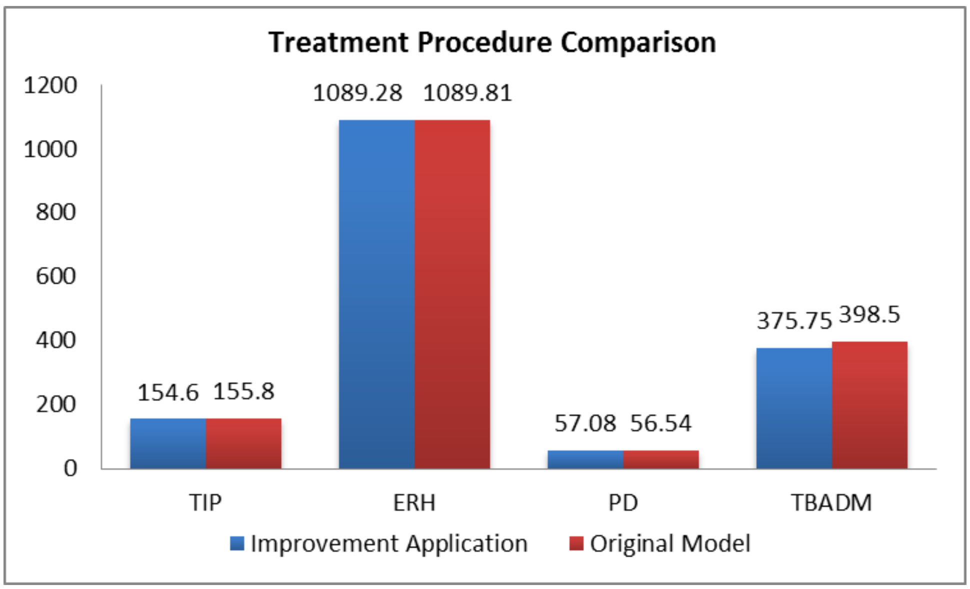

Figure 7-4: Treatment Procedure Comparison

As mentioned previously, the method selection is to have a proper improvement way without much physical adjustment. Using lean thinking is the other way for the waiting-time reduction through reducing process-time of treatment procedures. The potential application of lean thinking in healthcare will be introduced in the next chapter

7.5 Summary

The "see-and-treat" method is a validated alternative to accelerate the patient-flow in the emergency department (ED). Compared to other improvement strategies, this method does not require much layout changing or medical staff hiring. The model output indicates this method has the significant impact for the waiting-time (WTBS) reduction which is good to enhance the ED care delivery efficiency. To maximize the positive impact, the method is recommended to be applied in the daytime from 8:00 am to 7:00 pm to minimize the waiting-time.

Chapter 8

Conclusions and Future Work

8.1 Conclusions

Simulation technology is used in this research as an appropriate investigation tool to analyze the ED operation. Discrete-Event Simulation (DES) is proofed as a validated method to represent the ED operation and to predict effects of related elements. The ED model built using the DES method mainly focuses on the high level of the system operation with certain details. In the ED operation, it is identified that the long process-time is accumulated by previous arrival patients waiting for treatment. In the initial step of the research, comparing the process-time of each treatment procedures with the other hospital operation reveals that the factor enlarging treatment time mainly happens at TIP and ERH procedures. It also indicates that the TBADM time caused by the transfer delay is a common case, which is not the main reason that enlarges process-time. This fact is validated using the DOE method. The result of DOE analysis clearly shows that the process-time of ERH procedure has the significant impact for the waiting-time duration. Additionally, the model implanted with the optimization indicates a direction to reduce waiting-time. With the precondition for maintaining a certain utilization level of the ED treatment areas, the research result indicates the optimal and realizable time-saving ranges of treatment procedures for waiting-time minimizing. Finally, the ED model is used to estimate the effect of an improvement method. The alternative design focuses on the treatment strategy changing to reduce waiting-time. Based on the literature review of ED improvement strategies, a modified "see-and-treat" method is proposed to use a team replacing the triage nurse at the step of initial assessment. Considering the budget saving, the proposed method does not require much physical changing which will not impact the current ED layout and staff scheduling. The start time and the duration of the improvement strategy application are modified to match the ED condition to minimize the waiting-time.

8.2 Research Contributions

This research developed a foundational framework for the ED improvement, which contains the necessary components for the problem investigation as well as open ports to enhance model details for the future research. Unlike recognizing the ED treatment as a simple system in the previous research, four general procedures of treatment process are used to represent the entire activities of the patient flow. Considering these procedures respectively helps to narrow searching range of the bottleneck identification. Additionally, the close observation of ED operations reveals the fact that the treatment of TIP procedure is a cycling process. It means the TIP time is enlarged by waiting-time accumulating among the necessary treatment steps in the TIP period. Representing this case in the model is realized by setting the specific number of treatment cycle times for patients with different acuity levels. These efforts make the built model better match the real ED operation, which increases the accuracy level of the ED model. If more features are required to be added in the model, it is realizable to adding more factors in each treatment procedure based on the current model.

In addition, this research applies several novel methods to analyze the ED performance for the potential improvement capacity based on the ED model built by using a DES method. Since most healthcare systems involve massive factors related to the operation efficiency, the first work done identified the elements with the significant impact. In this research, the DOE method is successfully applied to investigate the procedure impact for the waiting-time. The Scatter Search method is proposed to accelerate the searching process for the optimal configuration identification with the aim of waiting-time minimizing. To meet the requirements in solving various optimization problems, this method is flexibly implanted with other meta-heuristic methods such as genetic algorithm.

Designing an improvement strategy for the ED waiting-time reduction without budget increasing is another goal of this research. Without changing the amount of the ED physical resources to realize waiting-time reduction, a modified "see-and-treat" method is proposed in the model for treatment procedure modification. This improvement strategy is modified specifically to match the condition of the ED at VGH, and the waiting-time is minimized in the research of 78 scenarios in the ED operation.

In summary, following contributions have been made in this research:

1) A simulation model of ED operations is built using DES method to accelerate the process of bottleneck identification and improvement method evaluation. Considering certain detail levels guarantees ED model accuracy.
2) Several novel methods are integrated to analyze the ED performance for the potential improvement capacity. The impacts of treatment procedures are estimated by DOE method. Scatter Search indicates the optimal procedure to minimize waiting-time.
3) An improvement method is proposed to reduce the waiting-time with less physical adjustment to avoid disturbing the ED daily operation.

8.3 Improvement Suggestion

Considering the cost of ED improvement, the suggested improvement strategies are proposed from two aspects: alternatives based on current ED resources and using additional resource to release the imbalance between ED capacity and treatment requests. For the waiting-time reduction, one way is to design alternatives considered from the treatment process changing. The first recommended improvement method is “see-and-treat” method which is proofed as a validated improvement method based on the model outputs. The other way is to adjust shifts of the related teams at ERH procedure to better match the fluctuation of the request to reduce the ERH time.

On the other hand, adding necessary ED resources is a direct way to reduce waiting-time. Physician shortage is an important reason enlarging TIP time. Considering the cost of hiring an additional physician, adding physician assistants (PA) as SOGH does is a potential way to enhance the physician utilization. It will let physician better focus on the treatment requests matching their abilities, such as diagnosis, and let physician assistant conduct less important physical exams, diagnosis and treatment. It can benefit TIP time reduction and further reducing the whole length of stay. Using another area to contain admitted patients and discharged patients will release ED stretcher shortage. It can save the time for new arrival patients waiting to receive assessment and diagnosis once they lie in stretchers.

8.4 Future Work

The ED performance and DOE analysis indicates that the ERH process-time is the main factor that extends patient’s length of stay (LOS) to cause waiting-time increasing for later arrival patients. Activities in the ERH period require a close cooperation of several teams to complete patients’ condition estimating. In order to further analyze the performance of the each team, a way is to increase the detail level of the ED model for the corresponding part. The current model uses a distribution function to represent the required ERH process-time for an individual patient. Once the necessary information is gathered, the module of ERH activities can be directly added to the model to replace the ERH distribution function without modifying other parts. Methods of DOE and the model optimization also can be extended to analyze the related performances of ERH activities in the future research. For example, the DOE method can be used to estimate the importance of the ERH factors, and the model optimization could provide the optimal combination of the start time of each team. Since the ERH order is related to the staff in other departments such as hospitalist, the research may be extended to the related departments rather than only focusing on the ED.

On the other hand, increasing the bed capacity is always recognized as a universal solution for ED improvement. However, inefficient factors may exist. The result of the model optimization indicates the combination of reduction ranges of treatment procedures to minimize the waiting-time. It provides an improvement direction but still requires further work to realize. The process-time reduction of each treatment procedure requires the cooperation of medical staffs. The improvement strategies considered through lean thinking is a validated way to avoid the time waste in the treatment process and achieve the aim of reducing process-time. The lean thinking applications will be introduced in the next paragraph.

“Lean” is a term adopted from Japanese manufacturing defining a philosophy to eliminate non-value-added activities. The application of lean thinking is a continuous improvement process which requires employee involvement and empowerment (Ōno 1988). The aim is to remove duplicate process and unnecessary procedures. Patients can be recognized as products that passing through several steps to finish treatment tasks. Medical staffs (physician and nurse) are operators in the treatment process. It matches the application of lean thinking: it is like designing alternatives with a focus on manufacturing process rather than the final product (Dickson 2009). The initial step starting lean is to draw a Value Stream Map (VSM) based on the current flow-chart of patient flow. The VSM is used to assess the waste amount of treatment activities and it quantifiably indicates the amounts of value-added and no value-added time in each step. The unnecessary steps can be identified and then eliminated.

Both simulation and lean have a similar motivation: improvement of process and service delivery. Using DES modeling with lean implantation is a feasible way to investigate the performance target system improvement. In the industrial field, DES model enables designers to explore the impact of alternatives based on lean principles. Lean strategies are considered from batch size, workstation process time, rework time and WIP storage capacity (Shannon 2010). The fusion of DES and lean is also applied in the healthcare field. The integration of DES and lean can be used in three aspects (Robinson 2012): playing an educational role in teaching key lean principles, using DES to create a dynamic process map to facilitate alternative idea exploration, and using model output to evaluate effectiveness of designed alternatives. Holden (2011) lists more than fifty work process and work structure changes resulting from Lean implementation though reviewing eighteen articles describing Lean initiatives in 15 EDs. The changes benefiting VGH performance are identified based on the corresponding estimation of the model output.

The last potential way is using a dynamic strategy to adjust the patient distribution. The sequence of patient entering ER is mainly decided by nurse experience. CTAS 1 and CTAS 2 patients have priority to enter, but there is no clear role directing the decision making of entering sequence for the patients from CTAS 3 to CTAS 5. Considering the mixed impact of waiting-time increasing and CTAS level is a potential way to design a flexible mechanism which uses waiting time as a weight to effect entering priority. For example, the priority of a CTAS 4 patient keeps increasing and finally enters ER earlier than a CTAS 3 patient if the CTAS 4 patient has waited much more time than a CTAS 3 patient does.

8.5 Further Development of the ED Model

The current ED model is developed based on 2 months of data, and the third month data is used for the model validation. To further investigate features of arrival patients, more data will enhance the application scope of built ED model. The new data should be imported quarterly to represent the impact of seasonal changing. It suggests that using one year data covering consistent four seasons to represent the symptom changing of arrival patients which impacts patient distribution and process-time. Since the model operation follows the conceptual model, patient follow in the model does not need to change. As it uses different distribution function to represent the process-time in each treatment area, it also does not need to change the current distribution function. The statistical analysis of the new data is used for setting new age distribution of arrival patient constitution, CTAS level distribution and patient distribution of treatment location. These three factors are impacted by seasonal changing.

The requirement of model further development is still under the consideration at the initial step of model development. The statistical result of each selected feature is imported into the model using individual "Global Table" of the simulation software. As changing one factor only requires changing the data of the corresponding "Global Table", it leads to significant time savings for model adjustment.

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Appendix A

Full Table

Distribution Function (Parameters)
beta(min, max, shape1, shape2)
exponential (location, scale)
johnsonbounded (min, max, shape1, shape2)
loglogistic (location, scale, shape)
pearsont6 (location, scale, shape1, shape2)
triangular (min, max, mode)

Table 9-1: Parameter Definition of Generated Distribution Functions

Walk-in Patient	
Part 1	johnsonbounded(0.62, 128.93, 1.142, 0.75)
Part 2	johnsonbounded(1.23, 298.72, 1.69, 0.79)
Part 3	johnsonbounded(0.47, 345.81, 1.48, 0.69)
Part 4	randomwalk(0.24, 0.075, 0.03)
Part 5	pearsont6(0.89, 20.17, 1.72, 2.67)
Part 6	pearsont6(0.53, 25.13, 2.00, 4.83)
Part 7	johnsonbounded(0.12, 166.83, 2.99, 1.09)
Part 8	johnsonbounded(0.33, 150.84, 2.83, 1.10)
Part 9	johnsonbounded(0.15, 210.63, 2.81, 1.03)
Part 10	pearsont6(0.000000, 22.21, 2.79, 4.83)
Part 11	randomwalk(0.09, 0.13, 0.13)
Part 12	johnsonbounded(0.18, 149.34, 2.32, 1.03)
Ambulance Patient	
Part 1	pearsont6(0.85, 895.66, 1.05, 11.16)

Table 9-2: Distribution Functions of Arrival Frequency

Walk-in Patients					
	CTAS1	CTAS2	CTAS3	CTAS4	CTAS5
Age 0~9	10.00%	2.63%	3.17%	7.21%	8.26%
Age 10~19	0.00%	5.12%	7.32%	12.46%	11.05%
Age 20~29	6.67%	14.91%	18.54%	20.32%	19.20%
Age 30~39	6.67%	14.47%	12.95%	14.07%	13.39%
Age 40~49	6.67%	17.25%	13.16%	12.98%	14.73%
Age 50~59	10.00%	15.06%	12.39%	10.54%	11.38%
Age 60~69	20.00%	12.13%	11.47%	8.10%	9.15%
Age 70~79	30.00%	8.77%	10.19%	6.69%	6.58%
Age 80~89	10.00%	8.19%	8.29%	5.77%	4.58%
More	0.00%	1.46%	2.51%	1.85%	1.67%
Total	100%	100%	100%	100%	100%
Ambulance Patients					
	CTAS1	CTAS2	CTAS3	CTAS4	CTAS5
Age 0~9	0.00%	0.00%	0.00%	0.40%	2.56%
Age 10~19	0.00%	3.42%	3.41%	4.36%	0.00%
Age 20~29	9.09%	9.93%	6.06%	8.71%	10.26%
Age 30~39	6.82%	4.11%	7.77%	9.50%	12.82%
Age 40~49	13.64%	9.25%	7.95%	7.33%	2.56%
Age 50~59	13.64%	11.64%	10.80%	8.12%	7.69%
Age 60~69	22.73%	13.01%	9.09%	10.69%	7.69%
Age 70~79	18.18%	13.70%	16.67%	13.47%	12.82%
Age 80~89	11.36%	25.68%	27.08%	25.15%	28.21%
More	4.55%	9.25%	11.17%	12.28%	15.38%
Total	100%	100%	100%	100%	100%

Table 9-3: Age Distribution

CTAS 1				
	Age Category 1	Age Category 2	Age Category 3	Age Category 4
Resuscitation Area	33.33%	52.63%	52.38%	40.00%
Monitor Area	66.67%	36.84%	40.48%	50.00%
Treatment Area	0.00%	5.26%	2.38%	0.00%
MTA	0.00%	5.26%	4.76%	10.00%
Total	100.00%	100.00%	100.00%	100.00%
CTAS 2				
	Age Category 1	Age Category 2	Age Category 3	Age Category 4
Resuscitation Area	22.22%	3.12%	8.76%	7.14%
Monitor Area	72.22%	61.15%	73.45%	81.55%
Treatment Area	5.56%	30.46%	15.82%	10.12%
MTA	0.00%	5.28%	1.98%	1.19%
Total	100.00%	100.00%	100.00%	100.00%
CTAS 3				
	Age Category 1	Age Category 2	Age Category 3	Age Category 4
Resuscitation Area	5.26%	2.17%	2.46%	2.01%
Monitor Area	22.81%	35.16%	51.60%	72.68%
Treatment Area	22.81%	36.66%	28.57%	20.55%
MTA	49.12%	26.01%	17.36%	4.76%
Total	100.00%	100.00%	100.00%	100.00%
CTAS 4				
	Age Category 1	Age Category 2	Age Category 3	Age Category 4
Resuscitation Area	0.98%	0.61%	0.46%	0.74%
Monitor Area	4.88%	12.71%	33.53%	61.14%
Treatment Area	11.71%	25.64%	26.36%	25.25%
MTA	82.44%	61.04%	39.65%	12.87%
Total	100.00%	100.00%	100.00%	100.00%
CTAS 5				
	Age Category 1	Age Category 2	Age Category 3	Age Category 4
Resuscitation Area	0.00%	0.94%	1.30%	0.00%
Monitor Area	9.46%	8.08%	6.06%	35.38%
Treatment Area	10.81%	22.83%	29.00%	32.31%
MTA	79.73%	68.15%	63.64%	32.31%
Total	100.00%	100.00%	100.00%	100.00%

Table 9-4: Location Distribution

	Age 0~9	Age 10~49	Age 50~79	Age 80~99+
CTAS 1	0.00%	27.78%	22.50%	44.44%
CTAS 2	0.00%	12.93%	26.21%	43.37%
CTAS 3	2.94%	8.37%	22.73%	32.99%
CTAS 4	0.00%	3.90%	15.95%	30.64%
CTAS 5	0.00%	1.12%	2.80%	7.69%

Table 9-5: ERH Probability

	Age 0~9	Age 10~49	Age 50~79	Age 80~99+
CTAS 1	0.00%	44.44%	47.50%	77.78%
CTAS 2	0.00%	7.07%	20.51%	36.14%
CTAS 3	0.00%	7.00%	14.92%	28.43%
CTAS 4	0.00%	1.13%	12.72%	19.50%
CTAS 5	0.00%	3.93%	5.61%	5.77%

Table 9-6: TBADM Probability

Monitor Area	
ERH	loglogistic(0.000000, 742.713167, 2.182043, 1)
TBADM	inversegaussian(0.000000, 352.101099, 124.319049, 1)
PD	pearsont6(5.688266, 107.905991, 0.861129, 2.743060, 1)
Trauma Area	
ERH	pearsont6(0.000000, 4371.572034, 1.774469, 8.005374, 1)
TBADM	inversegaussian(2.066408, 395.433592, 109.770127, 1)
PD	pearsont6(5.786107, 52.866709, 0.872598, 2.279502, 1)
MTA	
ERH	beta(67.902593, 2191.627531, 0.611827, 1.472136, 1)
PD	lognormal2(5.252067, 13.878656, 1.325749, 1)

Table 9-7: Distribution Function of Treatment Procedure

Appendix B

Program Code

Main Window

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Windows;
using System.Windows.Controls;
using System.Windows.Data;
using System.Windows.Documents;
using System.Windows.Input;
using System.Windows.Media;
using System.Windows.Media.Imaging;
using System.Windows.Navigation;
using System.Windows.Shapes;
using System.IO;
using TrialSolutionGenerator_WPF.Program;


namespace TrialSolutionGenerator_WPF
{
    /// <summary>
    /// Interaction logic for MainWindow.xaml
    /// </summary>
    public partial class MainWindow : Window
    {
```

```
        string SOLUTION_POOL_FILE_PATH = "./dbfile/solutionPoolDB.txt";
        string SOLUTION_COLLECTION_PATH = "./dbfile/solutionsCollection.txt";
        string TOP_10_SOLUTION_PATH = "./dbfile/top10solutions.txt";

        SolutionPool thePool; // existing solution pool, will be stored in solu-
tionPoolDB.txt
        TrailSolution[] solutionCollection; // the 7000 solutions read from solu-
tionsCollection.txt
        TrailSolution[] toptenSolutions; // the top 10 solutions read from
top10solutions.txt
        TrailSolution[] toptenYSolutions; // the B2 set of reference set
        TrailSolution[] improveResultList; // the final result lest

        // NOTE:
        // this string can be modified by user
        // so it is not necessary the same as
        // the top 10 in "./dbfile/top10solutions.txt"
        // when start processing
        string topTenStr = "";
        string topTenYStr = "";
        string resultSolutionStr = "";

        public MainWindow()
        {
            InitializeComponent();
            thePool = new Program.SolutionPool(SOLUTION_POOL_FILE_PATH);
            //thePool.addSolution(new Program.TrailSolution(new double[4] {5, 5,
25, 2}));
        }

        // load top 10 solution button event listener
        private void loadtoptenbutton_Click(object sender, RoutedEventArgs e)
        {
            readSolutionCollectionDB(SOLUTION_COLLECTION_PATH);
            readTopTenSolutionDB(TOP_10_SOLUTION_PATH);
            outputTopTenSolution();

            // distance calcuation
            toptenYSolutions = new TrailSolution[10];
            for (int i = 0; i < toptenSolutions.Length; i++)
            {
                double currMaxDis = 0;
                int maxIndex = 0;
                double tempDis = 0;
                for (int j = 0; j < 7140; j++)
                {
                    tempDis = toptenSolu-
tions[i].getDistance(solutionCollection[j]);
                    if (currMaxDis < tempDis)
                    {
                        currMaxDis = tempDis;
```

```
                    maxIndex = j;
                }
            }
            toptenYSolutions[i] = solutionCollection[maxIndex];
        }
        outputTopTenYSolution();
    }

    // output to textbox
    public void outputTopTenSolution()
    {
        topTenStr = "";
        for (int i = 0; i < toptenSolutions.Length; i++)
        {
            topTenStr +=
                toptenSolutions[i].toStringwithTab() + "\n";
        }
        top10TBox.Text = topTenStr;
    }
    public void outputTopTenYSolution()
    {
        topTenYStr = "";
        for (int i = 0; i < toptenYSolutions.Length; i++)
        {
            topTenYStr +=
                toptenYSolutions[i].toStringwithTab() + "\n";
        }
        top10YTBox.Text = topTenYStr;
    }

    // file reader for top10solutions.txt
    public void readTopTenSolutionDB(string filepath)
    {
        string[] dataListStr = new string[5];
        TrailSolution currSolution;
        string line;
        int i = 0;
        toptenSolutions = new TrailSolution[10];
        try
        {
            using (StreamReader sr = new StreamReader(filepath))
            {
                // ignore the first line;
                line = sr.ReadLine();

                while ((line = sr.ReadLine()) != null)
                {
                    dataListStr = line.Split(new Char[] { ' ', '\t' });
                    currSolution =
                        new TrailSolution
                        (
                        Convert.ToDouble(dataListStr[0]),
```

```
                    Convert.ToDouble(dataListStr[1]),
                    Convert.ToDouble(dataListStr[2]),
                    Convert.ToDouble(dataListStr[3])
                    );
                currSolution.setPoss(Convert.ToDouble(dataListStr[4]));
                toptenSolutions[i] = currSolution;
                i++;
            }
        }
    }
    catch (Exception e)
    {
        Console.WriteLine("The collection db file could not be read:");
        Console.WriteLine(e.Message);
    }
}

// file reader for solutionsCollection.txt
public void readSolutionCollectionDB(string filepath)
{
    string[] dataListStr = new string[5];
    TrailSolution currSolution;
    string line;
    int i = 0;
    solutionCollection = new TrailSolution[8000];
    try
    {
        using (StreamReader sr = new StreamReader(filepath))
        {
            // ignore the first line;
            line = sr.ReadLine();

            while ((line = sr.ReadLine()) != null)
            {
                dataListStr = line.Split(new Char[] { ' ', '\t' });
                currSolution = new TrailSolution(dataListStr);
                solutionCollection[i] = currSolution;
                i++;
            }
        }
    }
    catch (Exception e)
    {
        Console.WriteLine("The collection db file could not be read:");
        Console.WriteLine(e.Message);
    }
}

// Generate Trial Solution button event listener
private void TSGenerateButton_Click(object sender, RoutedEventArgs e)
{
    Random r = new Random();
```

```
            int selectedXindex = r.Next(0, 10);

            TrailSolution selectedXSolution = toptenSolutions[selectedXindex];

            // index range [0, 19]
            int selectedYindex = r.Next(0, 20);
            while (true)
            {
                if (selectedYindex == selectedXindex)
                    selectedYindex = r.Next(0, 20);
                else
                    break;
            }

            TrailSolution selectedYSolution;

            if (selectedYindex < 10)
            {
                selectedYSolution = toptenSolutions[selectedYindex];
            }
            else
            {
                selectedYSolution = toptenYSolutions[selectedYindex - 10];
            }

            // comResult is the X'
            TrailSolution comResult = selectedXSolu-
tion.getCombination(selectedYSolution);

            improveResultList = new TrailSolution[5];
            improveResultList = comResult.improveSolution();

            checkExistInPool();


            for (int i = 0; i < improveResultList.Length; i++)
            {
                thePool.addSolution(improveResultList[i]);
            }

            outputResultSolution();
        }

        // solution Pool check
        public void checkExistInPool()
        {
            for (int i = 0; i < improveResultList.Length; i++)
            {
                foreach (TrailSolution curr in thePool.getData())
                {
                    if (curr.isTheSameAs(improveResultList[i]))
                    {
```

```
                    // if curr result exist, modify it to a blank object
                    improveResultList[i] = new TrailSolution();
                }
            }
        }
    }

    public void outputResultSolution()
    {
        resultSolutionStr = "";
        for (int i = 0; i < improveResultList.Length; i++)
        {
            resultSolutionStr +=
                improveResultList[i].toStringwithTab() + "\n";
        }
        resultTBox.Text = resultSolutionStr;
    }

    private void resetButton_Click(object sender, RoutedEventArgs e)
    {
        thePool.resetPool();
    }
}}
```

Trail Solution Generator

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace TrialSolutionGenerator_WPF.Program
{
    class TrailSolution
    {
        double TIP;
        double ERH;
        double PD;
        double TBADM;
        double[] dataList;
        double selectPoss;
        bool possSeted = false;

        public TrailSolution()
        {
            this.TIP = -1;
            this.ERH = -1;
            this.PD = -1;
            this.TBADM = -1;
            this.dataList = new double[] { -1, -1, -1, -1 };
            this.selectPoss = 0.0;
            possSeted = false;
        }

        public TrailSolution(double TIP, double ERH, double PD, double TBADM)
        {
            this.TIP = TIP;
            this.ERH = ERH;
            this.PD = PD;
            this.TBADM = TBADM;
            this.dataList =  new double[] {TIP, ERH, PD, TBADM};
            this.selectPoss = 0.0;
            possSeted = false;
        }
        public TrailSolution(double[] dataList)
        {
            this.TIP = dataList[0];
            this.ERH = dataList[1];
            this.PD = dataList[2];
            this.TBADM = dataList[3];
            this.dataList = dataList;
```

```
            this.selectPoss = 0.0;
            possSeted = false;
        }

        public TrailSolution(string[] dataList)
        {
            this.TIP = Convert.ToDouble(dataList[0]);
            this.ERH = Convert.ToDouble(dataList[1]);
            this.PD = Convert.ToDouble(dataList[2]);
            this.TBADM = Convert.ToDouble(dataList[3]);
            this.dataList = new double[4] { TIP, ERH, PD, TBADM };
            this.selectPoss = 0.0;
            possSeted = false;
        }

        // calculate distance betweent target and this object
        public double getDistance(TrailSolution target)
        {
            double distance = 0.0;

            distance += Math.Abs(target.getTIP() - this.TIP);
            distance += Math.Abs(target.getERH() - this.ERH);
            distance += Math.Abs(target.getPD() - this.PD);
            distance += Math.Abs(target.getTBADM() - this.TBADM);

            return distance;
        }

        // combination process with target
        public TrailSolution getCombination(TrailSolution target)
        {
            Random r = new Random();

            var indexList = Enumerable.Range(0, 4).OrderBy(x =>
r.Next()).ToArray();

            Console.Out.WriteLine("Select Index: [" + indexList[0] + ", " + in-
dexList[1] + "]");

            double[] resultDataList = this.getDataList();
            double[] targetDataList = target.getDataList();

            resultDataList[indexList[0]] = targetDataList[indexList[0]];
            resultDataList[indexList[1]] = targetDataList[indexList[1]];

            return new TrailSolution(resultDataList);
        }

        public double getTIP()
        {
            return TIP;
        }
```

```
        public double getERH()
        {
            return ERH;
        }
        public double getPD()
        {
            return PD;
        }
        public double getTBADM()
        {
            return TBADM;
        }

        public double getSelectPoss()
        {
            return selectPoss;
        }
        public double[] getDataList()
        {
            return dataList;
        }

        public bool hasPoss()
        {
            return possSeted;
        }

        public string toString()
        {
            return TIP + " " + ERH + " " + PD + " " + TBADM;
        }

        public string toStringwithTab()
        {
            return TIP + "\t" + ERH + "\t" + PD + "\t" + TBADM;
        }

        public TrailSolution[] improveSolution()
        {
            TrailSolution[] resultList = new TrailSolution[5];

            resultList[0] = this;

            if (this.TIP - 0.05 >= 0.45)
            {
                resultList[1] =
                    new TrailSolution(this.TIP - 0.05, this.ERH, this.PD,
this.TBADM);
            }
            else
            {
                resultList[1] =
```

```
                new TrailSolution(0.45, this.ERH, this.PD, this.TBADM);
            }

            if (this.ERH - 0.05 >= 0.7)
            {
                resultList[2] =
                    new TrailSolution(this.TIP, this.ERH - 0.05, this.PD,
this.TBADM);
            }
            else
            {
                resultList[2] =
                    new TrailSolution(this.TIP, 0.7, this.PD, this.TBADM);
            }

            if (this.PD - 0.05 >= 0.2)
            {
                resultList[3] =
                    new TrailSolution(this.TIP, this.ERH, this.PD - 0.05,
this.TBADM);
            }
            else
            {
                resultList[3] =
                    new TrailSolution(this.TIP, this.ERH, 0.2, this.TBADM);
            }

            if (this.PD - 0.05 >= 0.8)
            {
                resultList[4] =
                    new TrailSolution(this.TIP, this.ERH, this.PD, this.TBADM -
0.05);
            }
            else
            {
                resultList[4] =
                    new TrailSolution(this.TIP, this.ERH, this.PD, 0.8);
            }

            return resultList;

        }

        public void setPoss(double newPoss)
        {
            this.selectPoss = newPoss;
            possSeted = true;
        }

        public void setTIP(double newTIP)
        {
            this.TIP = newTIP;
```

```
            this.dataList[0] = newTIP;
        }
        public void setERH(double newERH)
        {
            this.ERH = newERH;
            this.dataList[1] = newERH;
        }
        public void setPD(double newPD)
        {
            this.PD = newPD;
            this.dataList[2] = newPD;
        }
        public void setTBADM(double newTBADM)
        {
            this.TBADM = newTBADM;
            this.dataList[3] = newTBADM;
        }

        public bool isTheSameAs(TrailSolution target)
        {
            for (int i = 0; i < dataList.Length; i++)
            {
                if (this.dataList[i] != target.getDataList()[i])
                    return false;
            }
            return true;
        }

    }
}
```

Solution Pool

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.IO;

namespace TrialSolutionGenerator_WPF.Program
{
    class SolutionPool
    {
        List<TrailSolution> thePool;
        StreamReader sr;
        string filepath;

        public SolutionPool(string filepath)
        {
            thePool = new List<TrailSolution>();
            this.filepath = filepath;

            readPoolFile();
        }

        public void readPoolFile()
        {
            string[] dataListStr = new string[4];
            string line;
            try
            {
                using (sr = new StreamReader(filepath))
                {
                    while ((line = sr.ReadLine()) != null)
                    {
                        dataListStr = line.Split(new Char[] { ' ', '\t' });
                        thePool.Add(new TrailSolution(dataListStr));
                    }
                }
            }
            catch (Exception e)
            {
                Console.WriteLine("The pool db file could not be read:");
                Console.WriteLine(e.Message);
            }
        }

        public void addSolution(TrailSolution newSolution)
        {
            thePool.Add(newSolution);
```

```
            // add new Solution to db file
            using (StreamWriter sw = File.AppendText(filepath))
            {
                // Add some text to the file.
                sw.WriteLine(newSolution.toString());
            }

        }

        // check existing trail solution
        public bool contains(TrailSolution target)
        {
            foreach (TrailSolution curr in thePool)
            {
                if (curr.isTheSameAs(target))
                {
                    return true;
                }
            }
            return false;
        }

        public int getSize()
        {
            return thePool.Count;
        }

        public List<TrailSolution> getData()
        {
            return thePool;
        }

        public void resetPool()
        {
            thePool = new List<TrailSolution>();

            string newfilepath = @"./dbfile/solutionPoolDB_backup_" +
string.Format("{0:MM dd HH mm ss}", DateTime.Now) + ".txt";

            string oldfilepath = @"./dbfile/solutionPoolDB.txt";

            try
            {
                System.IO.File.Copy(oldfilepath, newfilepath);
                System.IO.File.Delete(oldfilepath);
            }
            catch (System.IO.IOException e)
            {
                Console.WriteLine(e.Message);
                return;
            } }}}
```