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THE EVACUATION PROBLEM IN MULTI-STORY BUILDINGS

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THE EVACUATION PROBLEM IN MULTI-STORY BUILDINGS

A Thesis Presented

by

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ABSTRACT

THE EVACUATION PROBLEM IN MULTI-STORY BUILDINGS

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The pressure from high population density leads to the creation of high-rise structures within urban areas. Consequently, the design of facilities which confront the challenges of emergency evacuation from high-rise buildings become a complex concern. This paper proposes an embedded program which combines a deterministic (GMAFLAD) and stochastic model (M/G/C/C State Dependent Queueing model) into one program, GMAF_MGCC, to solve an evacuation problem. An evacuation problem belongs to Quadratic Assignment Problem (QAP) class which will be formulated as a Quadratic Set Packing model (QSP) including the random flow out of the building and the random pairwise traffic flow among activities. The procedure starts with solving the QSP model to find all potential optimal layouts for the problem. Then, the stochastic model calculates an evacuation time of each solution which is the primary decision variable to figure the best design for the building. Here we also discuss relevant topics to the new program including the computational accuracy and the correlation between a successful rate of solving and problems' scale. This thesis examines the relationship of independent variables including arrival rate, population and a number of stories with the dependent variable, evacuation time. Finally, the study also analyzes the probability distribution of an evacuation time for a wide range of problem scale.

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GLOSSARY

GMAF_MGCC	Graphic user interface for Multi-Attribute Facility layout and design integrated with MGCC state dependent queueing model
MAFLAD	Multi-Attribute Facility Layout and Design
GMAFLAD	Graphic User Interface (GUI) for Multi-Attribute Facility Layout and Design
MSAP	Multi-Story Assignment Problems
QAP	Quadratic Assignment Problems
QSP	Quadratic Set Packing
GQAP	Generalized Quadratic Assignment Problems
Q3AP	Quadratic 3 Dimensions Assignment Problems
M/G/C/C	State Dependent Queueing model

CHAPTER 1

INTRODUCTION

When designing a building, there are multiple-goals for building designers. One of primary goals for building centers around the building capacity (maximum number of occupants can be hold in a certain point in time). In order to maintain the expected capacity under the limitation of a building site (i.e. construction area or space), architects focus on increasing the height of the building, instead of its width and length. This leads to the vertical expansion of buildings in urban areas.

A typical example of the high density of skyscrapers in South East Asia is Ho Chi Minh City in Vietnam. With the estimated population of 8.4 million, growing annually at roughly 2.09 percent and the density around 4,025 people per kilometer square, the demand of housing in Ho Chi Minh City imposes a huge pressure on the government (The General Statistic Office of Vietnam, 2016).

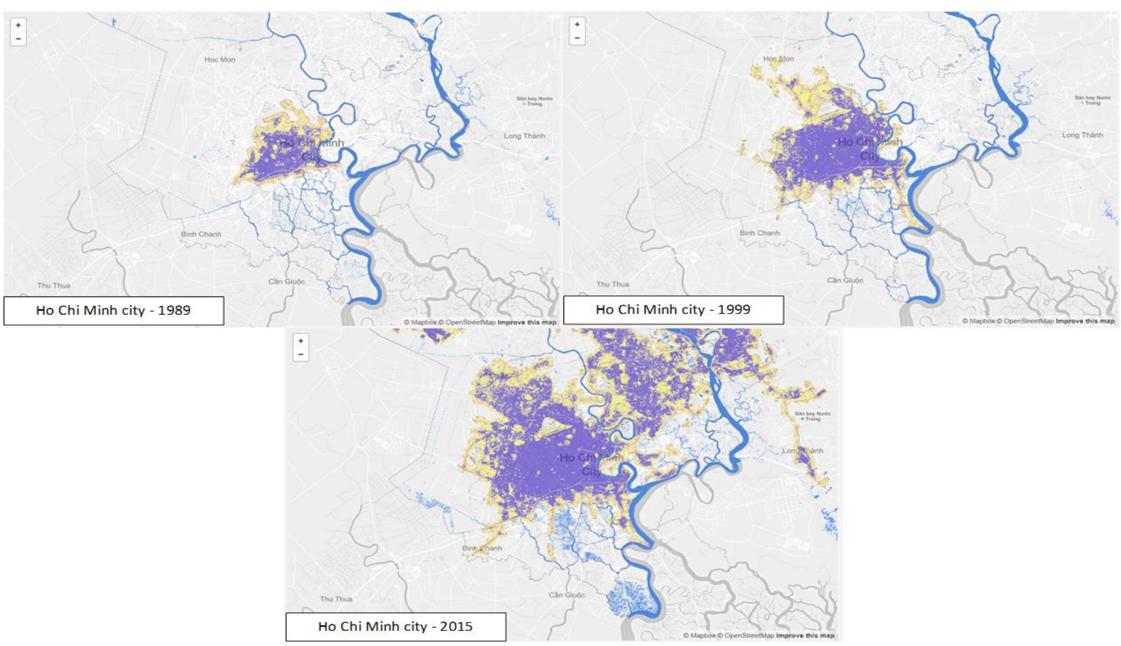


Figure 1- The Urbanization Map of Ho Chi Minh City from 1989 to 2015

(Source: http://www.atlasofurbanexpansion.org/cities/view/Ho_Chi_Minh_City)

The uneven distribution and high concentration of population leads to a rapid increase of high-rise buildings – Figure 1. According to website "www.skyscrapercenter.com", there are 16 buildings above 150 meters in the city, among which the tallest one is 461 meters. In addition, there are hundreds of apartments and buildings with more than ten stories.

The high density of high-rise buildings in big cities like Ho Chi Minh is a challenge for firefighting. The rescue and evacuation mission in skyscrapers face difficulties due to the sudden inflation of occupants during an event. In general, the construction contractors and architects pay little attention in optimizing the arrangement of activities. The pre-evaluation of capacity and arrival rate for each level of the building will benefit the evacuation task as well as optimizing inner-flows among floors.

1.1. Background

Two primary factors that block the evacuee flow during the catastrophe are the density of traffic flow and the limited number of exits or discharges. The arbitrary arrangement and in consideration of traffic densities of constructions layout (on the vertical dimension) can create congestion and increase the clearance time to evacuate occupants.

The evacuation problem is related to the quadratic assignment problem which covers a broad class of facility planning layout problems. We expect to maximize the traffic flow of occupants out of the building in an emergency, hence the QAP will be transformed into the QSP model which contains two terms, the flow out of the building (linear placement cost term) and the occupants flow of pair-wise interaction among activities (an inter-activity traffic flow term).

For instance, we consider arranging the set of k activities into the N floors of a multi-story dimensional building ($n \leq m$) with the cost of placing each activity k onto each of the m^{th} floor equal to the average number of occupants escaping from the system from the k^{th} activity at the m^{th} floor and the cost of the traffic flow between activity k at the m^{th} floor to activity j at the n^{th} floor. In this case, the gap among levels will be a fixed distance d_{mn} which is the length of the stair connecting two stories (in an emergency situation, people are not recommended to use the elevator). In accordance with the functional purpose of this problem, we ignore the difference in the occupied shape of each, and it is assumed that each activity will encompass the floor's area that it captures. Regarding the two essential terms of the objective, the cost of the outflow and between-flows can be characterized by a Poisson process, and the k^{th} activity will have one value of arrival rate for each t^{th} alternative of the outflow, λ_{kt}, and a set of arrival rate associate to between-flow with other activities, λ_{kj}. The objective is to select an optimal layout which will maximize total flow out of the building (a vector of evacuation flows) and cluster activities which frequently interact with each other into a group (a matrix of traffic flows among activities).

The evacuation flow, λ_{kt} and internal traffic flow, λ_{kj} are not deterministic. These parameters can be changed over time (dynamic) and are uncertain (stochastic). Unfortunately, the underlying QSP equations do not include any stochastic analysis. Here we embed the simulation model, which contains queueing network state-dependent properties, into the new program to analyze an evacuation problem in the stochastic perspective.

Regarding the queueing network, each activity, stairwell, and corridor at each floor (landing) will be considered as the node of the queueing system, and the logical connection between two *nodes* will create an *arc*. Meanwhile, the activity will be a queue of occupants, the corridor and stairwell will play the role of a server in the queueing network. The designs from the QSP model will be transformed into a queueing network system involving nodes and arcs where each node will contain a set of parameters including arrival rate, population, origin, and destination. These parameters will be put into a matrix form, which will be discussed in the below section and using the M/G/C/C transient model to analyze the robustness of the design.

1.2. **Outline**

The primary purpose of this research is establishing a standard algorithmic procedure of combining deterministic and stochastic models and embedding this protocol into an Integration program to solve the QAP problem for a high-rise building. This thesis covers the historical background of deterministic and stochastic simulation methodologies in the second chapter. In the 3rd and 4th sections we introduce the mathematical formulations of referred models and supported software, Benchmark. The principal of this research, GMAF_MGCC, and other relevant studies involving computational accuracy and correlation of solving rate and problems' scale are elaborated in the 5th section. This research studies the behavior of the egress time due to the variation of arrival rate, population and a number of stories through experiments in the 6th section. The final section discusses on accomplishments of this research as well as extension and opportunities for future research.

CHAPTER 2

LITERATURE REVIEW

2.1. Deterministic model – Quadratic Assignment Problem:

The QAP belongs to a family of NP-Hard problems and has a long history of development. In 1957, the QAP was formulated by Koopmans and Beckmann which wanted to locate N desired departments among N fixed locations where there is a certain flow between a pair of departments, which was placed in the certain pair of positions with a corresponding known distance between them. The cost of transportation between department k in location n and department i in location j was calculated as the following: $f(i,k) * d(j,n) + f(k,i) * d(n,j)$. The objective is to find an optimal arrangement which can minimize the total of transportation cost. Dickey and Hopkins (1972) used the quadratic assignment problem to assign buildings on a University campus. Kouvelis and Kiran (1990) formulated the QAP by elaborating the throughput requirement of a manufacturing system in 1990. Besides, many other researches implemented relevant versions of the QAP and they are listed in Figure 2.

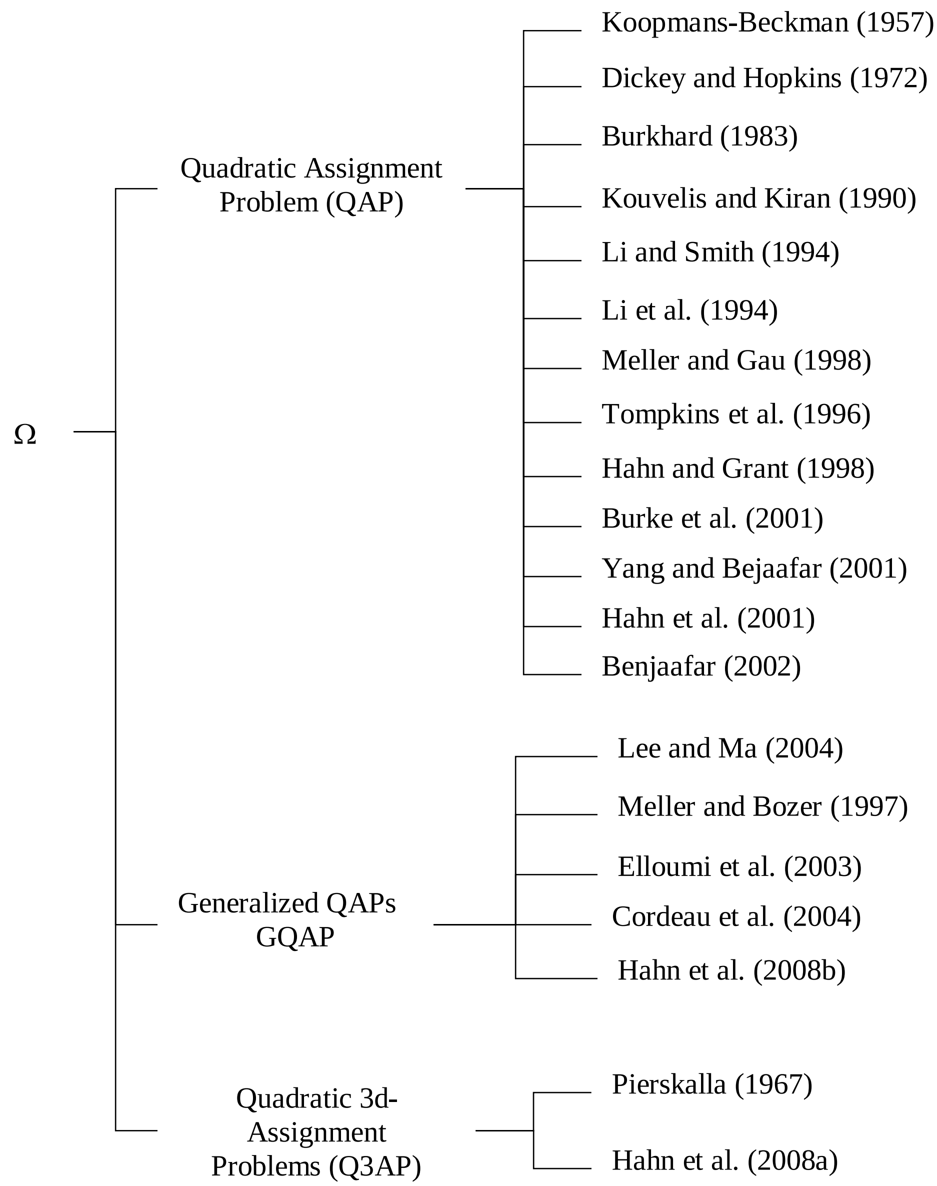


Figure 2 – Development of Quadratic Assignment Problem Research – QAP

The QAP does not have a polynomial time approximation scheme which makes it one of the most challenging problems (Sahni and Gonzalez, 1976). The attempt to find an exact solution for QAP is only successful in examples with the size smaller than 30 ($N \leq 30$). Thus, heuristic methods with proper local optimum and reasonable amounts of processing time become the most promising solving strategy for QAP and receive particular attention from researchers. There were many publications about a heuristic method such as Burkard

(1983), Li and MacGregor Smith (1994, 1995 and 1998), Li et al. (1994), Hoos and Stutzle (2004), Connolly (1990), Taillard (1991 and 1998), Stutzle (2006) etc. Heuristic methods have also accomplished specific achievements in solving QAP problems. In particular, they have successfully addressed 27 QAP instances (out of 41) of QAPLIB with size ranging from 30 to 256. However, it is unnecessarily acceptable gap between lower bound and the best-known optimum, which is around 9%. Thus, the solution from the heuristic model is reliable, and the difference between a heuristic solution and the best-known result will be even smaller in case the linear cost of QAPLIB is non-zero.

One of the most successful searching techniques for the quadratic assignment problem is Stochastic Local Search (SLS) (Hoos and Stutzle, 2004). This method can find optimal solutions with much shorter computing time compared to the best performance of exact algorithms. Furthermore, SLS can achieve the feasible solutions even in the massive scale problems with tight constraints. Several remarkable methods of SLS include the Simulated Annealing algorithm (Connolly, 1990), the Robust Tabu Search algorithm - RoTS or Fast Ant System - FANT (Taillard, 1991 & 1998) and the iterated local search algorithm – ILS (Stutzle, 2006). The problem of heuristic methods is the lack of optimality of its solution; thus, it is better to use solutions from heuristic as an initial upper bound for specific approaches.

2.2. **Stochastic Simulation model**

The simulation model of evacuation problem from buildings was introduced around 1980 for the first time by several researchers who analyzed the evacuation process by applying analytical and simulation models in both deterministic and stochastic aspects. There have been a lot of methods developed since 1980, such as Geoff Berlin’s, one of the pioneer researchers in this area, who published several important papers on simulation models for evacuation problem. In Chalmet et al. (1982) developed a deterministic network model to analyze the building evacuation problem. Later, Choi et al. (1988) also formulated a deterministic model based on dynamic network flow. For the first time, Smith and Towsley (1981) successfully expressed the closed queueing network for evacuation process. The result of this research became the cornerstone of queueing concepts for the later studies. Among the stochastic network models, we should mention the model of Yuhaski and Smith (1989) which achieved a significant milestone in analyzing the evacuation problem by using the formulation of the M/G/C/C state dependent queue. The research of Yuhaski and Smith in 1989 laid the foundation for subsequent analysis.

In addition to analytical models, researchers have also been interested in developing simulation models for the evacuation problem. In 1993, Drager created the EVACSIM. In 2006, Ko, Spearpoint, and Teo introduced the simulation model named EvactionNZ and discussed several models in their research. In 2007, Cruz, Smith, and Mederios created the transient M/G/C/C simulation model, which was improved with regional evacuation networks one year later by Stepanov and Smith. The summary of building evacuation models will be summarized as below.

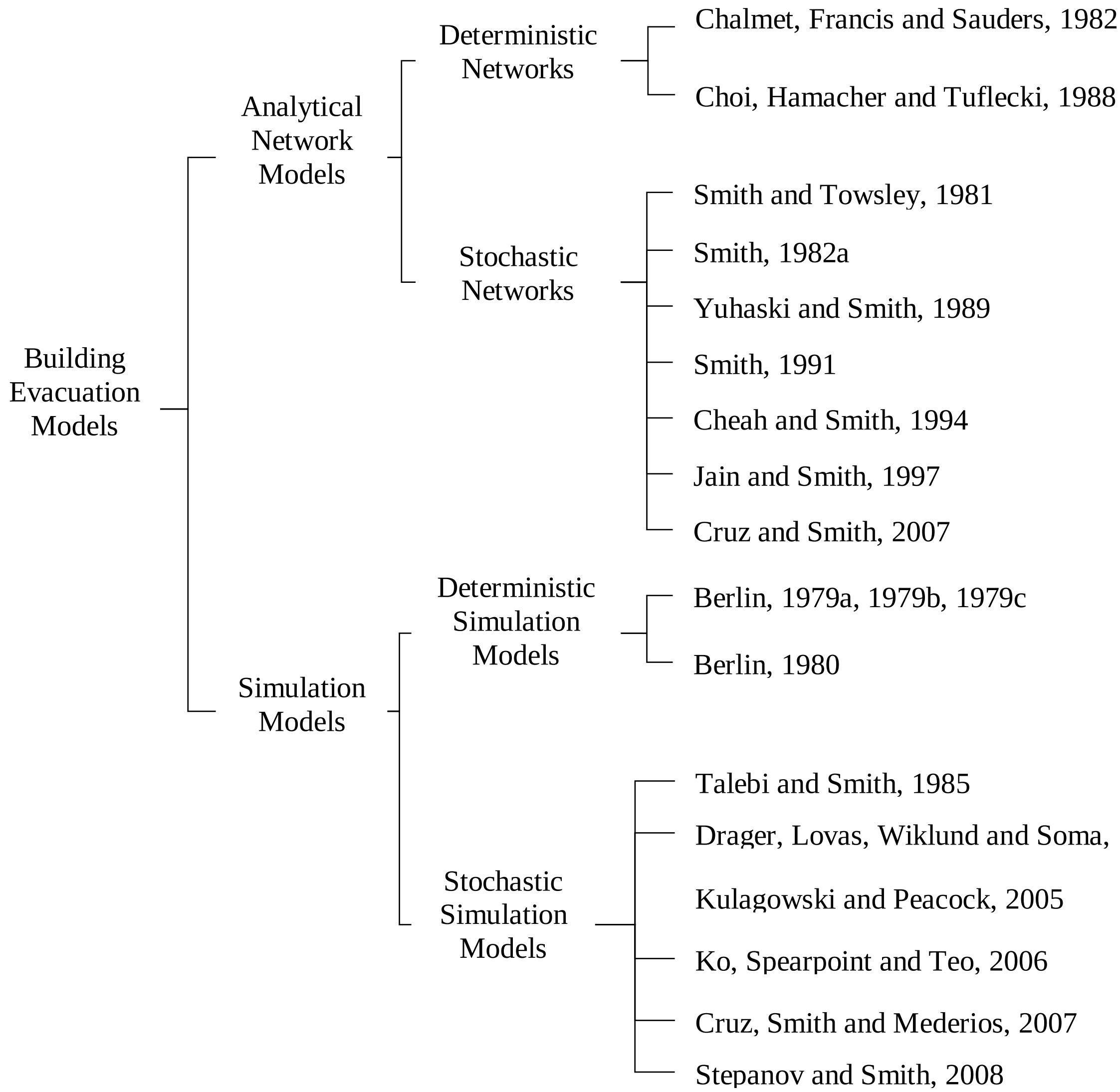


Figure 3 – Development of Building Evacuation Problems

CHAPTER 3

MATHEMATICAL FORMULATION FOR GMAFLAD

In this section, we establish a mathematical formulation for the evacuation problem, the general structure of evacuation problem can be stated in the form of QSP model as follows:

$$Maximize\ Z = \sum_{k}\sum_{t} u_{kt}\mathrm{x}_{kt} + \sum_{k}\sum_{j} u_{kj}\Big(\sum_{m,n\in A} \frac{1}{\mathrm{d}_{mn}}\mathrm{x}_{km}\mathrm{x}_{jn}\Big)$$

$$Subject\ to:$$

$$\sum_{k}\sum_{t} \alpha_{kt}\mathrm{x}_{kt} \le 1 \quad i = 1, 2, \dots I\ (subareas)$$

$$\sum_{k} \mathrm{x}_{kt} = 1 \quad k = 1, 2, \dots, K\ (activities)$$

$$\mathrm{x}_{kt} = 0{,}1 \quad k = 1, \dots, K; t = 1, \dots, T$$

Where,

x_{kt}: is the binary variable which denotes the position t^{th} of subareas occupied by the k^{th} activity/department; x_{kt}: is the binary variable; x_{kt} =1 if the k^{th} activity/department is assigned to the combination of subareas designated by t, and $x_{kt} = 0$ otherwise.

α_{ikt}: is the binary variable; $\alpha_{ikt} = 1$, if the k^{th} activity/department is assigned to i^{th} subarea, and $\alpha_{ikt} = 0$ otherwise.

A: is a set of planar arcs indicating a critical relationship between activity/department x_k and x_j for each alternative (x_{km}, x_{jn}).

d_{mn}: is the Euclidean/rectilinear distance between activity/department alternates x_{km} and x_{jn}.

u_{kt}: is a deterministic/expected utility of place coefficient for the t^{th} combination of cell activity/department x_k.

u_{kj}: is a deterministic/expected utility of flows coefficient between activities/department x_k and x_j.

In the evacuation problem, the arrival rate λ_{kt} and λ_{kj} will replace u_{kt} and u_{kj} in the objective function. This substitution will support the objective function to find the design that maximizes the flow of occupants moving out of the building. This is the primary concern of the evacuation problem. Meanwhile, we also couple the pair-wise of activities which have the high density of occupants' close together by replacing arrival rate (between a pair of activities) λ_{kj} into the position of $u_{kj.}$ The objective function becomes:

$$Maximize\ Z = \sum_{k}\sum_{t} \lambda_{kt} x_{kt} + \sum_{k}\sum_{j} \lambda_{kj} (\sum_{m,n \in A} \frac{1}{d_{mn}} x_{km} x_{jn})$$

$$Subject\ to:$$

$$\sum_{k}\sum_{t} \alpha_{kt} x_{kt} \le 1 \quad i = 1, 2, \dots I\ (subareas)$$

$$\sum_{k} x_{kt} = 1 \quad k = 1, 2, \dots, K\ (activities)$$

$$x_{kt} = 0,1 \quad k = 1, \dots, K; t = 1, \dots, T$$

After formulating the function for QAP problem, we discuss one possible means of input data which is used for GMAFLAD. We use a software named Benchmark to generate random parameters for the QAP problem. We note that other fixed data inputs from the real situation are possible.

3.1. **The Benchmark software**

This software will request the necessary information including dimension for the grid, number of desired activities, number of alternates for each activity, range for the size of activity, place value for each activity, flow value for the critical pair and the flow density. Benchmark will create a data file with a separate matrix of parameters for GMAFLAD:

- The first section includes the number of activities and alternates for each activity and flow values (arrival rate) for each alternate. The matrix has two columns (only consider one-dimensional QAP). The first column is the activity one and the second column indicates the occupied floor of each alternate and arrival rate (λ). The first row consists the number of desired activities which is declared by users, while the rest of the matrix consist N (number of alternates) sub-matrices (2, M), where M equals to [2xN+1]. The first row of each sub-matrix introduces the order number of activity (the first column) and the number of alternates (the second column). In the remaining sub-matrix, each alternate will occupy two rows and the necessary parameters of each alternate will be contained in the second column which includes the occupied floor and place value or arrival rate (λ).

- The second section consists of data related to the traffic flow among activities. The first column represents the origin, the second column indicates the destination and the between-flow (μ).

- This file is saved as an ASCII text file which is also the general structure of input data for GMAFLAD.

The next step is solving the problem with GMAFLAD, which was developed by Robert Macleod (1985) as a part of his MSc. Degree at the University of Massachusetts. This program offers three heuristic searching methods: “The Greedy Heuristic”, “Best Future

Value" and "Limited Lookahead". GMAFLAD can solve and display numerical solution as well as provide graphical one if requested by the users. In most of the case, GMAFLAD will give a few feasible designs for the evacuation problem, and these combinations will be transformed into the stochastic problem by using EWT to simulate the operation of the layout.

We consider a high-rise building of M stories and each floor will be assigned one department. At each level, there are two stairwells, and the occupants are assumed to use both stairwells equally.

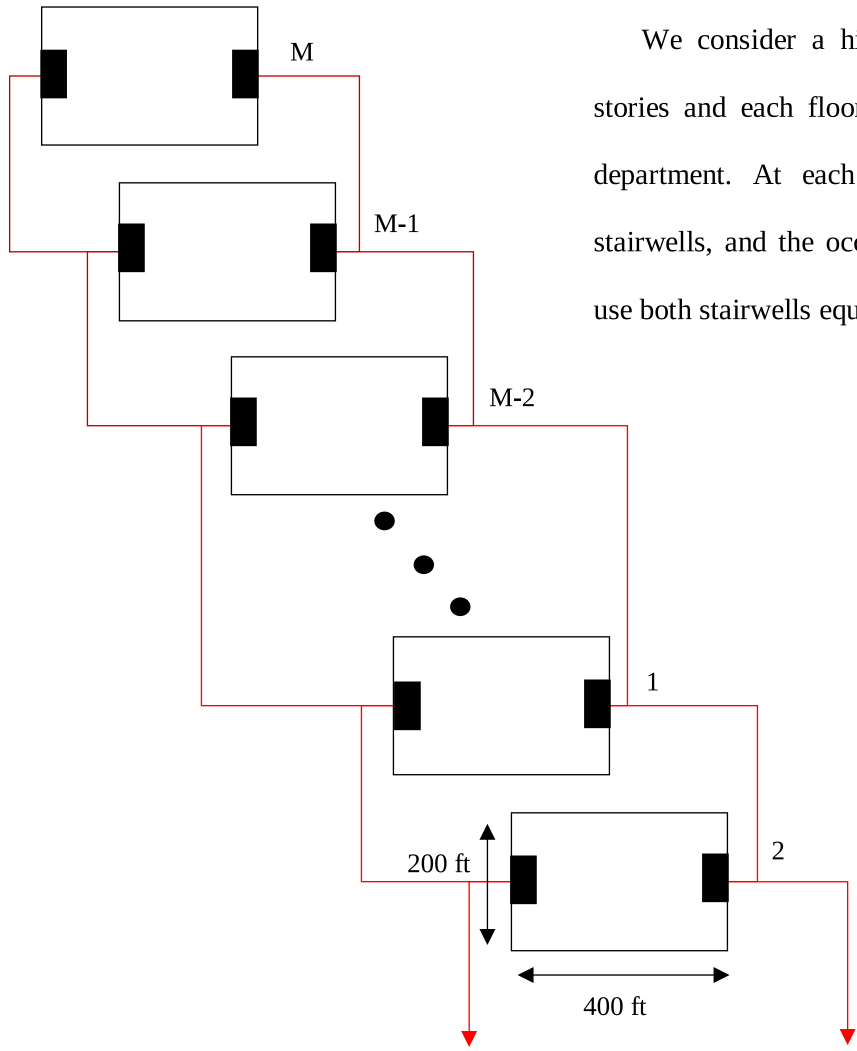


Figure 4 – General Structure of High-rise Building

CHAPTER 4

MATHEMATICAL FORMULATION OF STOCHASTIC SIMULATION M/G/C/C STATE DEPENDENT QUEUEING MODEL

Before formulating a stochastic simulation M/G/C/C model, we will introduce some necessary terminology for queueing network models. The queueing network system is a set of "nodes" and "arcs" which will connect to each other to create the evacuation network for the problem. In the evacuation problem, the "node" refers to activities, stairwells or corridors, while the "arc" represents a logical connector which will link appropriate nodes depicting the path of movement flow among nodes in the queueing system. Each arc represents an M/G/C/C node while each node represents a decision point or switch. In case of multi-connections of a particular node, each pathway links to the node associated with a probability that a corresponding arc will be used by the pedestrian, vehicle or material flow.

Next, we will discuss the matrix of parameters for input file (ASCII text file) for simulation models

- The first part of the matrix contains the number of nodes and arcs of the model. The first three rows consist the title of the column – "Node", the number of nodes and the list of titles include "Arc", "Origin", "Dest" and "Prob" respectively. The parameters of each node and arc will be written down to each column corresponding to the title in the third row of this section.

- The second section is the sub-matrix with m rows corresponding to m nodes of queueing network. The section starts with a row of title for each type of coefficient of the node including "Node", "Service", "Length", "Width", "V1" (speed of pedestrian or vehicle), "kmax", "λ", "Population", "FailIT", "RecovT" and "InitLoad". All necessary information of the node will be defined in this section.

- The third part is a row vector. Each row defines the identification number of each node, and this section starts with the title "Exit Nodes" in the first cell of the vector.

- After getting the result from GMAFLAD, the parametric of feasible solutions from GMAFLAD will be converted to the matrix form as in the above discussion and stored as the input file for stochastic simulation. The detailed steps will be discussed in the following paragraphs.

- The necessary parametric (arrival rate - λ) for simulation model is collected from feasible solutions of deterministic model (each feasible solution produces an independent input file).

- Define nodes and arcs of the network. In evacuation problem, the activities or departments, stairwell landing, stairs and ground floor exits are nodes of the queueing network. Meanwhile, the connection of activity and docking (corridor on each floor), landing to the stairwell and vice versa, and stairwell to ground exits are arcs of the simulation model.

- Measure the geometric size (width and length) of the corridor, stairwell landing, stairs and exits landing.

The general steps of analyzing the model by stochastic simulation are importing input files, executing the program and saving the output. The stochastic model will analyze the discharge rate of all layout candidates suggested by deterministic model, identify the congestion or bottleneck node, and calculate the expected evacuation time of the recommended layout. The mathematical formulations are used in M/G/C/C queueing model provided in sections 4.1 and 4.2, and section 4.3 introduces its notation.

4.1. **Notation**

This is the brief description of necessary notations which is used in M/G/C/C state dependent queueing models:

c: capacity of a corridor in number of pedestrians

l: length of corridor in meters

w: width of corridor in meters

V_n: average walking speed for n occupants in a corridor in meter per second

V_1: average lone occupant walking speed in meter per second

V_a: average walking velocity when occupant density is 2 pedestrians per meter squared in meter per second

V_b: average walking speed when pedestrian density is 4 pedestrian per meter squared in meter per second

γ, β: shape and scale parameter for exponential model

λ: occupant arrival rate in pedestrian per second

N: the number of occupants per corridor

p(n): probability of N = n pedestrian in the system, for n =1, 2…, c

p(0): probability of N = 0 pedestrian in the system

p(c): probability of N = c or blocking probability

θ: throughput in pedestrian per second

L: expected number of occupants in the system or work-in-process

W: E[T], expected waiting time or service time in seconds

E[T1]: expected waiting time for single occupants in seconds

4.2. **Pedestrian Congestion Modeling**

The congestion is one of the significant factors which causes the delay during an evacuation process. It occurs when the number of pedestrians arrives at an individual node, such as stairwells and corridors, exceed its capacity. The congestion increases the traffic density, reduce average walking velocity and jam the entire system. The Pedestrian Congestion Modeling measure capacity of the node and average velocity under different traffic density by the following formulation:

$$c = [5 \times l \times w]$$

$$Vn = V1 \times \frac{c + 1 - n}{c}$$

$$Vn = V1 \times \left[- \left(\frac{n-1}{\beta} \right)^{\gamma} \right]$$

$$\gamma = \frac{\ln \left[\frac{\ln(\frac{Va}{V1})}{\ln(\frac{Vb}{V1})} \right]}{\ln \left(\frac{a-1}{b-1} \right)} \; ; \; \beta = \frac{a-1}{\left[\ln(\frac{V1}{Va}) \right]^{1/\gamma}} = \frac{b-1}{\left[\ln(\frac{V1}{Vb}) \right]^{1/\gamma}}$$

4.3. **Simulator Validation**

The simulation measures the performance of the design through blocking probability, throughput time, an expected number of occupants in the system (or work-in-process, WIP) and the mean waiting time. The computation of simulation module is shown in the following formula:

$$p(n) = \left(\frac{\left[\lambda E[T1]\right]^n}{n!\, f(n) \dots f(2) f(1)} \right) p(0), \forall\, n = 1,2 \dots c$$

$$p(0)^{-1} = 1 + \sum_{i=1}^{c} \left(\frac{\left[\lambda E[T1]\right]^i}{i!\, f(i) \dots f(2) f(1)} \right)$$

$$\theta = \lambda(1 - p(c))$$

$$L = E(N) = \sum_{n=1}^{c} (np(n))$$

$$W = L/\theta$$

CHAPTER 5

GMAF_MGCC, INTEGRATION OF DETERMINISTIC AND STOCHASTIC M/G/C/C STATE DEPENDENT QUEUEING MODEL

5.1. Overview GMAF_MGCC

As mentioned in the introduction, the main purpose of this research is to create an integration model which combines GMAFLAD and Stochastic model M/G/C/C State Dependent to solve an evacuation problem. We apply functional and modular programming to transfer data between deterministic and stochastic modules.

In regard to general structure, GMAF_MGCC includes three main modules which are (1) GMAFLAD, (2) Conversion module and (3) Stochastic Model M/G/C/C. The input file will be imported to the library of GMAFLAD module where extracts crucial coefficients for QSP such as λ_{kt} and λ_{kj} to figure out optimal solutions. In case of infeasible problem, the program will immediately stop, otherwise, it will produce outcome, then transmit them to the second module. A primary task of Conversion module is transforming outputs of the first module to inputs scheme for the simulation module. At the final stage, the stochastic module simulates and provide a complete processing time analysis for each available building layout which will be used to find out a global optimal design.

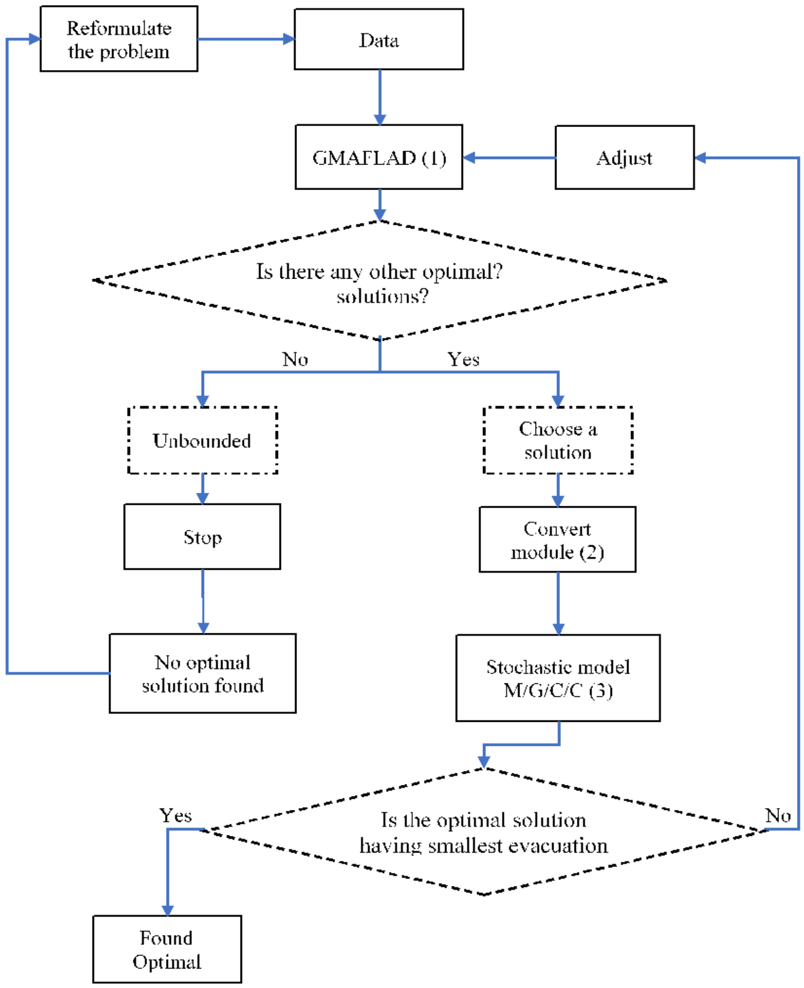


Figure 5 - The Programming Diagram of GMAF_MGCC Software

Regarding to GMAFLAD module, the software will be pointed to a directory where contain an input file saved as a text file. The first module solves and returns a complete set of potential building layouts in matrix form as well as 2D-graph. The output of this module will be the input for the second module, Conversion module.

Concerning the conversion process, this module transforms each outcome of GMAFLAD into matrix input for simulation module. The input matrix obtains primary properties of queueing network for high-rise building including node (floors, stairwell and landing area) and arc (a feasible connection between two nodes).

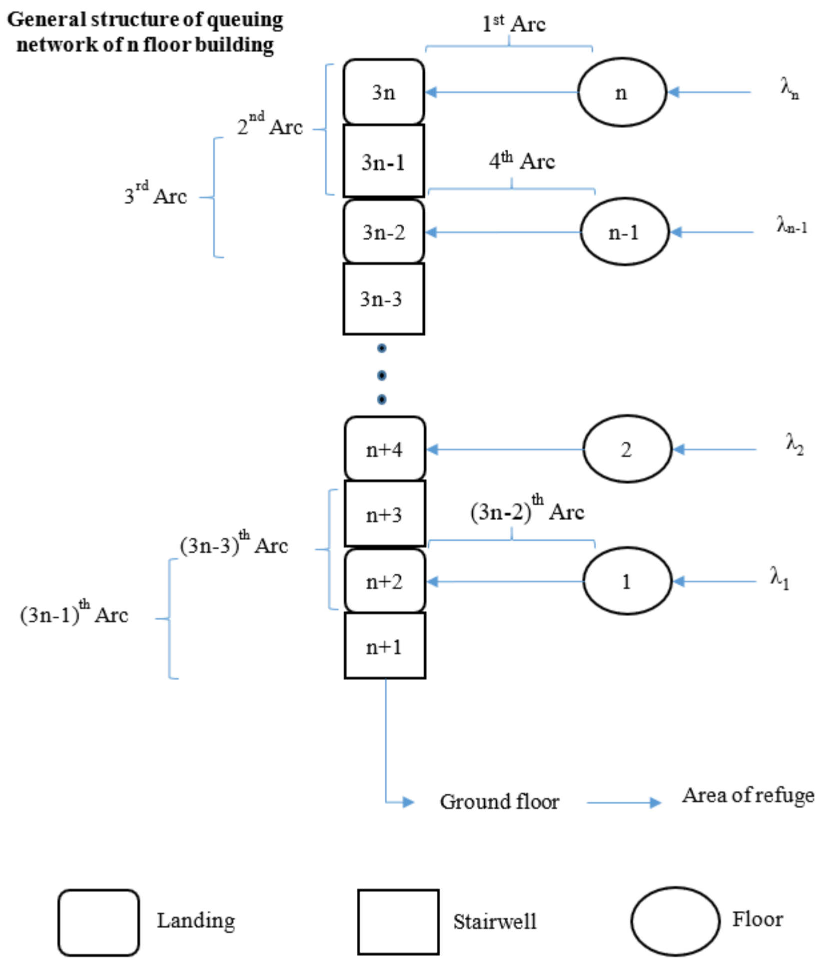


Figure 6 - General Structure of Queueing Network of N-Floor Building

The general structure of n-story building has two stairwells system or servers (C=2); the elevator system is suspended during tragic events occurs. There are 3n nodes for in the queueing network of a general n-floor building general. The n-story building has 3n-1 arcs which is a pathway to connect two consecutive arcs. Figure 7 is the detail description of general structure of queueing network for an n-floor building. With the building layout from GMAFLAD, the conversion module produces a corresponding input for the simulation module.

The output of conversion module will be passed to Stochastic model M/G/C/C state dependent as a string argument. The simulation module computes the processing for each building layout in the default setting including the population is 50 occupants per story and the limit processing time is 2000 seconds.

GMAF_MGCC primarily build on the source code of GMAFLAD software which is written in the C programming language. The modification on GMAFLAD code can utilize advantages of available resources including MAFLAD module and minimize the complexity of manipulating library between GMAFLAD and stochastic simulation model M/G/C/C. The further detail of the Integration Algorithm will be mentioned in the next section.

5.2. **GMAF_MGCC Algorithm**

GMAF_MGCC's pseudocode is illustrated in Figures 8 and 9. Figure 8 describes the general structure of GMAF_MGCC, while Figure 9 presents the conversion module.

A new function will be added on GMAFLAD interface which is checkbox `[Export Data Stochastic()]` to activates the simulation functionality. Also, users can adjust a value of population (at each story) through `[Population]` textbox on the user interface. When the `[Export Data Stochastic()]` is selected, a hidden text box, `[Population]`, will be visible with the default population parameter is 50, and this number is adjustable.

The execution of "Run" button will solve an evacuation problem by the deterministic model and store these results as well as the desired input `[Population]`. Those data will be transferred to the function [Export Data Stochastic()] to generate inputs corresponding to each output of GMAFLAD.

We create an additional “Run” event which only appears in case of selecting checkbox [Export Data Stochastic()] to simulate and store an analyzing data of each building layout. When “Run” button is triggered, the function [StochasticButton__Click()] will get inputs’ location, create a new folder, followed the default format name, for the simulation outputs, and interact with the simulation module by the function [ExportResultStochastic()].

[ExportResultStochastic()] receives two string arguments involving inputs’ directory and location to store simulation analysis. These two string arguments are combined and assigned to [mgcc_ped.exe] as a string argument to implement stochastic analysis and convert it to the text file.

Regarding the conversion module, there are five functions included in this module. The first function is [GetNode()] which returns nodes’ properties including utility value corresponding to each assigned activity in optimizing layouts. These data will be sent to remaining functions to generate input files for the simulation model.

```
Pseudo-code to create check box option of solving with simulation module:
* Create the check box panel object:
public class MainForm: form
        private CheckBox chkExportDataSochastic;
*Add on condition inside Run event of GMAFLAD to produce inputs for simulation:
bool ShowOutput(string Solution File) {
...
        if (this.chkExportDataSochastic.Checked) {
                foreach (Solution sol in solutions) {
                 * Check Directory Folder to Create input file:
                        Global.CheckDirectory_Stochastic();
                        Global.INPUT_STOCHASTIC ←"Stochastic Directory" +
        "Case name" + "Input Stochastic Const" + ".txt";
                * Call Function to Create Input File for Stochastic Algorithm:
                sol.ExportDataStochastic(Global.INPUT_STOCHASTIC);
                end Foreach }
                lblstochasticOutput.Text ← Global.STOCHASTIC_DIRECTORY;
                StochasticPanel.Visible ← true;
        end if }
        return True
end function }
*Add on functions to collect the population value from user:
private void Popular_TextChanged(object, EventArgs) {
        Globals.POPULAR_CONST ←txtPopular.Text.ToString();
end function }
* Check exporting input for simulation module:
private void chkExportDataSochastic_CheckedChanged(object, EventArgs) {
        lblPopular.Visible ← chkExportDataSochastic.Checked;
        txtPopular.Visible ← chkExportDataSochastic.Checked;
end function }
```

```
Pseudo-code for conversion module:
public bool ExportDataStochastic(string fileName) {
        * Counting number of node of the problem
        nodes_count ←3*this.problem.Activities.Count;
        * Get the alternates and its lamdba from the problem:
        nodes ← GetNodes(this.problem, this.alternates);
        * Call 4 functions to generate matrix input for simulation module:
        create a <string text file> to store matrix input;
        outputText ← output_Stochastic_1();
        outputText ← output_Stochastic_2();
        outputText ← output_Stochastic_3();
        outputText ← output_Stochastic_4();
        * Print outputText to the text file:
        print (fileName, outputText)
end function }
```

```
Pseudo-code to get the directory input file for simulation module:
private void StochasticButton_Click(object, EventArgs) {
        foreach (Solution sol in solutions) {
        * Create Directory, name structure for Input and Output file
                Global.CheckDirectory_Stochastic();
                * Create name auto-structure for output file:
                inputFilename ← "Case name" + "Directory"+ ".txt";
                outputFilename ← "Case name" + "Directory" + ".txt";
                *Call function to get Result from Simulation Algorithm:
                sol.ExportResultStochastic(inputFilename, OutputFilename);
        end for }
end function }
```

```
Pseudocode for ExportResultStochastic function:
public bool ExportResultStochastic (inputFileName, outputFileName) {
        ...
        * Call out "mgcc_ped.exe" and pass string argument to simulate
building layout:
        process.StartInfo.FileName ← "mgcc_ped.exe";
        arguments ←"Set up" + "Case name" + "inputFilename" + "Case
name" + "outputFilename";
        process.StartInfo.Arguments ← arguments;
        ...
        * Store result of simulation model:
        resultStochastic ←process.StandardOutput.ReadToEnd();
        * Add on a function print result as text file:
        filePathOutput ←"Directory"+ "Case name" + "Stochastic" +
"outputFilname;
        AppendText(filePathOutput , resultStochastic);
end function }
* Add on an AppendText function to convert result of simulation model as text:
private void AppendText(string filename, string OutputText): {
        * Check if is there any existing files:
        if (!File.Exitsts(filename)) {
                File.WriteAllText(fileName, outputText);
        else
                File.AppendAllText(fileName, outputText);
        end if }
end function }
```

Figure 7 - Pseudocode for Integration Program

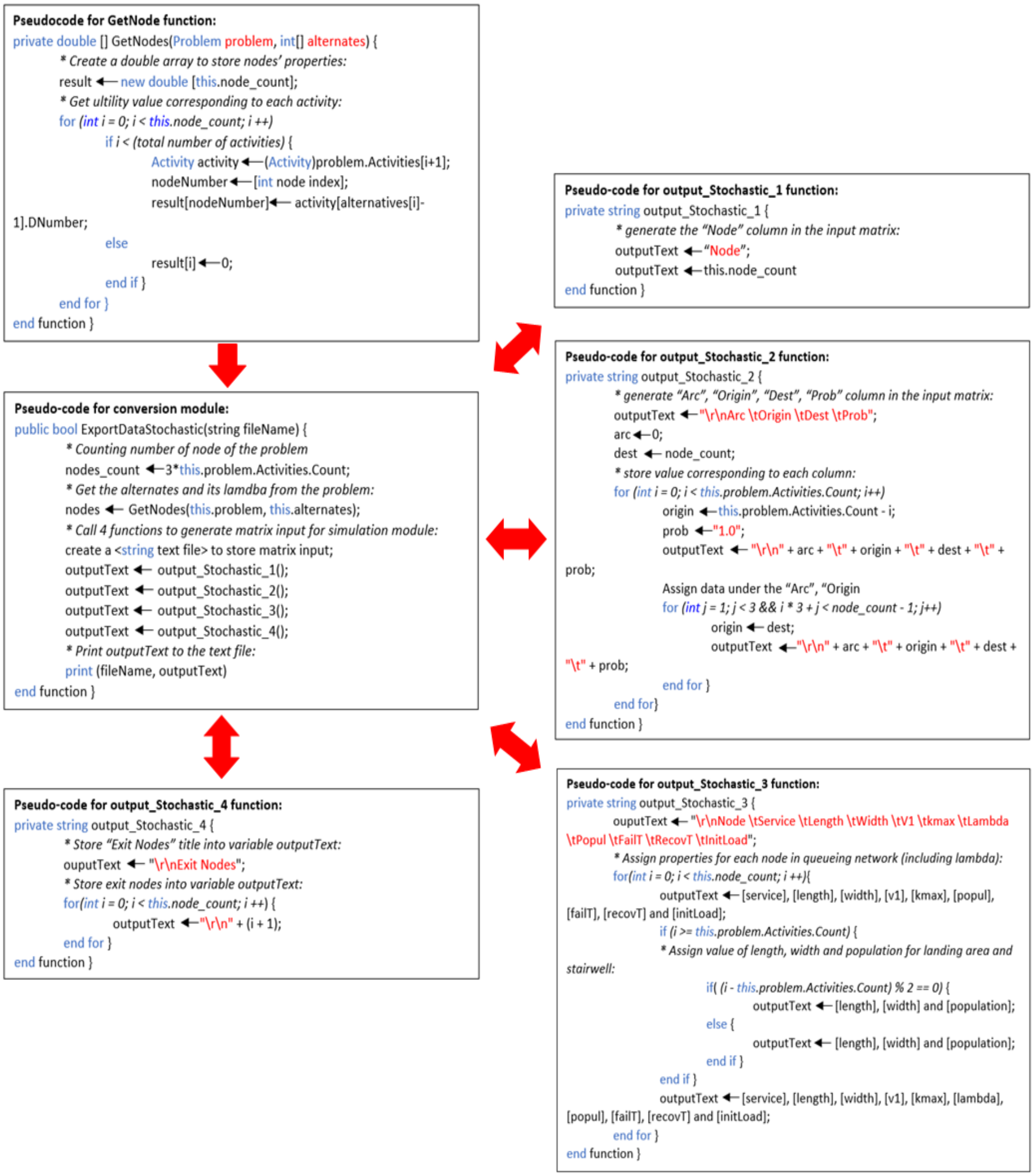
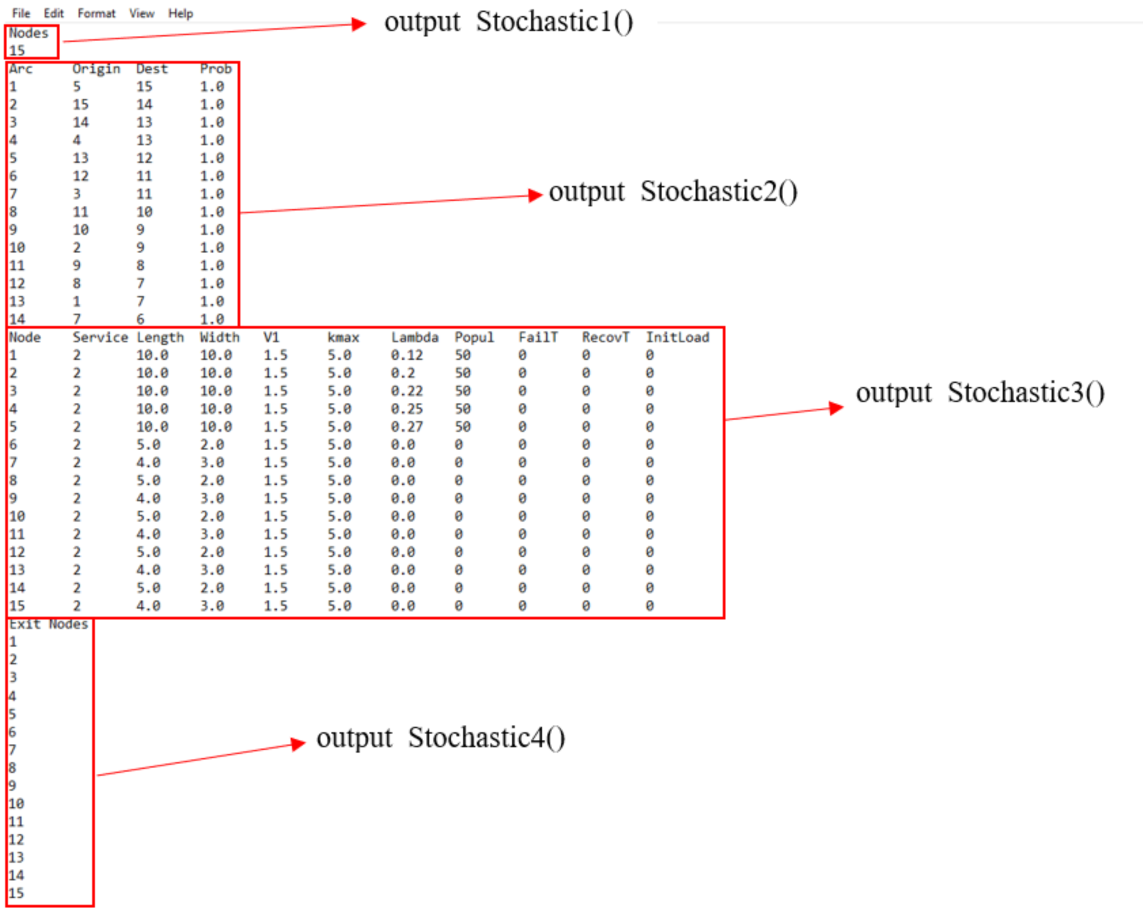


Figure 8 - Pseudocode for Conversion Module



Nodes
15

Arc	Origin	Dest	Prob
1	5	15	1.0
2	15	14	1.0
3	14	13	1.0
4	4	13	1.0
5	13	12	1.0
6	12	11	1.0
7	3	11	1.0
8	11	10	1.0
9	10	9	1.0
10	2	9	1.0
11	9	8	1.0
12	8	7	1.0
13	1	7	1.0
14	7	6	1.0

Node	Service	Length	Width	V1	kmax	Lambda	Popul	FailT	RecovT	InitLoad
1	2	10.0	10.0	1.5	5.0	0.12	50	0	0	0
2	2	10.0	10.0	1.5	5.0	0.2	50	0	0	0
3	2	10.0	10.0	1.5	5.0	0.22	50	0	0	0
4	2	10.0	10.0	1.5	5.0	0.25	50	0	0	0
5	2	10.0	10.0	1.5	5.0	0.27	50	0	0	0
6	2	5.0	2.0	1.5	5.0	0.0	0	0	0	0
7	2	4.0	3.0	1.5	5.0	0.0	0	0	0	0
8	2	5.0	2.0	1.5	5.0	0.0	0	0	0	0
9	2	4.0	3.0	1.5	5.0	0.0	0	0	0	0
10	2	5.0	2.0	1.5	5.0	0.0	0	0	0	0
11	2	4.0	3.0	1.5	5.0	0.0	0	0	0	0
12	2	5.0	2.0	1.5	5.0	0.0	0	0	0	0
13	2	4.0	3.0	1.5	5.0	0.0	0	0	0	0
14	2	5.0	2.0	1.5	5.0	0.0	0	0	0	0
15	2	4.0	3.0	1.5	5.0	0.0	0	0	0	0

Exit Nodes
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Figure 9 - Structure of Simulation's Input Matrix

The input matrix will be broken down into four sections – figure 9, and each division will be written by one function. The `[output_Stochastic_1()]` generate the first part of the matrix which includes "Node" title and number of nodes. The `[output_Stochastic_2()]` counts and calculates arcs, origin nodes, destination nodes as well as assign the probability for each arc. In the third part, the utility value and other relevant properties of the node from `[GetNode()]` will be sent to `[output_Stochastic_3()]` to assign to an appropriate node. The "Exit Nodes" section will be handled by the `[output_Stochastic_4()]` function.

5.3. Example of solving an evacuation problem with GMAF_MGCC

To illustrate the operation of GMAF_MGCC program, we will solve an example of an evacuation problem of five stories building. The input matrix of example is shown in Figure 10.

test5 - Notepad

File Edit Format View Help

```
  1    5
  1    1
  1     2
       0.07
  2    4
  1     1
       0.15
  1     5
       0.12
  1     3
       0.16
  1     2
       0.12
  3    3
  1     1
       0.16
  1     3
       0.18
  1     4
       0.09
  4    2
  1     1
       0.19
  1     5
       0.10
  5    4
  1     3
       0.18
  1     4
       0.18
  1     2
       0.07
  1     5
       0.08
 -1   -1   -1
  1    4         0.14
  1    2         0.09
  2    3         0.16
  3    4         0.14
 -1   -1   -1
```

Figure 10 - Example for GMAF_MGCC

This file will be stored in the folder of Example in the directory: “D:\IMPORTANT\Example”. At the window of GMAF_MGCC, we click on the “Begin” button to start the program. Then, choose the option “Open” to find a location of the problem, in this case, the location of the file is in the directory: “D:\IMPORTANT\Example\test5.dat”.

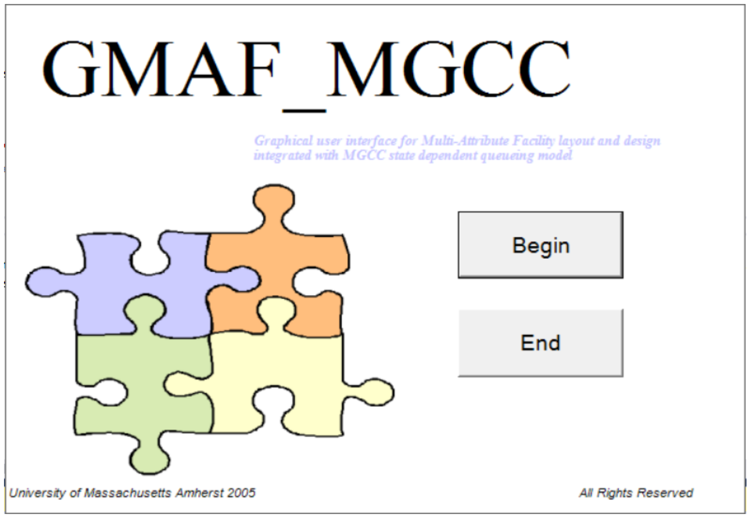


Figure 11 – Starting Window of GMAF_MGCC

After selecting an appropriate file, we need to pick solving methods which are in “Select Heuristic” box; then choose the “Export Data Stochastic” option and adjust “Population” textbox in the “Solution Options” box.

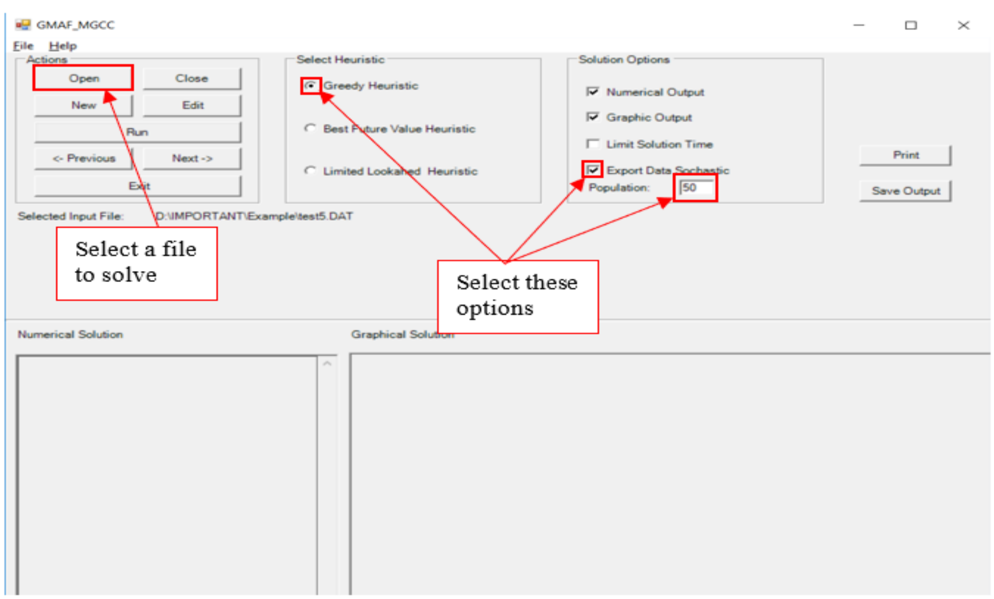


Figure 12 - Working Screen of GMAF_MGCC

By selecting an option “Export Data Stochastic”, GMAF_MGCC will generate a folder named “test5-Stochastic” which includes all potential input text-files for simulation model after solving the problem with the deterministic module. Then, activating the process by clicking on “Run” button to solve an evacuation problem by the deterministic model. A hidden option of analysis with stochastic simulation model will appear on the working screen of GMAF-MGCC in the “Stochastic Option” box; click on “Run” button to analyze all feasible layouts by the simulation model.

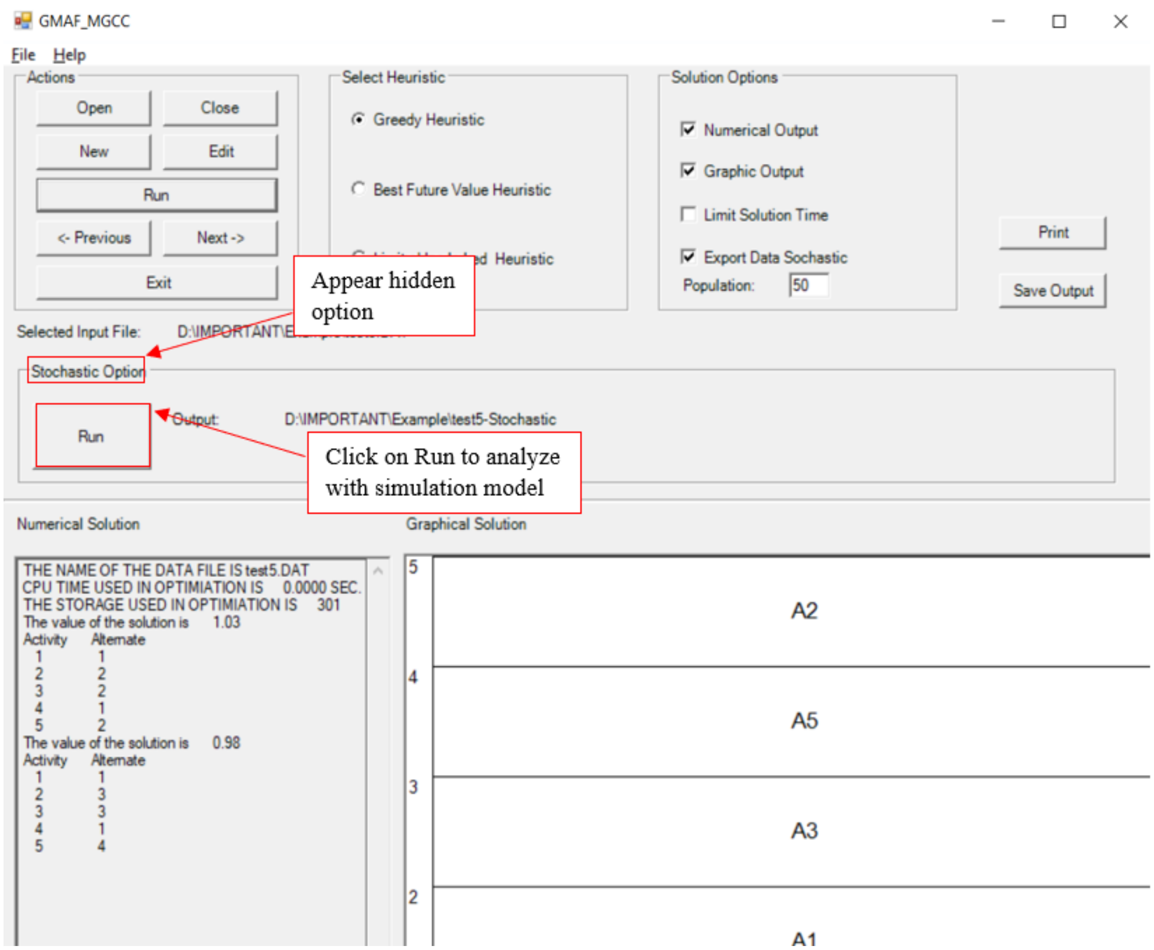


Figure 13 - Hidden Option to Solve with Stochastic MGCC State Dependent Queuing Model

After completing the process, inside the “test5-Stochastic”, it will contain input files as well as result files of the simulation model. The content of input files and result files is shown in below figures.

test5_INPUT1 - Notepad

File Edit Format View Help

```
Nodes
15
Arc	Origin	Dest	Prob
1	5	15	1.0
2	15	14	1.0
3	14	13	1.0
4	4	13	1.0
5	13	12	1.0
6	12	11	1.0
7	3	11	1.0
8	11	10	1.0
9	10	9	1.0
10	2	9	1.0
11	9	8	1.0
12	8	7	1.0
13	1	7	1.0
14	7	6	1.0
Node	Service		Length	Width	V1	kmax	Lambda	Popul	FailT	RecovT	InitLoad
1	2		10.0	10.0	1.5	5.0	0.19	50	0	0	0
2	2		10.0	10.0	1.5	5.0	0.07	50	0	0	0
3	2		10.0	10.0	1.5	5.0	0.18	50	0	0	0
4	2		10.0	10.0	1.5	5.0	0.18	50	0	0	0
5	2		10.0	10.0	1.5	5.0	0.12	50	0	0	0
6	2		5.0	2.0	1.5	5.0	0.00	0	0	0	0
7	2		4.0	3.0	1.5	5.0	0.00	0	0	0	0
8	2		5.0	2.0	1.5	5.0	0.00	0	0	0	0
9	2		4.0	3.0	1.5	5.0	0.00	0	0	0	0
10	2		5.0	2.0	1.5	5.0	0.00	0	0	0	0
11	2		4.0	3.0	1.5	5.0	0.00	0	0	0	0
12	2		5.0	2.0	1.5	5.0	0.00	0	0	0	0
13	2		4.0	3.0	1.5	5.0	0.00	0	0	0	0
14	2		5.0	2.0	1.5	5.0	0.00	0	0	0	0
15	2		4.0	3.0	1.5	5.0	0.00	0	0	0	0
Exit Nodes
1
2
3
4
5
6
7
8
9
10
```

Figure 14 – First Input File of Example "test5"

test5_INPUT2 - Notepad

File Edit Format View Help

```
Nodes
15
Arc     Origin  Dest    Prob
1       5       15      1.0
2       15      14      1.0
3       14      13      1.0
4       4       13      1.0
5       13      12      1.0
6       12      11      1.0
7       3       11      1.0
8       11      10      1.0
9       10      9       1.0
10      2       9       1.0
11      9       8       1.0
12      8       7       1.0
13      1       7       1.0
14      7       6       1.0
Node    Service         Length  Width   V1      kmax    Lambda  Popul   FailT   RecovT  InitLoad
1       2               10.0    10.0    1.5     5.0     0.19    50      0       0       0
2       2               10.0    10.0    1.5     5.0     0.07    50      0       0       0
3       2               10.0    10.0    1.5     5.0     0.16    50      0       0       0
4       2               10.0    10.0    1.5     5.0     0.09    50      0       0       0
5       2               10.0    10.0    1.5     5.0     0.08    50      0       0       0
6       2               5.0     2.0     1.5     5.0     0.00    0       0       0       0
7       2               4.0     3.0     1.5     5.0     0.00    0       0       0       0
8       2               5.0     2.0     1.5     5.0     0.00    0       0       0       0
9       2               4.0     3.0     1.5     5.0     0.00    0       0       0       0
10      2               5.0     2.0     1.5     5.0     0.00    0       0       0       0
11      2               4.0     3.0     1.5     5.0     0.00    0       0       0       0
12      2               5.0     2.0     1.5     5.0     0.00    0       0       0       0
13      2               4.0     3.0     1.5     5.0     0.00    0       0       0       0
14      2               5.0     2.0     1.5     5.0     0.00    0       0       0       0
15      2               4.0     3.0     1.5     5.0     0.00    0       0       0       0
Exit Nodes
1
2
3
4
5
6
7
8
9
10
```

Figure 15 - Second Input File of Example "test5"

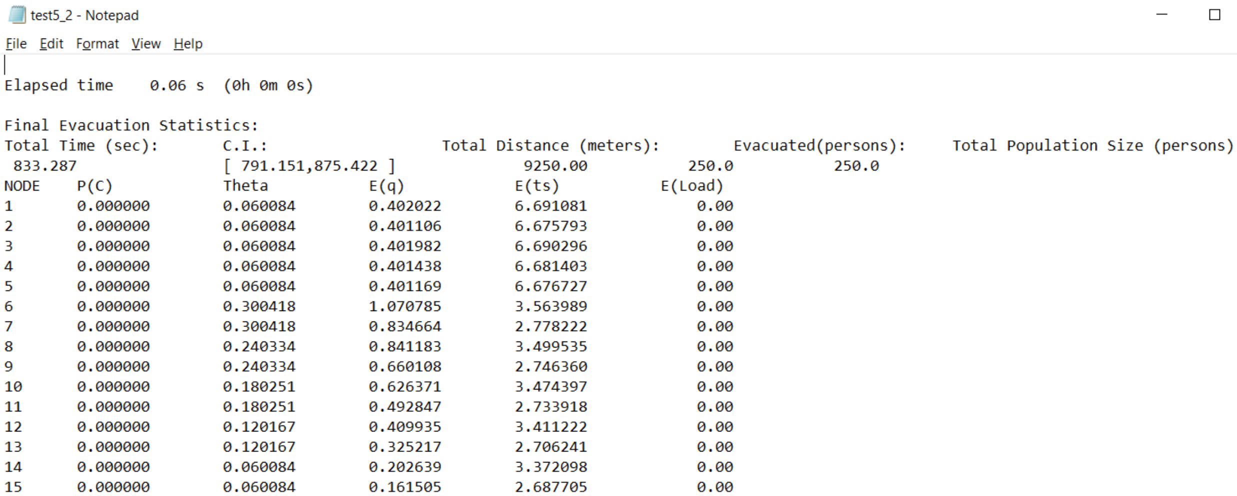
test5_1 - Notepad

File Edit Format View Help

```
Elapsed time    0.05 s  (0h 0m 0s)

Final Evacuation Statistics:
Total Time (sec):       C.I.:                   Total Distance (meters):        Evacuated(persons):     Total Population Size (persons)
 727.956                [ 634.054,821.858 ]             9250.00         250.0           250.0
NODE    P(C)            Theta           E(q)            E(ts)           E(Load)
1       0.000000        0.069280        0.463859        6.695884             0.00
2       0.000000        0.069280        0.462449        6.675105             0.00
3       0.000000        0.069280        0.463162        6.685523             0.00
4       0.000000        0.069280        0.463561        6.691066             0.00
5       0.000000        0.069280        0.463411        6.688834             0.00
6       0.000000        0.346401        1.272119        3.669428             0.00
7       0.000000        0.346401        0.979837        2.827391             0.00
8       0.000000        0.277120        0.993010        3.581540             0.00
9       0.000000        0.277120        0.772783        2.787896             0.00
10      0.000000        0.207840        0.743828        3.578740             0.00
11      0.000000        0.207840        0.579225        2.786929             0.00
12      0.000000        0.138560        0.483930        3.492292             0.00
13      0.000000        0.138560        0.380233        2.744213             0.00
14      0.000000        0.069280        0.236814        3.418061             0.00
15      0.000000        0.069280        0.187810        2.710889             0.00
```

Figure 16 - First Output File of Example "test5"


test5_2 - Notepad

File Edit Format View Help

Elapsed time 0.06 s (0h 0m 0s)

Final Evacuation Statistics:

Total Time (sec):	C.I.:	Total Distance (meters):	Evacuated(persons):	Total Population Size (persons)
833.287	[791.151,875.422]	9250.00	250.0	250.0

NODE	P(C)	Theta	E(q)	E(ts)	E(Load)
1	0.000000	0.060084	0.402022	6.691081	0.00
2	0.000000	0.060084	0.401106	6.675793	0.00
3	0.000000	0.060084	0.401982	6.690296	0.00
4	0.000000	0.060084	0.401438	6.681403	0.00
5	0.000000	0.060084	0.401169	6.676727	0.00
6	0.000000	0.300418	1.070785	3.563989	0.00
7	0.000000	0.300418	0.834664	2.778222	0.00
8	0.000000	0.240334	0.841183	3.499535	0.00
9	0.000000	0.240334	0.660108	2.746360	0.00
10	0.000000	0.180251	0.626371	3.474397	0.00
11	0.000000	0.180251	0.492847	2.733918	0.00
12	0.000000	0.120167	0.409935	3.411222	0.00
13	0.000000	0.120167	0.325217	2.706241	0.00
14	0.000000	0.060084	0.202639	3.372098	0.00
15	0.000000	0.060084	0.161505	2.687705	0.00

Figure 17 - Second Output File of Example "test5"

In this example, two available layouts were found by the deterministic model. Hence, there are two input files for simulation models, and there also have two output files for each feasible arrangement. From the result, we can decide to choose the best design among feasible layouts; in this case, both deterministic and stochastic model give the same answer.

5.4. Validation of GMAF_MGCC

5.4.1. Computational Accuracy

In order to affirm an accuracy of the new program, we conduct a short-test to verify the robustness in GMAF_MGCC's computation. The test compares the manual analysis method and the calculation of GMAF_MGCC. Nevertheless, the manual step of transforming a deterministic solution into a stochastic input matrix is burdensome and difficult, notably the high-rise building with over ten floors. So, this test only restrains for problem size from five to nine stories; the result of the test is presented in the below table.

Table 1 – Validation of The Computational Result between Manual Analyze and GMAF_MGCC Program

Problems' Scale	Result of Manual Analyze		Result of Integration Analyze GMAF_MGCC	
	Deterministic model (number of solution)	**Simulation model (second)**	**Deterministic model (number of solution)**	**Simulation model (second)**
5_story	2	1st layout: 727.956	2	1st layout: 727.956
		2nd layout: 833.287		2nd layout: 833.287
6_story	2	1st layout: 712.184	2	1st layout: 712.184
		2nd layout: 733.751		2nd layout: 733.751
7_story	3	1st layout: 622.756	3	1st layout: 622.756
		2nd layout: 797.957		2nd layout: 797.957
		3rd layout: 680.317		3rd layout: 680.317
8_story	1	Layout: 787.410	1	Layout: 787.410
9_story	2	1st layout: 659.124	2	1st layout: 659.124
		2nd layout: 644.249		2nd layout: 644.249

According to the comparison, the new program and the manual analysis give exact same answers for all cases. Even though, GMAF_MGCC successfully analyze all problem in the test, it is necessary to implement further research to validate the performance of this program, exclusively with larger problem scale.

5.4.2. Correlation of Successful Rate of Solving and Problems' Scale

Regarding the performance of the embedded program, there is no clear evidence about the influence of the size of evacuation problems on the failure rate of solving. Notwithstanding, we encountered the high rate of failure, while conducting experiments with GMAF_MGCC; it raised the high concern of the performance of the embedded program. Thus, A minor test was implemented to observe the program's behaviors and explore probable errors causing the failure in solving large-scale problems.

- Observed factors: a probability of successful solving problem and cardinal number of floors.
- Experimental scope: five to thirty stories.
- Experimental programs: Benchmark and GMAF_MGCC.
- Experiment Device: CPU i7-7700HQ 2.8GHz (8 CPUs), RAM 8192MB, on Windows 10 64-bits.
- Experiment Setup:

Benchmark software will be used to generate deterministic samples randomly, and GMAF_MGCC will produce stochastic samples. Respecting the deterministic model, there are 30 deterministic examples for each class of problem, so the total number of samples is 780. A sample quantity for stochastic samples is uncertain due to an unpredicted cardinal number of solutions acquired from the deterministic model.

The primary purpose is counting a quantity of samples (events) that are successfully solved either by stochastic or deterministic model. The action of solving a sample is considered as a single event. An event is successful when GMAF_MGCC resolves a sample, and it fails if either deterministic or stochastic model cannot solve it or the solving time is over 15 minutes. If a problem is infeasible, an event will be counted as a failure event. A binary variable will be assigned for an event, it takes value of 1 for successful event and 0 otherwise. Likewise, a successful rate of each model is also gathered for profound analysis.

Regarding calculation, the probability of successful solving will be calculated by dividing the frequency of events for total collected samples. The probability will be visualized on two-dimensional graph with x-axis is a number of floors and y-axis as probability of successful solving.

- Experimental Result:

There are three kinds of evacuation problem which are categorized as "No Issue", "Partially Solved" and "Infeasible Problem". Concerning the problems type's definition, "No Issues" indicates GMAF_MGCC could handle a problem without errors, meanwhile "Partially Solved" represents those problems which are partially or completely failed to solve by Stochastic model and "Infeasible Problems" indicate unbounded problems. Table 2 summaries the results' test.

Table 2 - Rate of Failure in Solving an Evacuation Problem

Type of problems	Frequency	Percentage (%)
No Issue	231	29.62
Solved by Deterministic & partially or fully fail to solve by Stochastic model	72	9.23
Infeasible problem	477	61.15
Total	780	100

The first type, "No Issue," is a success event so that the decision variable for them hold the value of 1, meanwhile the others two are both considered as failure event and take zero for their value. The next figure presents the probability of successful solving of GMAF_MGCC.

According to Figure 18, the probability of success event reduces drastically due to the increase in the height of the building. In cases of low floors building, less than nine stories, the probability of successful events is exceptionally high, over 0.8. The probability of successful solving quickly drops when a number of stories are higher than ten, exclusively for those which have more than twenty stories, the probability value equal to 0.

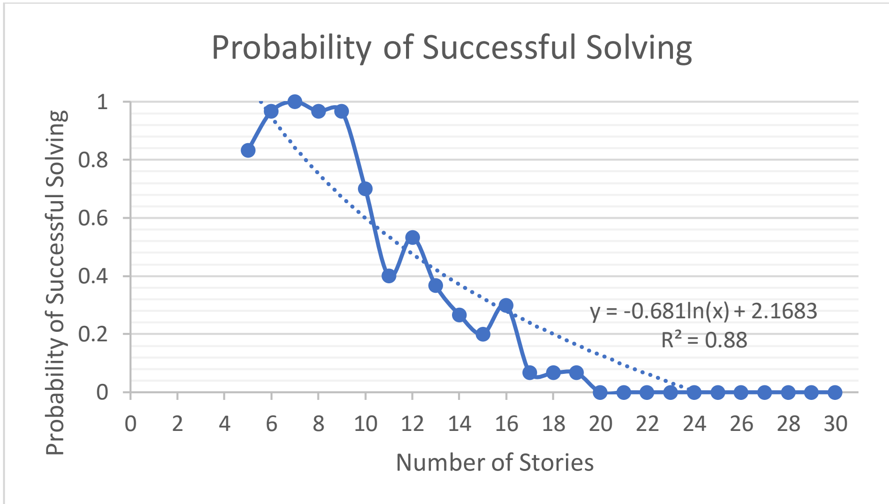


Figure 18 - Probability of Successful Solving of GMAF_MGCC

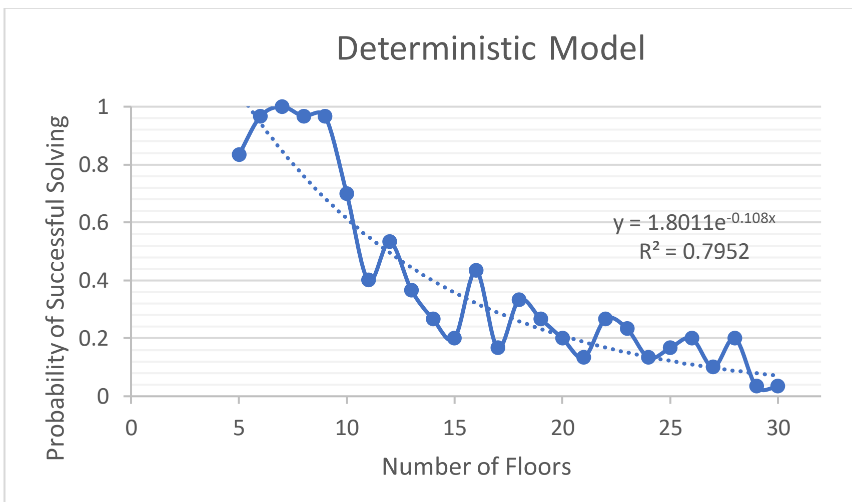


Figure 19- Probability of Successful Solving of Deterministic Model

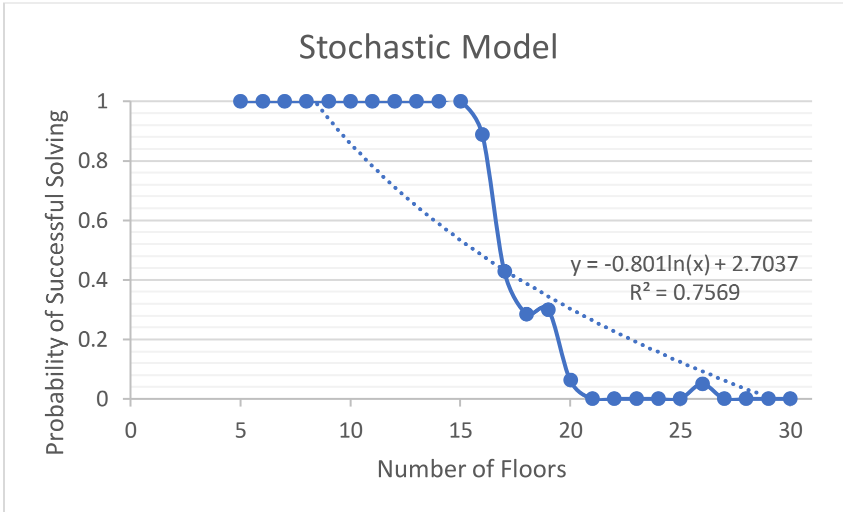


Figure 20- Probability of Successful Solving of Stochastic Model

Figures 19 and 20 present the experimental data of the Deterministic model and Stochastic model, respectively. According to the above figures, the deterministic model shares an identical shape with GMAF_MGCC; meanwhile, the stochastic model got a distinct shape compared to others. In Figure 19, the deterministic model gets a high chance of success from five to ten floors, the value in the range from 0.8 to 1. Nevertheless, the probability rapidly decreases after ten stories and slowly go down close to 0 when the level of building over twenty floors. In contrary, there is a divergence trend in the behaviors of the stochastic model compared to others. The relationship curve of the stochastic model prolong remains at a value of 1 from five to fifteen stories, and it remarkably declines and fluctuates around 0 when the building reach over twenty floors.

We can conclude that the probability of successful solving of GMAF_MGCC robustly involves the performance of deterministic model. Albeit, the result from this experiment is not robust due to the reduction of a number of inputs for stochastic model.

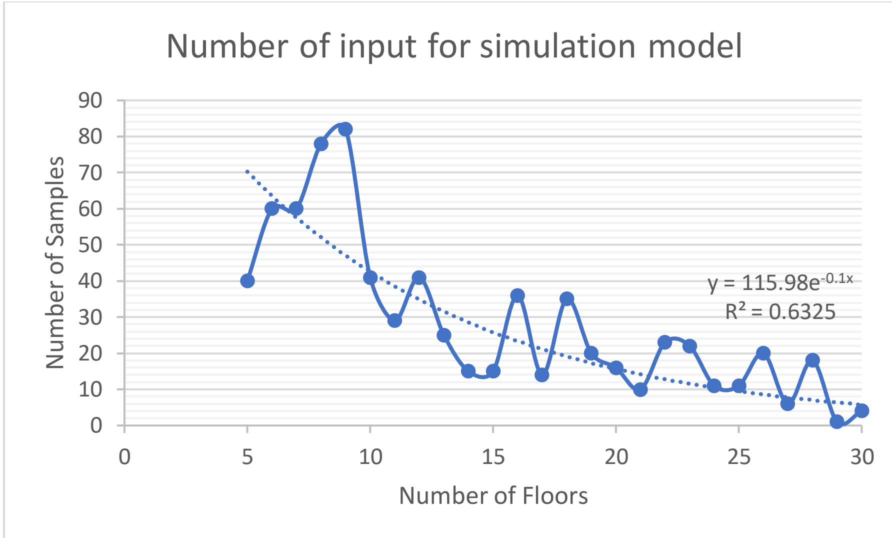


Figure 21 – Number of Inputs for Simulation Model

Figure 21 indicates a cardinal number of simulation model's input along the problems' size. A number of samples are dependent and decreasing due to the blooming of an infeasible issue with massive scale problems. Hence, further research is recommended to improve the robustness of the above conclusion.

CHAPTER 6

EXPERIMENTS OF THE INFLUENCE OF MULTIPLE FACTORS ON EVACUATION TIME

In this section, these following experiments study the significance of several potential factors including Arrival Rate, (initial) Population and Number of Story. We examine the single as well as interaction impacts of these factors on the egression time. Section 6.1 research on behavior of Arrival Rate, while the section 6.2 studies the impact of Number of Story and Population on processing time. The section 6.3, we research on both individual and interaction term of these factors on evacuation time. Finally, we conduct the analysis of egression time on multiple dimension in section 6.4. Each section covers the overview involving purpose, setting as well as other vital related information of the experiment and analyze those experimental result.

Regarding to Arrival Rate experiment, besides escaping time, the experiment also observes on other outcomes such as feasible ranges of arrival rate and blocking probability. About experiment of Number of Story and Population, we analyze these two variables in one experiment due to the correlation between them. The variation in Number of Story or Population or both can cause a significance change in total evacuation population of the problem. Thus, the integration of Number of Story and Population into one experiment will be an appropriate approach. In the last section, we examine the impact of multiple variables and interaction among them on the egression time.

6.1. Arrival Rate

6.1.1. Experiment Overview

The primary purpose of this experiment is observing the relationship of arrival rate and evacuation time and figuring the tolerance range of arrival rate for numerous scales of building. The next paragraphs will introduce the experimental setting including observed factors, experimental scope, programs, device, and experiment setup. The following summarizes the information of experiment.

- Dependent variable: Evacuation Time (t), Blocking Probability (Pb).
- Independent variable: Arrival Rate (λ).
- Experimental Scope: A Number of Story is in [5, 15] (increment is 1), Population is fixed at 50 occupants per story.
- Experimental programs: Benchmark, GMAF_MGCC Program and Stochastic M/G/C/C state dependent queuing model.
- Experiment Device: CPU i7-7700HQ 2.8GHz (8 CPUs), RAM 8192MB, on Windows 10 64-bits.
- Assumptions:

The experiment needs to apply several assumptions to limit the scope of the problem:

- ✓ Arrival rate will equally assign to each story of the building.
- ✓ The building will be fulfilled with one activity at each floor (one lambda for each story).
- ✓ There are only two stairwells during the urgent event (no elevator or escalator operate).
- ✓ There is no occupants' flow upward, only exits downward flow during analysis.

- Experimental Setup:

Benchmark and GMAF_MGCC program will genuinely use to generate samples for the simulation model M/G/C/C. Meanwhile, Benchmark creates problems for the deterministic model, GMAF_MGCC will solve them and produce samples for the simulation model.

Then, these samples will be passed to the stochastic model M/G/C/C to solve and all related data will be gathered based on problem scales, from five-floor to fifteen-floor. By increasing the lambda value, we can observe the interaction between processing time and arrival rate, also the occurrence of blocking probability p(c).

The experimental outcomes are analyzed and visualized in three distinct aspects including the range of arrival rate, the correlation of lambda and processing time and blocking probability in the next section.

6.1.2. Experimental Result

6.1.2.1. The range of arrival rate

Table 2 proposes feasible ranges of lambda for each class of problem and Figure 15 shows the visualization of lambda for each class of problem in the whiskey-box plot.

Table 3- Data of Arrival Rate

5_floor	6_Floors	7_Floors	8_Floors	9_Floors	10_Floors	11_floors	12_floor	13_floor	14_floor	15floor
0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04
0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.05	0.05	0.05
0.07	0.07	0.07	0.07	0.07	0.07	0.05	0.05	0.06	0.06	0.06
0.1	0.1	0.1	0.1	0.1	0.1	0.06	0.06	0.07	0.07	0.07
0.13	0.13	0.13	0.13	0.13	0.13	0.07	0.07	0.08	0.08	0.08
0.15	0.15	0.15	0.15	0.15	0.15	0.08	0.08	0.09	0.09	0.09
0.17	0.17	0.17	0.17	0.17	0.17	0.09	0.09	0.1	0.1	0.1
0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.11	0.11	0.11
0.23	0.23	0.23	0.23	0.23	0.21	0.11	0.11	0.12	0.12	0.12
0.25	0.25	0.25	0.25	0.25	0.215	0.12	0.12	0.13	0.13	0.13
0.27	0.27	0.27	0.28	0.256	0.2158	0.13	0.13	0.14	0.14	0.14
0.3	0.3	0.3	0.29	0.2565	0.21582	0.14	0.14	0.15	0.15	0.145
0.33	0.33	0.305	0.292	0.2568	0.21583	0.15	0.15	0.16	0.151	0.146
0.35	0.35	0.308	0.294	0.25681	0.21584	0.16	0.16	0.17	0.152	0.14601
0.37	0.37	0.309	0.2941	0.256815	0.2158405	0.17	0.17	0.176	0.152001	0.14602
0.4	0.4	0.30902	0.29412	0.256818	0.21584054	0.18	0.18	0.1765	0.152002	0.146025
0.43	0.405	0.30903	0.294121	0.2568184	0.2158405408	0.19	0.181	0.17652	0.15200201	0.14602501
0.45	0.4050000500	0.309032	0.2941212	0.256818480	0.21584054082	0.2	0.1811	0.176525	0.15200204	0.14602502
0.46	0.40500007	0.3090321	0.29412125	0.256818485	NA	0.205	0.18115	0.1765253	0.152002044	NA

0.468	0.405000075	0.30903212	0.2941212505	0.256818488	NA	0.2058	0.18119	0.17652539	NA	NA
0.4684	0.4050000755	0.30903212500	0.29412125051	NA	NA	0.20587	0.181195	0.176525391	NA	NA
0.468490	0.4050000756	0.309032126	0.2941212505102	NA	NA	0.2058780	0.181196	0.1765253916	NA	NA
0.468492	0.40500007569	NA	NA	NA	NA	0.2058784	0.1811965	0.17652539163	NA	NA
NA	0.405000075697	NA	NA	NA	NA	0.20587845	0.1811968	NA	NA	NA
NA	0.4050000756978	NA	NA	NA	NA	0.205878458	NA	NA	NA	NA

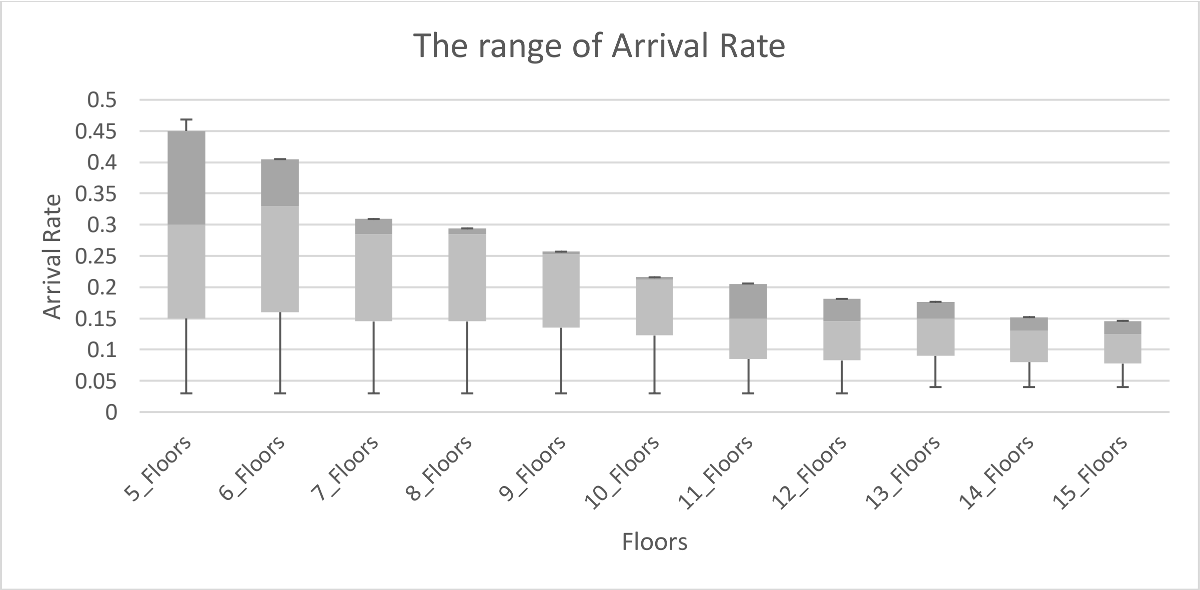


Figure 22 - The range of Arrival Rate

According to the Figure 22, the behaviors of lambda is antagonistic to the height of the building. The lambda range is decreased, while the number of floors increases; meanwhile the five-floor building problem has large range of arrival rate, from 0.03 to 0.47, the arrival range of fifteen-floor problem only has a narrow scope from, from 0.04 to 0.146. The graph indicates that the higher building reaches its threshold faster due to the high volume of passenger flow form each story (one activity on each floor). Hence, a tolerant range of arrival rate is narrower with the higher stories building, also the blocking probability occurs sooner than expected.

6.1.2.2. The relationship of the arrival rate and the processing time

This section studies the relation of the lambda and the evacuation time. Table 3 shows how the analysis result problems' scale from five-story to ten-story building, while Table 2 contains result of the problem with eleven-story to fifteen-stories. The "λ" column contains the arrival rate (person per second); meanwhile the evacuation time is stored in the "Time" column (seconds).

We visualize the correlation in two-dimensional graphs with x and y-axis are lambda and processing time respectively. The series of figures, including Figure 23, 24 and 25, exhibit the correlation curve between processing time and arrival rate.

Table 4 - Arrival Rate and Evacuation Time 1

5_floor		6_floor		7_floor		8_floor		9_floor		10_floor	
λ	**Time**	**λ**	**Time**	**λ**	**Time**	**λ**	**Time**	**λ**	**Time**	**λ**	**Time**
0.030	1966.9890	0.030	1989.1120	0.030	1958.5120	0.030	1327.3990	0.030	1917.220	0.030	1294.8440
0.050	1212.2260	0.050	1213.1360	0.050	1214.1750	0.050	1225.4940	0.050	1217.4890	0.050	1282.5140
0.070	873.6040	0.070	873.020	0.070	875.1010	0.070	884.6870	0.070	879.5510	0.070	926.5310
0.10	619.6380	0.10	618.0150	0.10	621.1980	0.10	629.0810	0.10	628.9590	0.10	662.7580
0.130	482.8890	0.130	480.7290	0.130	484.5810	0.130	491.4570	0.130	496.530	0.130	520.7960
0.150	422.1120	0.150	419.7230	0.150	423.8080	0.150	430.6080	0.150	437.6880	0.150	457.7030
0.170	375.6360	0.170	373.1030	0.170	377.3570	0.170	384.290	0.170	392.6910	0.170	409.4550
0.20	323.3520	0.20	320.710	0.20	325.1480	0.20	333.130	0.20	342.1240	0.20	355.1820
0.230	284.7130	0.230	282.140	0.230	286.8670	0.230	295.8010	0.230	304.7670	0.210	340.5380
0.250	264.1130	0.250	262.40	0.250	266.7730	0.250	275.9490	0.250	284.8530	0.2150	333.7290
0.270	246.5810	0.270	245.110	0.270	249.8790	0.280	251.5120	0.2560	279.4850	0.21580	332.6690
0.30	224.6770	0.30	224.150	0.30	229.1240	0.290	244.5340	0.25650	279.0490	0.215820	332.6430
0.330	206.7640	0.330	207.3550	0.3050	226.0870	0.2920	243.2040	0.25680	278.7880	0.215830	332.630
0.350	196.5330	0.350	198.0360	0.3080	224.3080	0.2940	242.0370	0.256810	278.780	0.2158400	332.6170
0.370	187.4110	0.370	189.830	0.3090	223.7220	0.29410	243.6690	0.2568150	278.7750	0.2158405	332.6160
0.40	175.4720	0.40	179.1020	0.309020	223.710	0.2941200	244.5410	0.2568180	278.7730	0.215840540	332.6160
0.430	165.2880	0.4050	177.4680	0.309030	223.7040	0.2941210	244.5880	0.2568184	278.7720	0.215840541	332.616
0.450	159.350	0.4050001	177.4680	0.309032	223.7030	0.2941212	244.5980	0.2568185	278.7720	0.215840541	332.6160
0.460	156.5940	0.40500007	177.4680	0.3090321	223.7030	0.2941213	244.60	0.2568185	278.7720	NA	NA
0.4680	154.4760	0.405000075	177.4680	0.3090321	NA	NA	NA	0.2568185	278.7720	NA	NA
0.46840	154.3720	0.4050000755	177.4680	0.3090321	NA	NA	NA	NA	NA	NA	NA
0.46849	154.3490	0.4050000756	177.4680	0.3090321	NA	NA	NA	NA	NA	NA	NA

Table 5 - Arrival Rate and Evacuation Time 2

11_floor		12_floor		13_floor		14_floor		15_floor	
λ	**Time**	**λ**	**Time**	**λ**	**Time**	**λ**	**Time**	**λ**	**Time**
0.030	1991.3020	0.030	1298.4710	0.040	1548.1480	0.040	1539.133	0.040	1693.2790
0.040	1604.7990	0.040	1507.8960	0.050	1286.7560	0.050	1241.440	0.050	1370.7570
0.050	1290.8640	0.050	1215.250	0.060	1078.7410	0.060	1042.9780	0.060	1155.742
0.060	1081.790	0.060	1020.1530	0.070	930.1590	0.070	901.2190	0.070	1002.1590
0.070	932.510	0.070	880.7980	0.080	818.7230	0.080	794.900	0.080	886.9730
0.080	820.6260	0.080	776.2810	0.090	732.0510	0.090	712.2620	0.090	797.3830
0.090	733.6720	0.090	694.9920	0.10	662.7130	0.1000	646.2690	0.100	725.7120
0.10	664.1140	0.10	629.9720	0.110	605.9820	0.1100	592.2870	0.110	667.0710
0.110	607.1320	0.110	576.9190	0.120	558.7060	0.1200	547.3020	0.120	618.2040
0.120	559.6030	0.120	532.7710	0.130	518.9630	0.1300	509.4190	0.130	576.8550
0.130	519.3880	0.130	496.0830	0.140	486.0230	0.1400	477.5880	0.140	541.4140
0.140	484.9370	0.140	464.950	0.150	457.6310	0.1500	450.2380	0.1450	525.5260
0.150	455.0940	0.150	437.6470	0.160	432.8740	0.1510	447.7120	0.1460	522.4790
0.160	428.9920	0.160	414.1770	0.170	411.0840	0.1520	445.2230	0.14601	522.4490
0.170	405.9680	0.170	393.6480	0.1760	399.2540	0.1520010	445.2200	0.14602	522.4190
0.180	385.5050	0.180	375.460	0.17650	398.3070	0.152002000	445.2180	0.146025	522.4040
0.190	367.1990	0.1810	375.1240	0.176520	398.2690	0.152002010	445.2180	0.146025	522.4040
0.20	350.7230	0.18110	375.6040	0.1765250	398.260	0.152002040	445.2170	0.146025	522.4040
0.2050	343.0890	0.181150	375.8130	0.1765253	398.2590	NA	NA	NA	NA
0.20580	341.9020	0.181190	376.0990	0.176525390	398.2590	NA	NA	NA	NA
0.2058700	341.7980	0.1811950	376.1260	0.1765253910	398.2590	NA	NA	NA	NA
0.2058780	341.7860	0.1811960	376.1380	0.1765253916	398.2590	NA	NA	NA	NA
0.2058784	341.7860	0.1811965	376.1380	0.1765253916	398.2590	NA	NA	NA	NA
0.2058785	341.7860	0.1811968	376.1380	NA	NA	NA	NA	NA	NA

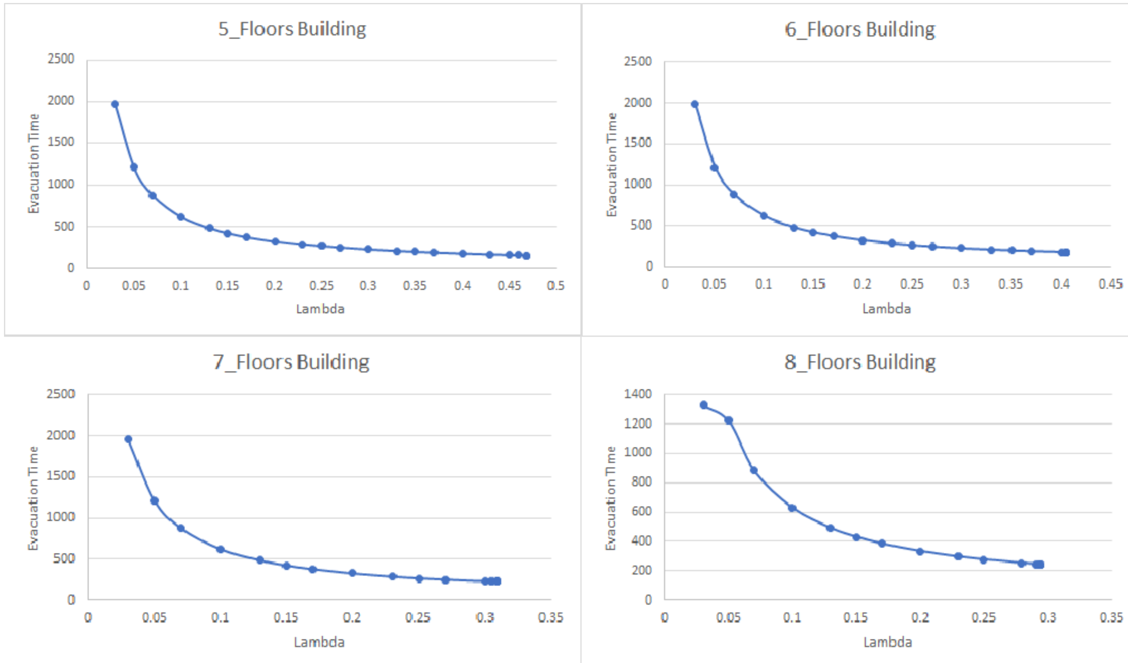


Figure 23 – Five-Floors to Eight-Floors Building

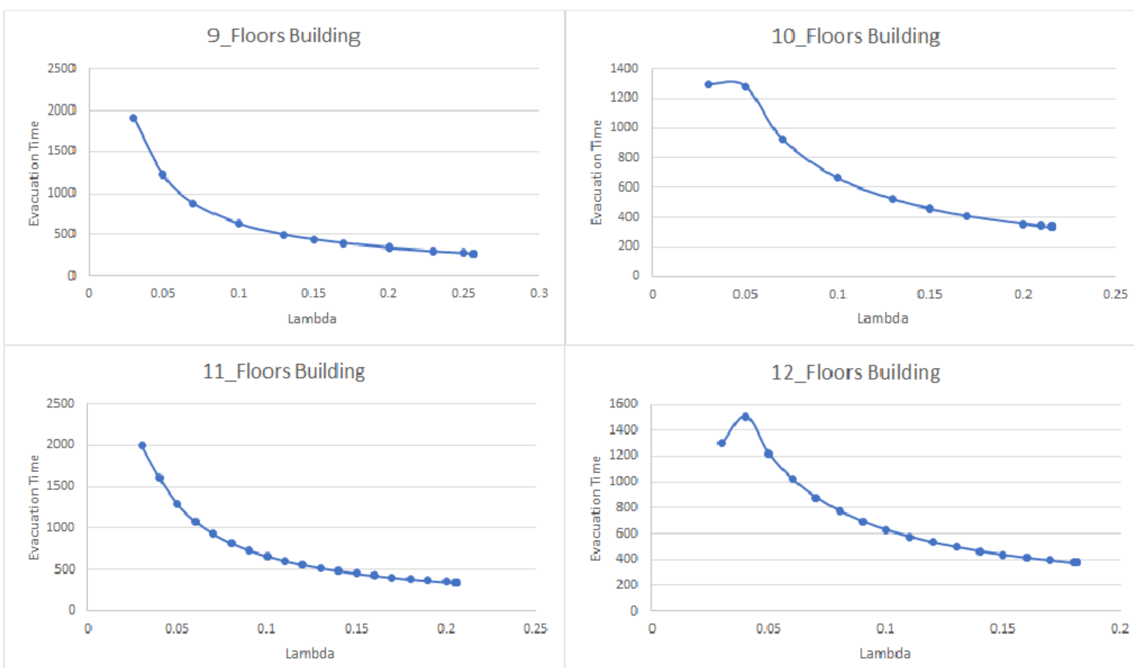


Figure 24 – Nine-Floors to Twelve-Floors Building

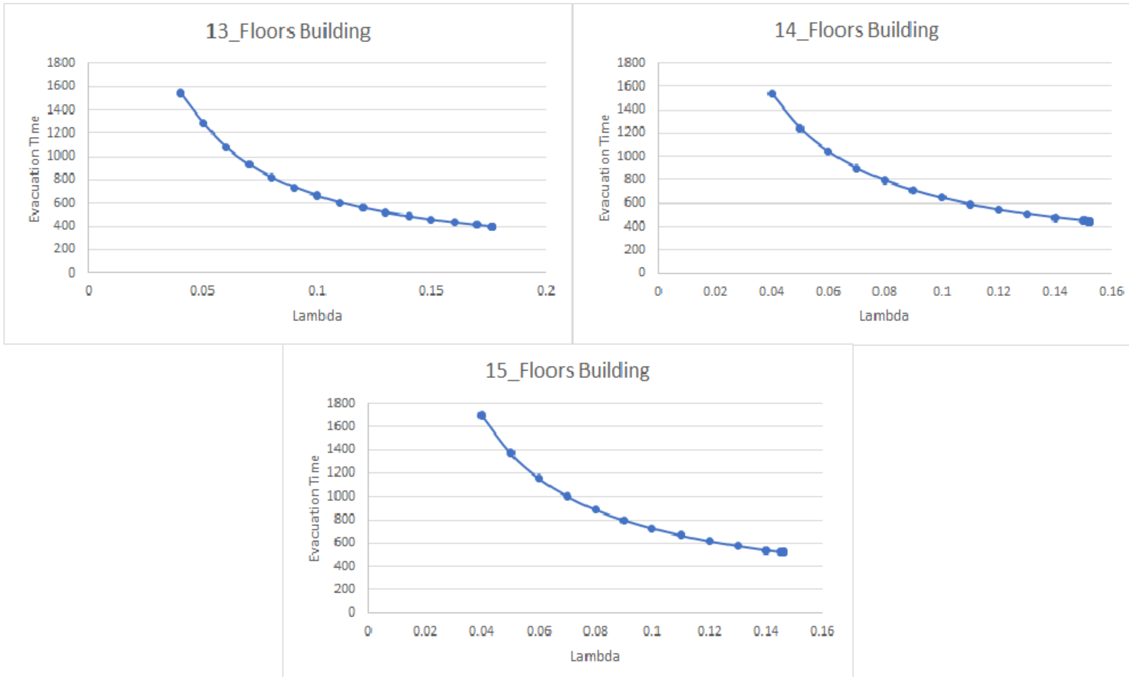


Figure 25 – Thirteen-Floors to Fifteen-Floors Building

Regarding Figures 23 to 25, the relationship curves are convex and share a similar shape with the exponential decay function. There is no conflict with the prognostication with the expectation of the researcher. Also, the outcome indicates lambda value has a significant effect on the processing time; the escaping time will be higher at higher arrival rate value. As a consequence, minimizing the processing time requires to maintain the high volume of occupants' evacuation.

6.1.2.3. Blocking Probability

This section discusses the blocking probability which causes the congestion during an evacuation event and giving negative effects on the escaping time. The research outcome is recorded in following tables including the value of lambda and its block probability.

Table 6- Blocking Probability 1

5_floor		6_floor		7_floor		8_floor		9_floor	
λ	**Pb**	**λ**	**Pb**	**λ**	**Pb**	**λ**	**Pb**	**λ**	**Pb**
0.468	0.026961	NA	NA	0.309032	0.002833	NA	NA	0.2568184	0.002937
0.4684	0.026961	NA	NA	0.3090321	0.002833	NA	NA	0.25681848	0.002937
0.46849	0.026961	NA	NA	0.30903212	0.002833	NA	NA	0.256818485	0.002937
0.468492	0.026961	NA	NA	0.309032125	0.002833	NA	NA	0.256818488	0.002937

Table 7 - Blocking Probability 2

10_floor		11_floor		12_floor		13_floor		14_floor		15_floor	
λ	**Pb**	**λ**	**Pb**	**λ**	**Pb**	**λ**	**Pb**	**λ**	**Pb**	**λ**	**Pb**
0.21584	0.001988	0.205878	0.002407	0.18119	0.000555	NA	NA	0.152002	0.004695	0.14602501	0.000444
0.2158405	0.001988	0.2058784	0.003003	0.181195	0.000555	NA	NA	0.15200201	0.004695	0.14602502	0.000444
NA	NA	0.20587845	0.003003	0.181196	0.000555	NA	NA	0.15200204	0.004695	NA	NA
NA	NA	0.205878458	0.003003	0.1811965	0.000555	NA	NA	0.152002044	0.004695	NA	NA

According to the result, the blocking probability occurs when lambda gets closed to an optimal value and its value stabilize at a fixed value. Although, there are a few exceptions such as six-story, eight-story and thirteen-story building. Even if the arrival rate closely approaches an optimal amount (the processing time tends to be unchanged, or it is re-increasing), the blocking probability value stays still at zero. Regarding to explain for those cases, the blocking probability p(c) could possibly raise at the point laying behind an optimal lambda.

6.2. Number of Story and Population

6.2.1. Experiment Overview

The experiment tests the behavior of egress time with variation in building scale and initial population. These are crucial factors which will directly affect on the total evacuee population. The settings of this experiment will be introduced in the below paragraphs.

- Dependent variable: Evacuation Time (t).
- Independent variables: Number of Story (N), Population (Pop).
- Experimental Scope: A Number of Story is in [10, 20] (increment is 10), Population is in [10 to 70] (increment is 5), Lambda is fixed at 0.075.
- Experimental programs: Benchmark, GMAF_MGCC Program and Stochastic M/G/C/C state dependent queuing model.
- Experiment Device: CPU i7-7700HQ 2.8GHz (8 CPUs), RAM 8192MB, on Windows 10 64-bits.
- Assumptions:

The experiment needs to apply several assumptions to limit the scope of the problem:

- ✓ Arrival rate will equally assign to each story of the building.
- ✓ The building will be fulfilled with one activity at each floor (one lambda for each story).
- ✓ There are only two stairwells during the urgent event (no elevator or escalator operate).
- ✓ There is no occupants' flow upward, only exits downward flow during analysis.

- Experimental Setup:

Similar to the experiment in section 6.1, we use Benchmark and GMAF_MGCC program to generate samples, then solve them with the simulation model M/G/C/C. For each level (N), we will vary initial population (Pop), from ten to seventy (occupants per floor). In order to serve the purpose of this experiment, egression time will be collected to observe the impact of the population (Pop) as well as a number of stories (N); the total number of observations is 143 (11x13).

6.2.2. Experimental Result

The outcome of this experiment is stored in Table 7. In this table, it includes Pop (occupants per story), N (A number of story) and the egress time (second).

Table 8 - Table Result of Experiment on The Impact of Initial Population and Number of Stories on Egress Time

N \ Pop	10	15	20	25	30	35	40	45	50	55	60	65	70
10	251.044	285.829	400.688	458.541	542.044	628.803	709.241	747.958	867.829	873.685	1024.192	1053.854	1138.051
11	226.065	313.679	391.858	543.719	539.209	576.262	731.908	798.149	872.824	888.819	994.228	1044.361	1118.928
12	224.091	317.69	402.921	431.212	536.504	610.877	709.79	780.749	825.056	933.374	971.342	1087.638	1138.865
13	242.787	343.251	470.584	529.598	552.086	650.74	750.611	812.009	870.726	933.526	1018.128	1091.572	1151.907
14	247.607	374.985	472.601	471.268	580.657	588.176	730.293	843.278	844.516	958.104	992.907	1059.341	1137.593
15	246.741	358.389	449.749	545.194	592.66	679.306	754.469	820.648	940.727	955.514	957.57	1102.47	1159.156
16	262.699	372.056	458.106	488.67	608.391	657.323	814.38	765.81	832.386	909.577	1062.308	1060.354	1153.825
17	292.54	379.354	445.995	500.552	599.788	693.14	750.954	777.66	927.089	971.115	1051.484	1098.352	1193.437
18	293.624	383.905	419.108	509.394	627.244	743.595	724.376	781.471	859.091	954.441	1074.759	1145.38	1177.133
19	323.134	358.17	444.898	555.089	584.133	705.359	721.776	796.76	991.899	980.137	1041.953	1154.336	1221.243
20	272.326	354.447	436.018	535.924	635.758	683.193	733.939	828.615	908.042	1026.607	1057.488	1140.587	1169.884

To observe the impact of each factor on the processing time, we separately plot each factor and the egress time on two dimensional graphs with the egress time on y-axis and observed factors on x-axis.

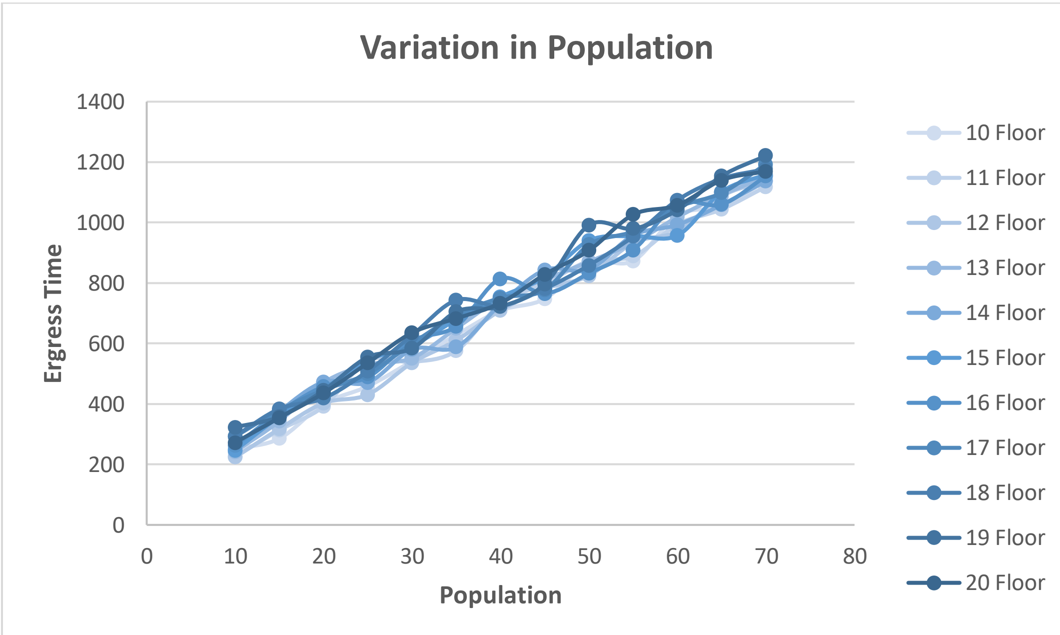


Figure 26 - Evacuation Time with Variation in Population

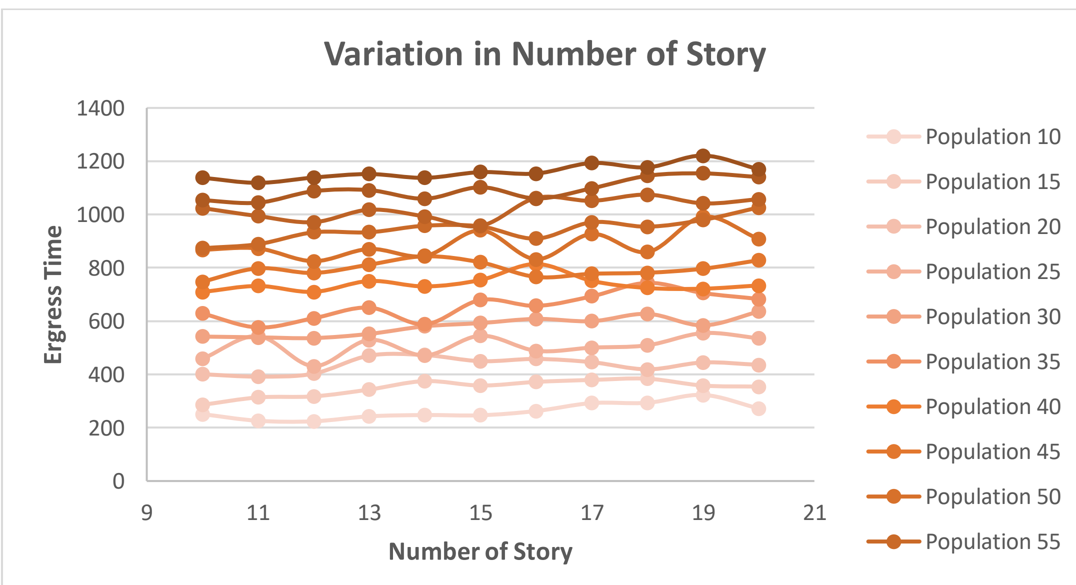


Figure 27 - Evacuation Time with Variation in Number of Stories

Figure 26 represents the processing time with the variation in the population. According to Figure 26, the relationship between the evacuation time and population is non-linear, and it is lifted when the number of floors is increased, but this correlation is neither convex nor concave.

Likewise, the egress time and the number of stories shows the non-linear shape, and it does not have convex as well as concave shape. However, unlike Figure 26, the polynomial form of egress time and a number of floors in Figure 27 is unclear, and at some population-lines, the correlation is roughly linear. Also, curves in Figure 26 have steeper slope compared to those in Figure 27; it indicates that the variation in floor does not impact as significant as the change in population.

6.3. Effects of Multiple Factors

6.3.1. Experiment Overview

After observing the singular effect of arrival rate, a number of floors and (initial) population, we expect to study aggregate as well as individual impacts of these three factors egress time. In this experiment, the egress time will be treated as a dependent variable and arrival rate, a number of story and population will be the dependent variable. To reduce to the complexity of this experiment, we will ignore other dependent variables such as blocking probability and total evacuee population. The setting of this experiment will be introduced in the below paragraph.

- Dependent variable: Evacuation Time (t).
- Independent variables: Arrival Rate (λ), A Number of Story (N) and Population (Pop).

- Experimental Scope: Arrival Rate in [0.05, 0.1] (increment is 0.01), A Number of Story in [10, 20] (increment is 10), and Population in [10, 60] (increment is 10).
- Experimental programs: Benchmark, GMAF_MGCC and Stochastic M/G/C/C state dependent queuing model, RStudio.
- Experiment Device: CPU i7-7700HQ 2.8GHz (8 CPUs), RAM 8192MB, on Windows 10 64-bits.
- Assumptions:

The experiment needs to apply several assumptions to limit the scope of the problem:

- ✓ Arrival rate will equally assign to each story of the building.
- ✓ The building will be fulfilled with one activity at each floor (one lambda for each story).
- ✓ There are only two stairwells during the urgent event (no elevator or escalator operate).
- ✓ There is no occupants' flow upward, only exits downward flow during analysis.

- Experimental Setup:

Regarding samples, there are 396 samples be prepared for this experiment. Those samples can be divided into groups by a number of floor (N); there are eleven groups. In each group by N, we sort internal samples of each group into six sub-groups followed by population, and in each sub-group, samples are classified into another six sub-groups based on arrival rate. The samples structure is presented in Figure 28.

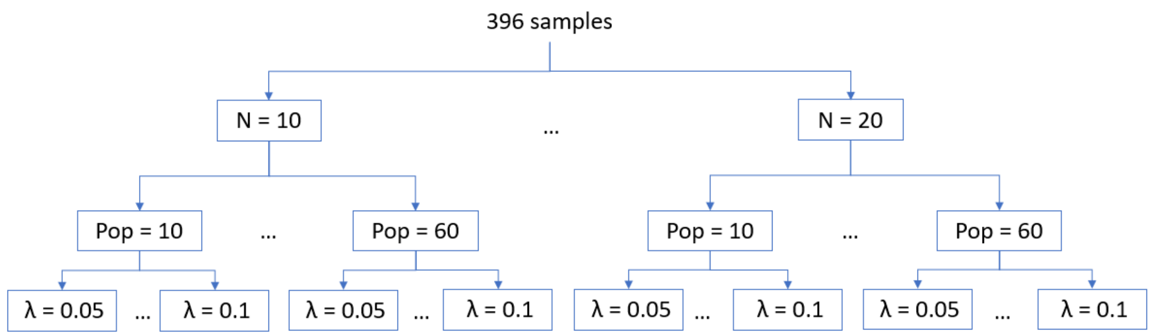


Figure 28 - Sample Structure

Then, these samples will be solved by the simulation model and the evacuation time will be collected to analyze. We expect that the behavior of egress time due to cumulative impacts of multiple factors will keep identical features which were found on the analysis of single factor:

- ✓ Arrival Rate (λ): nonlinear, significant impact.
- ✓ A Number of Story (N): (probably) linear, (slightly) significant impact.
- ✓ Population (Pop): nonlinear, significant impact.

The interactive effect of three independent variables on escaping time will be observed in this experiment. Besides, we believed that the behavior of an evacuation time with a particular building scale can be described by a statistical distribution. Hence, in the next section, we will apply Probability Distribution Fitting to analyze an egress time.

6.3.2. Experimental Result

The outcome of experiment is shown in Table 8. The table includes N (a number of story), Pop (occupants per story), λ (persons per second) and Evacuation Time – t (second).

Table 9 - Experiment on Impact of Multiple Factor

N	Pop	λ					
		0.05	**0.06**	**0.075**	**0.08**	**0.09**	**0.1**
10	**10**	345.231	302.637	251.044	238.146	216.649	199.452
	20	571.318	486.003	400.688	379.359	343.811	315.373
	30	785.731	663.887	542.044	511.583	460.816	420.219
	40	1041.529	875.385	709.241	667.705	598.48	543.099
	50	1282.514	1074.693	867.829	816.55	731.11	662.758
	60	1515.955	1270.074	1024.192	962.722	860.273	778.313
11	**10**	311.312	268.006	226.065	215.642	198.259	184.738
	20	563.524	477.656	391.858	370.409	334.731	306.857
	30	772.989	659.343	539.209	509.176	459.12	415.849
	40	1065.513	898.706	731.908	690.226	620.797	565.294
	50	1290.864	1081.79	872.824	820.626	733.672	664.114
	60	1450.931	1228.618	994.228	935.63	837.967	754.921
12	**10**	313.8	268.945	224.091	212.877	194.188	179.271
	20	585.049	493.985	402.921	380.155	342.212	311.858
	30	771.423	653.963	536.504	507.139	458.198	419.045
	40	1040.046	874.875	709.79	668.526	599.85	544.952
	50	1215.25	1020.153	825.056	776.281	694.992	629.972
	60	1426.68	1199.011	971.342	914.425	819.563	743.673
13	**10**	324.794	283.774	242.787	232.559	215.521	201.913
	20	674.541	572.562	470.584	445.09	402.599	368.607
	30	792.794	672.439	552.086	521.998	471.851	431.733
	40	1100.58	925.595	750.611	706.866	633.956	575.628
	50	1286.756	1078.741	870.726	818.723	732.051	662.713
	60	1488.857	1253.492	1018.128	959.287	861.2219	782.765
14	**10**	333.17	289.95	247.607	237.217	219.941	206.12
	20	668.556	570.576	472.601	448.135	407.357	374.759
	30	834.643	707.648	580.657	548.928	496.047	453.811
	40	1063.073	896.683	730.293	688.696	619.368	563.905
	50	1241.44	1042.978	844.516	794.9	712.262	646.269
	60	1463.526	1228.215	992.907	934.091	836.081	757.735
15	**10**	334.968	290.486	246.741	235.862	217.743	204.35
	20	673.784	543.674	449.749	426.293	387.219	356.039
	30	848.535	720.558	592.66	560.699	507.467	464.887
	40	1088.37	921.419	754.469	712.731	643.169	587.519

	50	1370.757	1155.742	940.727	886.973	797.383	725.712
	60	1396.615	1176.012	957.57	902.96	811.943	739.138
16	**10**	353.716	308.208	262.699	251.322	232.361	217.191
	20	644.857	549.825	458.106	435.643	398.216	368.28
	30	884.37	745.61	608.391	575.12	519.89	476.353
	40	1188.234	1001.307	814.38	767.648	689.762	627.453
	50	1213.466	1022.695	832.386	786.193	709.704	648.528
	60	1439.322	1310.399	1062.308	1000.291	896.953	815.359
17	**10**	401.475	347.007	292.54	278.924	256.229	238.074
	20	636.659	541.327	445.995	422.162	382.44	350.663
	30	888.835	753.13	599.788	587.275	515.121	488.031
	40	1089.488	920.221	750.954	708.675	638.251	581.966
	50	1350.247	1138.652	927.089	874.242	786.303	716.106
	60	1531.379	1291.386	1051.484	991.476	891.885	812.224
18	**10**	397.103	345.363	293.624	280.689	259.513	243.351
	20	581.605	500.235	419.108	398.882	365.174	338.24
	30	891.002	759.124	627.244	594.275	539.326	495.376
	40	1039.382	881.303	724.376	685.144	619.758	567.449
	50	1254.128	1056.548	859.091	809.768	727.578	661.828
	60	1521.834	1286.731	1074.759	1013.53	911.511	829.895
19	**10**	431.217	376.337	323.134	309.855	287.742	270.068
	20	612.2	527.921	444.898	424.241	389.484	361.783
	30	853.725	718.883	584.133	550.538	494.782	449.918
	40	1045.703	883.479	721.776	683.027	620.283	569.052
	50	1432.39	1212.104	991.899	936.878	845.205	771.895
	60	1506.326	1273.989	1041.953	984.022	887.542	809.904
20	**10**	362.393	317.36	272.326	261.5	246.478	233.216
	20	605.527	519.177	436.018	415.366	382.095	355.915
	30	902.304	769.032	635.758	602.44	546.91	502.488
	40	1066.486	900.184	733.939	692.388	623.163	567.79
	50	1309.73	1121.656	908.042	857.831	774.694	708.749
	60	1526.899	1292.194	1057.488	988.812	901.018	822.782

To visualize these data, we plot them into three-dimensional graphs. Nevertheless, a number of the desired dimension to adequately display these data is four which is impossible to observe by human eyes. Hence, the researcher decides to select the single independent variable (among N, Pop, and λ) to treat as the dummy variable in each time plotting. Figure 21, 22 and 23 are arranged in order of (dummy variable) N, Pop, and λ, respectively; in each figure, there are two plots which are scattered and 3D surface plots.

According to Figure 29, there are smooth curvilinear relationship in the 3D surface plot. As well, several surface layers are corresponding to each quality variable – a number of stories. The increase in a quality variable also increases the value of the response variable with a constant amount. As we can see, the variation in the dummy variable slightly impacts on the evacuation time. Besides, it is ambiguous about the interception among layers, those layers in Figure 29 tend to be parallel with each other. Also, we suspect about the existence of interaction effect between an arrival rate and a population on the evacuation time.

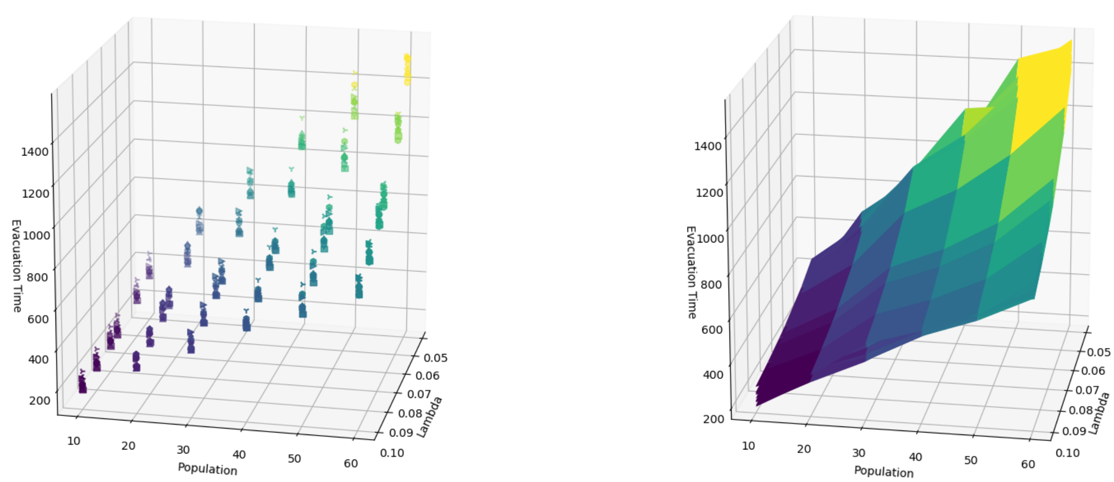


Figure 29 - Effect of Multiple Factors on Egress Time (Dummy Variable - Population)

In Figure 30, the population is selected to treat as a dummy variable. According to this figure, the low value of the quality variable corresponding to lower surfaces, as well, those planes with a high value of the quality variable are placed in the upper position. We notice the critical influence of the quality variable on the response variable in this case. Moreover, it is a convex trend that we can see in Figure 30. Regarding the scatter plot in Figure 30, we can observe the linear relationship between a number of floors and egress time at each level of lambda and population.

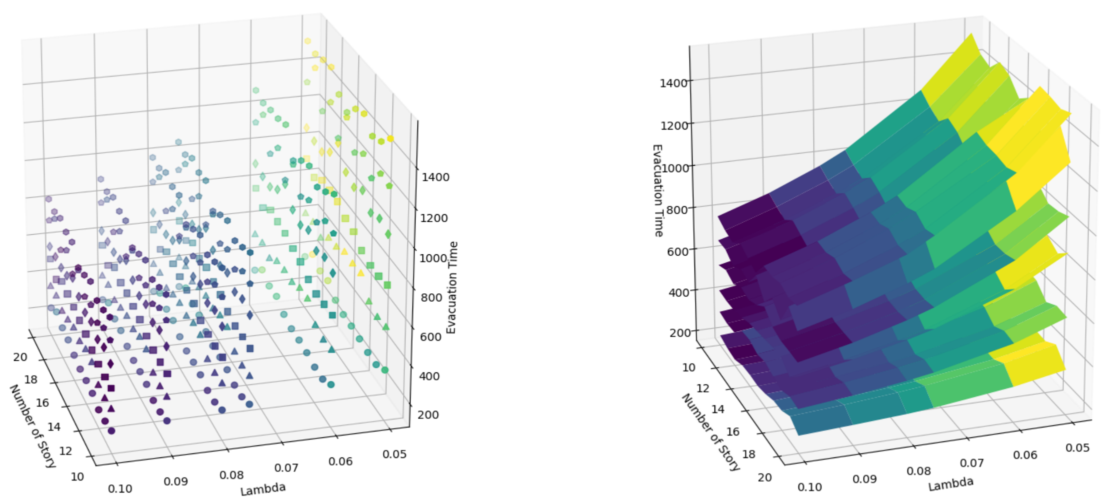


Figure 30 - Effect of Multiple Factors on Egress Time (Dummy Variable - A Number of Stories)

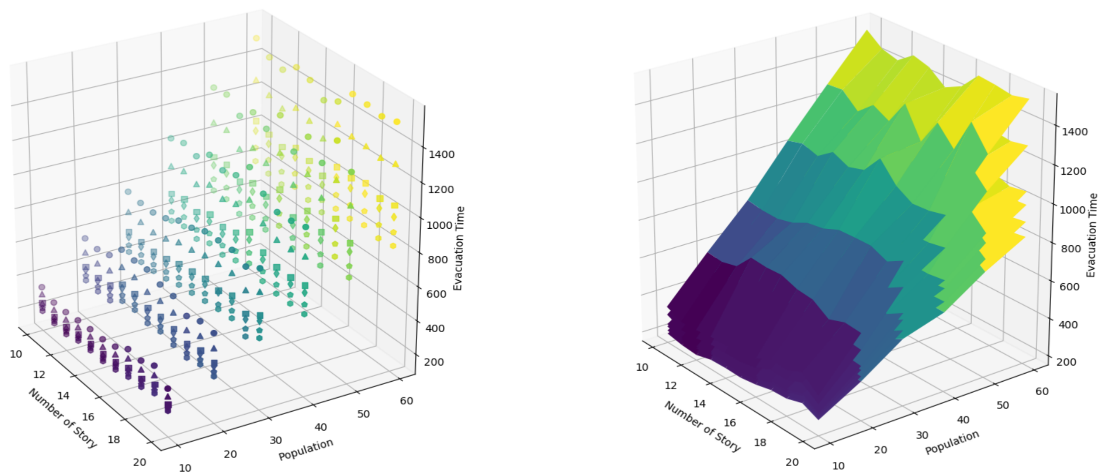


Figure 31 - Effect of Multiple Factors on Egress Time (Dummy Variable - Lambda)

Regarding Figure 31, the gap among surface is narrow at a low level of population; meanwhile, the higher value of population significantly increases the disparity among them. The position of the plane is correspondent to the value of lambda; the lower value leverages the location of the surface and vice versa. All planes in the figure show the non-linear curve, but there is no convex or concave shape. Again, the scattered plot indicates the linear relationship between a number of stories and escaping time at a particular population and lambda.

6.4. **Probability Distribution Fitting for An Evacuation Time**

Based on the data in section 6.3, we attempt to fit them with adequate distribution. An escaping time will be separately analyzed for each problem's scale, from ten to twenty stories. We search for the best distribution which adequately illustrates the egress time for a certain building structure with a variation in population and evacuation rate. Regarding the distribution, we decide to fit the data with Normal, Log-Normal, Weibull, Gamma, Logis, and Exponential distributions. The analysis was conducted on [RStudio] with the [fitdistrplus] package.

6.4.1. Probability Distribution Fitting Analysis

✓ *Ten-Story Building:*

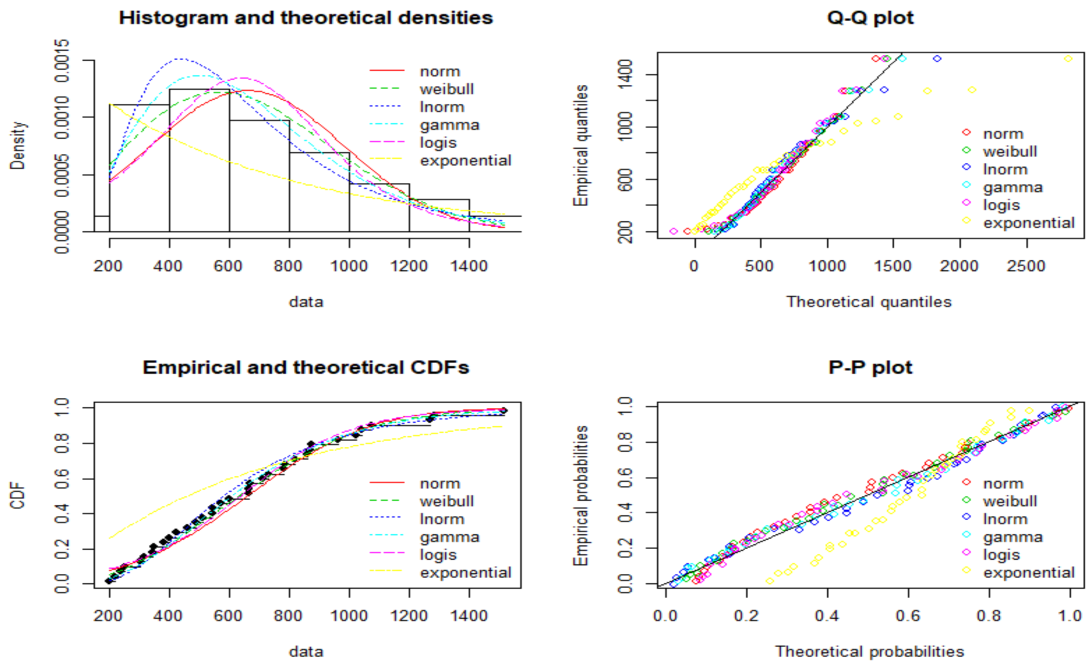


Figure 32 - Probability Distribution Fitting Test for Ten-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.08426732 0.05732464 0.10136016 0.07093112 0.08744181   0.2612202
Cramer-von Mises statistic   0.05542460 0.01980375 0.04493609 0.02312026 0.03959382   0.7812794
Anderson-Darling statistic   0.42679743 0.17834427 0.28827242 0.16996986 0.37073481   4.2190802

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 522.1925 517.7382 517.6487 516.8202 523.1134    541.3091
Bayesian Information Criterion 525.3595 520.9053 520.8157 519.9872 526.2804    542.8926
```

Figure 33 – Goodness of Fit for Ten-Story Building

According to the Goodness of Fit test, Weibull, Log-Normal and Gamma distributions are the best fit compared for the ten-story building compared to the other. The parameter of those distributions will provide in the below table:

Table 10 - Best Fitted Distribution for Ten-Story building

Weibull	Fitting of the distribution ' weibull ' by maximum likelihood Parameters : estimate Std. Error shape 2.181933 0.2796073 scale 746.616651 60.2903877 Loglikelihood: -256.8691 AIC: 517.7382 BIC: 520.9053 Correlation matrix: shape scale shape 1.0000000 0.3246616 scale 0.3246616 1.0000000
Log-Normal	Fitting of the distribution ' lnorm ' by maximum likelihood Parameters : estimate Std. Error meanlog 6.3618844 0.08728532 sdlog 0.5237119 0.06171903 Loglikelihood: -256.8243 AIC: 517.6487 BIC: 520.8157 Correlation matrix: meanlog sdlog meanlog 1 0 sdlog 0 1
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.047306046 0.812002219 rate 0.006144089 0.001276527 Loglikelihood: -256.4101 AIC: 516.8202 BIC: 519.9872 Correlation matrix: shape rate shape 1.0000000 0.9217293 rate 0.9217293 1.0000000

✓ ***Eleven-Story Building:***

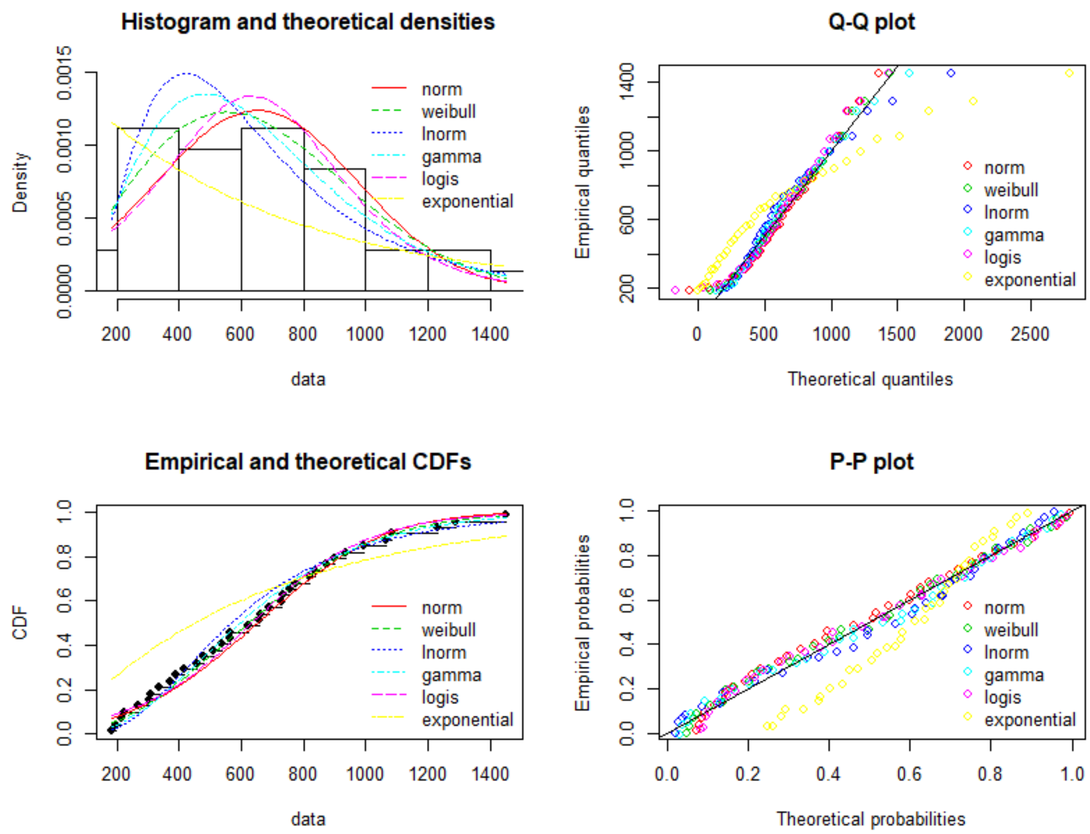


Figure 34 - Probability Distribution Fitting Test for Eleven-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.07725730 0.05611006 0.10770445 0.07785721 0.08387696   0.2469973
Cramer-von Mises statistic   0.04003623 0.01705234 0.06795538 0.03194904 0.03291782   0.7298551
Anderson-Darling statistic   0.33518052 0.15512590 0.42614885 0.22114740 0.31266381   3.9790973

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 522.0398 517.9396 519.5534 517.9034 523.4363    540.4753
Bayesian Information Criterion 525.2069 521.1066 522.7205 521.0704 526.6033    542.0589
```

Figure 35 - Goodness of Fit for Eleven-Story Building

For the eleven-floor building, Gamma and Weibull are two best distributions to describe the evacuation time. The parameter of these distributions is shown in Table 11:

Table 11 - Best Fitted Distribution for Eleven-Story Building

Weibull	`Fitting of the distribution ' weibull ' by maximum likelihood`
	`Parameters :`
	`         estimate Std. Error`
	`shape    2.158534  0.2808483`
	`scale 737.680637 60.1355525`
	`Loglikelihood:  -256.9698   AIC:  517.9396   BIC:  521.1066`
	`Correlation matrix:`
	`          shape     scale`
	`shape 1.0000000 0.3207907`
	`scale 0.3207907 1.0000000`

Gamma	`Fitting of the distribution ' gamma ' by maximum likelihood`
	`Parameters :`
	`         estimate  Std. Error`
	`shape 3.790911585 0.755141274`
	`rate  0.005822005 0.001202135`
	`Loglikelihood:  -256.9517   AIC:  517.9034   BIC:  521.0704`
	`Correlation matrix:`
	`          shape      rate`
	`shape 1.0000000 0.9156888`
	`rate  0.9156888 1.0000000`

✓ ***Twelve-Story Building:***

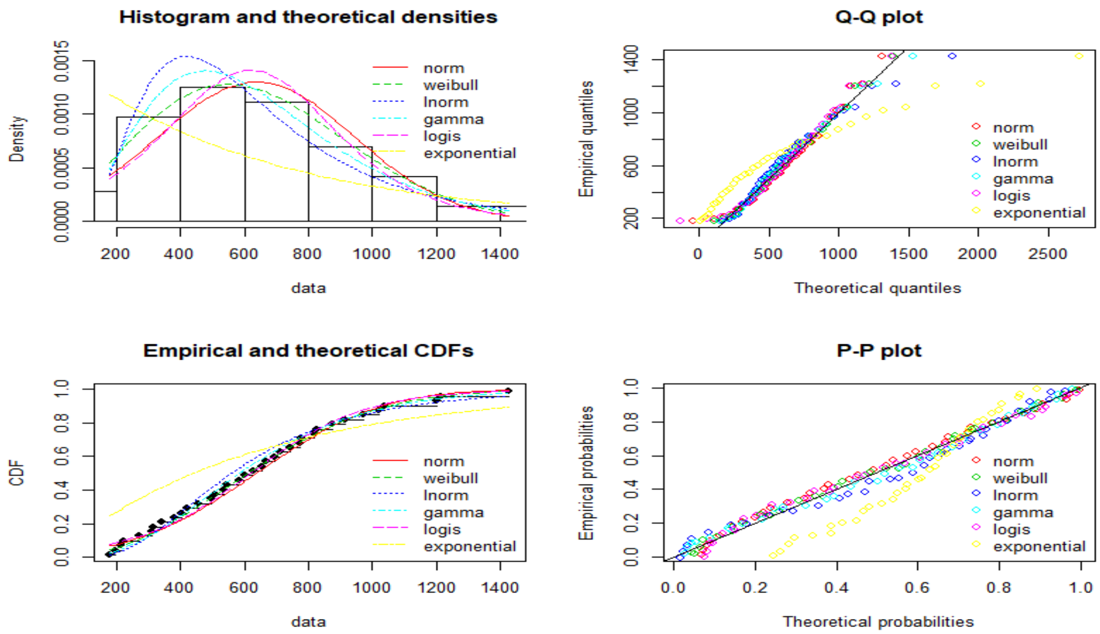


Figure 36 – Probability Distribution Fitting Test of Twelve-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.06834445 0.04792195 0.08973586 0.05935505 0.07730243   0.2482484
Cramer-von Mises statistic   0.03208161 0.01129879 0.06490105 0.02608656 0.02395908   0.7841980
Anderson-Darling statistic   0.28382257 0.12217426 0.41722135 0.19244009 0.25638252   4.2153239

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 518.6205 514.9068 516.7941 514.9353 519.7792    538.8813
Bayesian Information Criterion 521.7876 518.0738 519.9612 518.1023 522.9463    540.4648
```

Figure 37 - Goodness of Fit for Twelve-Story Building

In this test, there are two distributions suggested for the twelve-story building which are Weibull and Gamma. The parameter of these two distributions as the below table:

Table 12 - Best Fitted Distribution for Twelve-Story Building

Weibull	Fitting of the distribution ' weibull ' by maximum likelihood Parameters : estimate Std. Error shape 2.214054 0.2870892 scale 721.185427 57.3052325 Loglikelihood: -255.4534 AIC: 514.9068 BIC: 518.0738 Correlation matrix: shape scale shape 1.0000000 0.3201423 scale 0.3201423 1.0000000
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 3.975350583 0.801419807 rate 0.006240215 0.001305415 Loglikelihood: -255.4676 AIC: 514.9353 BIC: 518.1023 Correlation matrix: shape rate shape 1.0000000 0.9212375 rate 0.9212375 1.0000000

✓ *Thirteen-Story Building:*

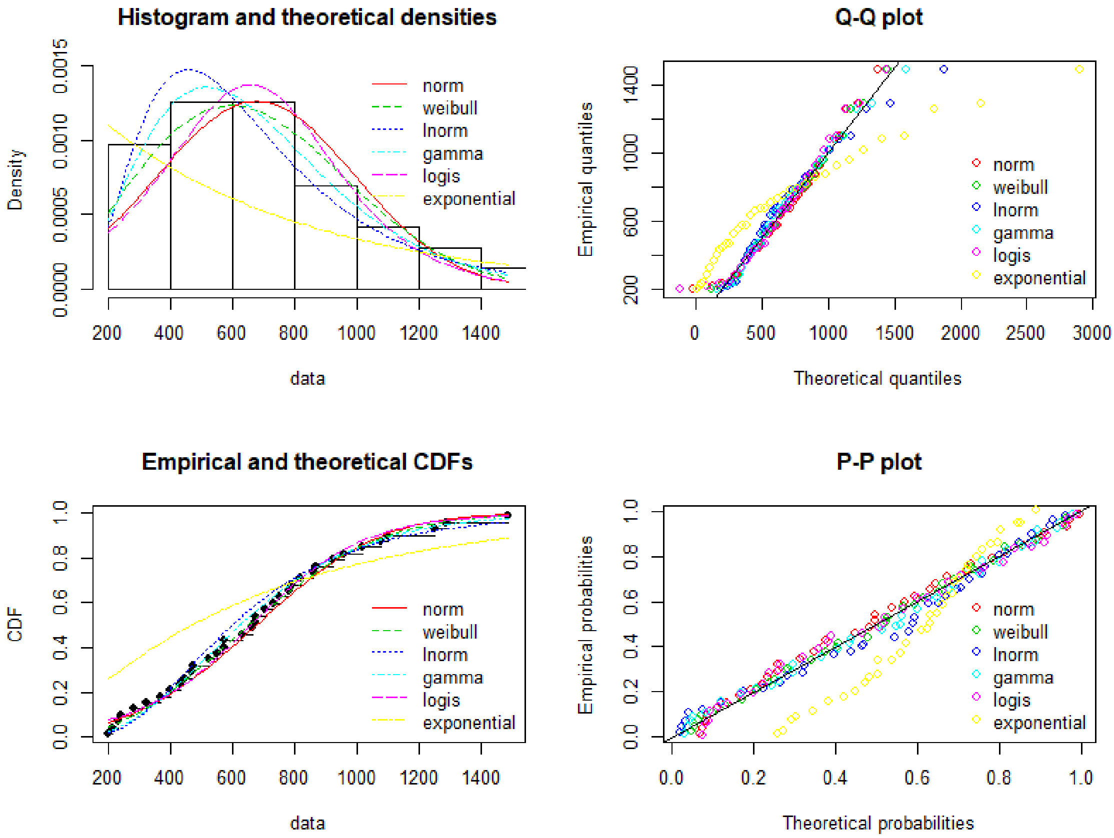


Figure 38 - Probability Distribution Fitting for Thirteen-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull     lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.07478572 0.05269241 0.1047701 0.07477141 0.07551063   0.2577644
Cramer-von Mises statistic   0.03269416 0.01216898 0.0610494 0.02382820 0.02221588   0.8505580
Anderson-Darling statistic   0.27818944 0.12694760 0.4166752 0.18930280 0.24095462   4.5130732

Goodness-of-fit criteria
                                   norm weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 520.8557 517.487 519.2675 517.4386 521.8885    543.3105
Bayesian Information Criterion 524.0228 520.654 522.4345 520.6056 525.0555    544.8940
```

Figure 39 - Goodness of Fit for Thirteen-Story Building

According to the test, the evacuation time can be described by Weibull and Gamma distribution. The parameter of distributions is presented in Table 12:

Table 13 - Best Fitted Distribution for Thirteen-Story Building

Weibull	Fitting of the distribution ' weibull ' by maximum likelihood Parameters : estimate Std. Error shape 2.287331 0.2955123 scale 766.751792 58.9894416 Loglikelihood: -256.7435 AIC: 517.487 BIC: 520.654 Correlation matrix: shape scale shape 1.0000000 0.3204766 scale 0.3204766 1.0000000
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.24283096 0.851728259 rate 0.00626381 0.001299801 Loglikelihood: -256.7193 AIC: 517.4386 BIC: 520.6056 Correlation matrix: shape rate shape 1.0000000 0.9251197 rate 0.9251197 1.0000000

✓ ***Fourteen-Story Building:***

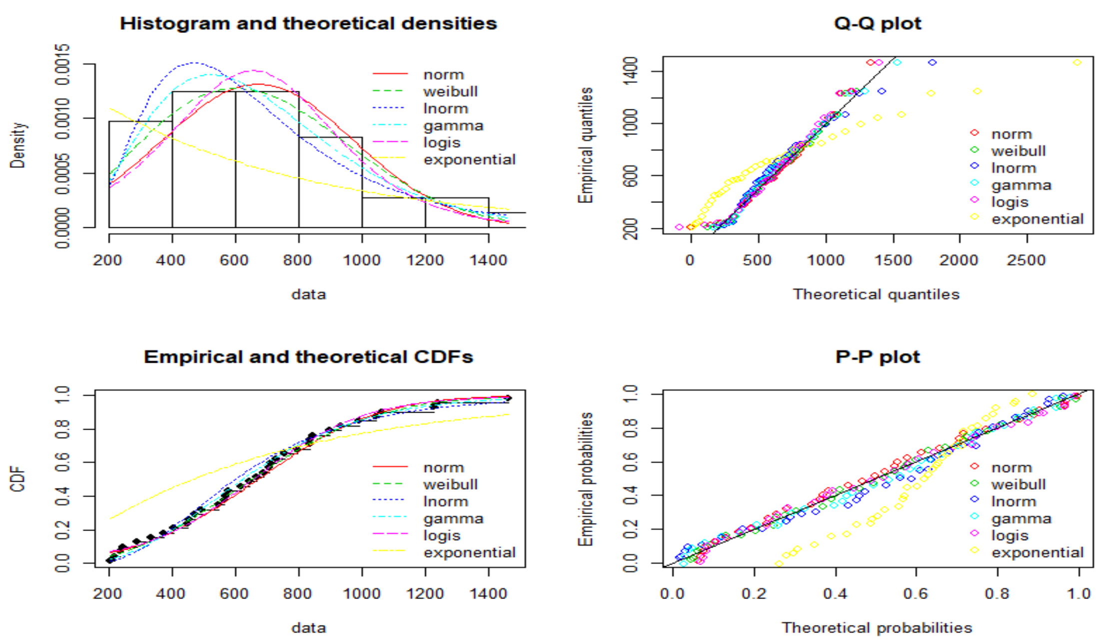


Figure 40 - Probability Distribution Fit for Fourteen-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.06269562 0.05312982 0.09779872 0.06635014 0.07009143   0.2649927
Cramer-von Mises statistic   0.02773899 0.01254704 0.06721212 0.02661233 0.01782040   0.9243630
Anderson-Darling statistic   0.24989832 0.13188089 0.45424120 0.20883718 0.20834920   4.8451276

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 517.6276 514.7117 516.6505 514.7087 518.4453    542.6274
Bayesian Information Criterion 520.7946 517.8788 519.8176 517.8757 521.6123    544.2109
```

Figure 41 - Goodness of Fit for Fourteen-Story Building

In the fourteen floors building, the test indicates that Weibull and Gamma are two best distributions which can illustrate the behavior of egress time. The parameter of distributions is displayed in Table 13:

Table 14 - Best Fitted Distribution for Fourteen-Story Building

Weibull	Fitting of the distribution ' weibull ' by maximum likelihood Parameters : estimate Std. Error shape 2.371149 0.3052423 scale 758.595190 56.2823816 Loglikelihood: -255.3559 AIC: 514.7117 BIC: 517.8788 Correlation matrix: shape scale shape 1.0000000 0.3210076 scale 0.3210076 1.0000000
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.545018646 0.923238469 rate 0.006775299 0.001422672 Loglikelihood: -255.3543 AIC: 514.7087 BIC: 517.8757 Correlation matrix: shape rate shape 1.0000000 0.9314056 rate 0.9314056 1.0000000

✓ ***Fifteen stories building:***

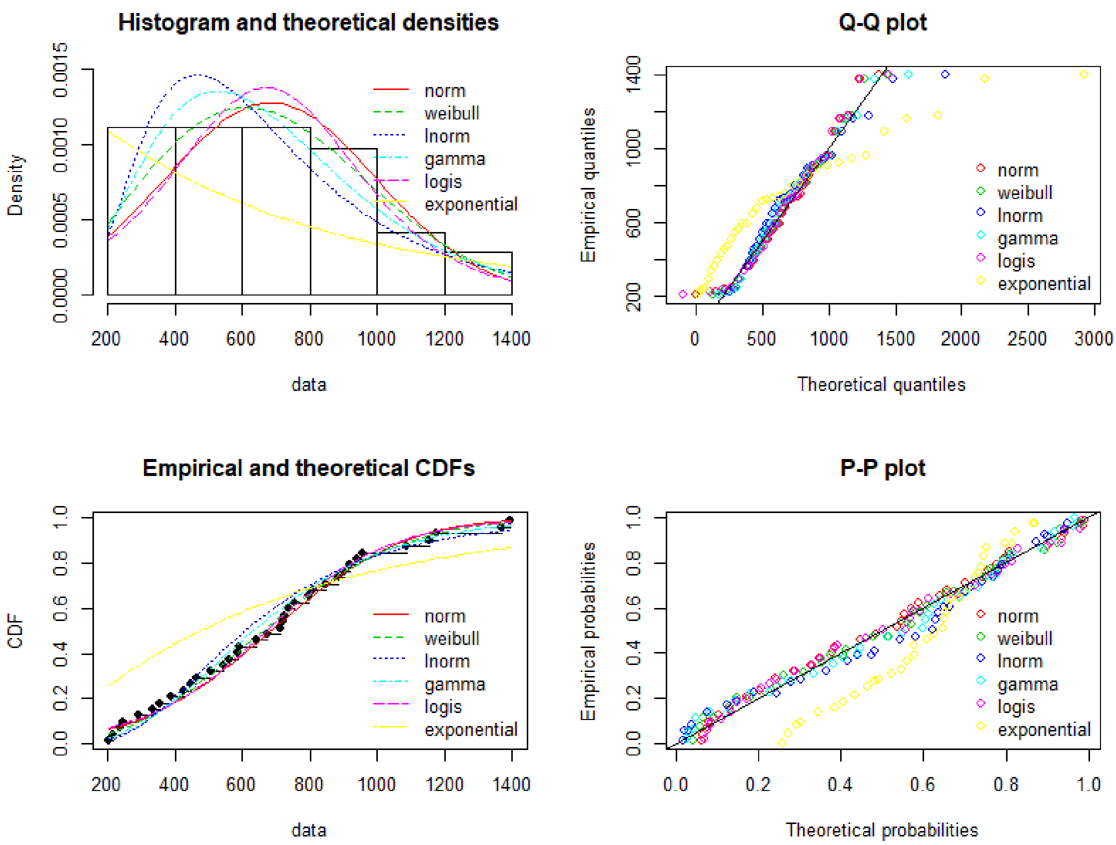


Figure 42 - Probability Distribution Fit for Fifteen-Story Building

Goodness-of-fit statistics

	norm	weibull	lnorm	gamma	logis	exponential
Kolmogorov-Smirnov statistic	0.06374274	0.06142594	0.12257463	0.09717272	0.07143320	0.2581983
Cramer-von Mises statistic	0.02752481	0.01789891	0.08570213	0.04139693	0.02529987	0.8722367
Anderson-Darling statistic	0.26658755	0.16864723	0.53997905	0.28257024	0.25258557	4.6305360

Goodness-of-fit criteria

	norm	weibull	lnorm	gamma	logis	exponential
Akaike's Information Criterion	519.908	517.0433	519.7783	517.5746	521.3377	544.0332
Bayesian Information Criterion	523.075	520.2104	522.9453	520.7416	524.5048	545.6167

Figure 43 - Goodness of fit for Fifteen-Story Building

The test shows that the data can adequately illustrate by Weibull and Gamma for Fifteen-floor building. The parameter of these distributions is presented in Table 13:

Table 15 - Best Fitted Distribution for Fifteen-Story Building

Weibull	Fitting of the distribution ' weibull ' by maximum likelihood Parameters : estimate Std. Error shape 2.348962 0.3066615 scale 773.866913 57.9166713 Loglikelihood: -256.5217 AIC: 517.0433 BIC: 520.2104 Correlation matrix: shape scale shape 1.0000000 0.3185749 scale 0.3185749 1.0000000
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.330225058 0.869868882 rate 0.006328884 0.001313355 Loglikelihood: -256.7873 AIC: 517.5746 BIC: 520.7416 Correlation matrix: shape rate shape 1.0000000 0.9266098 rate 0.9266098 1.0000000

✓ *Sixteen-Story Building:*

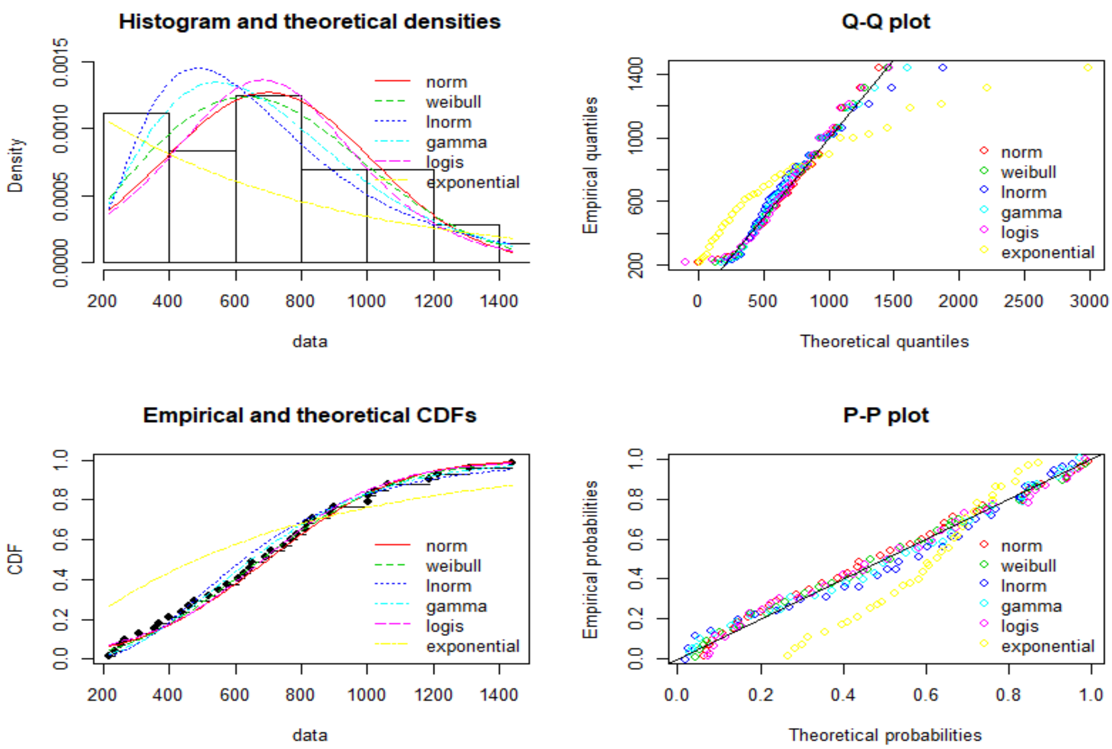


Figure 44 - Probability Distribution Fit for Sixteen-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.06492117 0.05064374 0.09333755 0.06220747 0.07297680   0.2675087
Cramer-von Mises statistic   0.02997574 0.01457032 0.06772713 0.03050892 0.02509395   0.8984262
Anderson-Darling statistic   0.25984355 0.14192907 0.44526761 0.22577551 0.25305126   4.7590474

Goodness-of-fit criteria
                                   norm weibull    lnorm    gamma   logis exponential
Akaike's Information Criterion 520.1817 517.353 519.5798 517.6706 521.797    545.4389
Bayesian Information Criterion 523.3488 520.520 522.7469 520.8377 524.964    547.0225
```

Figure 45 - Goodness of Fit for Sixteen-Story Building

Based on the test's result, there are two distributions, Weibull and Gamma, which can illustrate the behavior of evacuation time of sixteen-story problem. The parameter of Weibull and Gamma is shown in Table 14:

Table 16 - Best Fitted Distribution for Sixteen-Story Building

Weibull	Fitting of the distribution ' weibull ' by maximum likelihood Parameters : estimate Std. Error shape 2.392518 0.3120406 scale 789.277556 58.0245549 Loglikelihood: -256.6765 AIC: 517.353 BIC: 520.52 Correlation matrix: shape scale shape 1.0000000 0.3191041 scale 0.3191041 1.0000000
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.520192859 0.909660000 rate 0.006479181 0.001345293 Loglikelihood: -256.8353 AIC: 517.6706 BIC: 520.8377 Correlation matrix: shape rate shape 1.0000000 0.9297101 rate 0.9297101 1.0000000

✓ ***Seventeen-Story Building:***

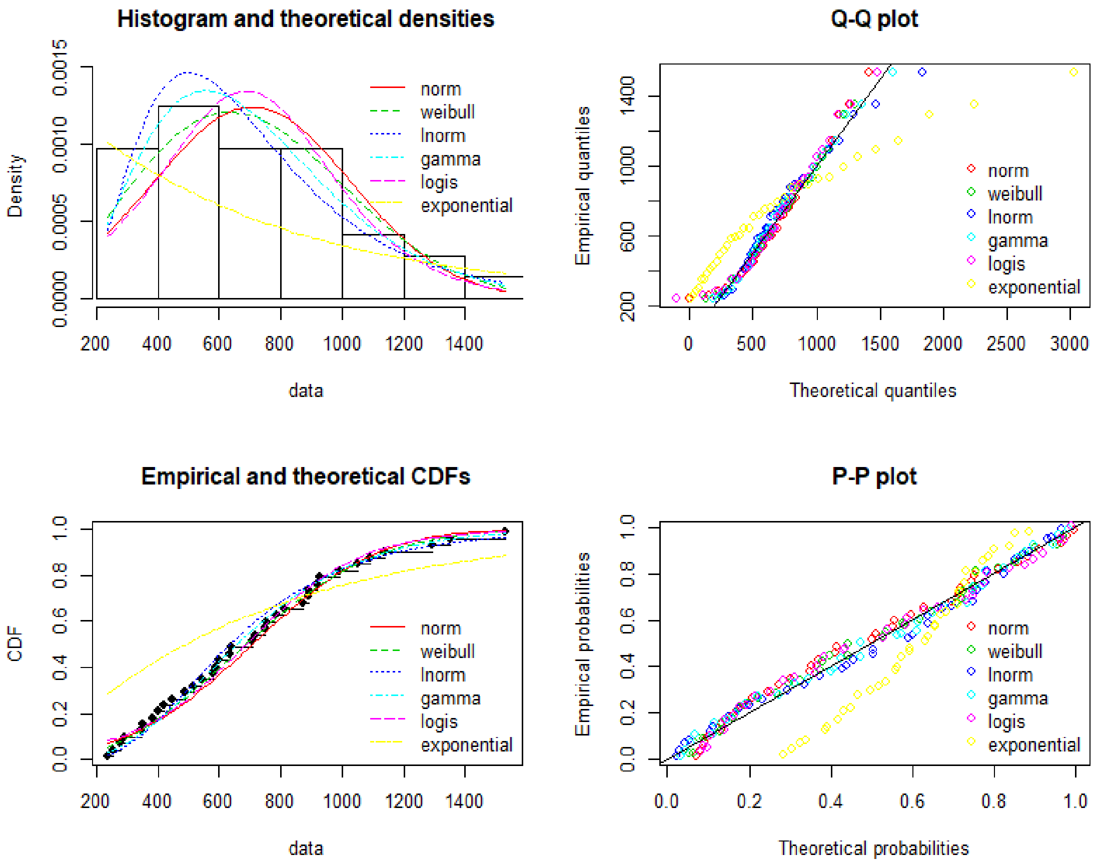


Figure 46 - Probability Distribution Fit for Seventeen-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.08549938 0.05753603 0.09121200 0.06783967 0.08182977   0.2856617
Cramer-von Mises statistic   0.04480340 0.01938332 0.04801517 0.02508921 0.03525756   0.9160804
Anderson-Darling statistic   0.35560449 0.17437420 0.30413538 0.17909475 0.32247165   4.8458665

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 521.8448 518.4416 518.4310 517.5676 522.9923    546.4669
Bayesian Information Criterion 525.0119 521.6087 521.5981 520.7347 526.1593    548.0504
```

Figure 47 - Goodness of Fit for Seventeen-Story Building

In this test, the best distribution which can describe an evacuation time for the seventeen-story building is Gamma. The parameter of Gamma distribution for this case is shown in Table15:

Table 17 - Best Fitted Distribution for Seventeen-Story Building

Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.693744264 0.946634135 rate 0.006632716 0.001378902 Loglikelihood: -256.7838 AIC: 517.5676 BIC: 520.7347 Correlation matrix: shape rate shape 1.0000000 0.9324138 rate 0.9324138 1.0000000

✓ *__Eighteen-Story Building:__*

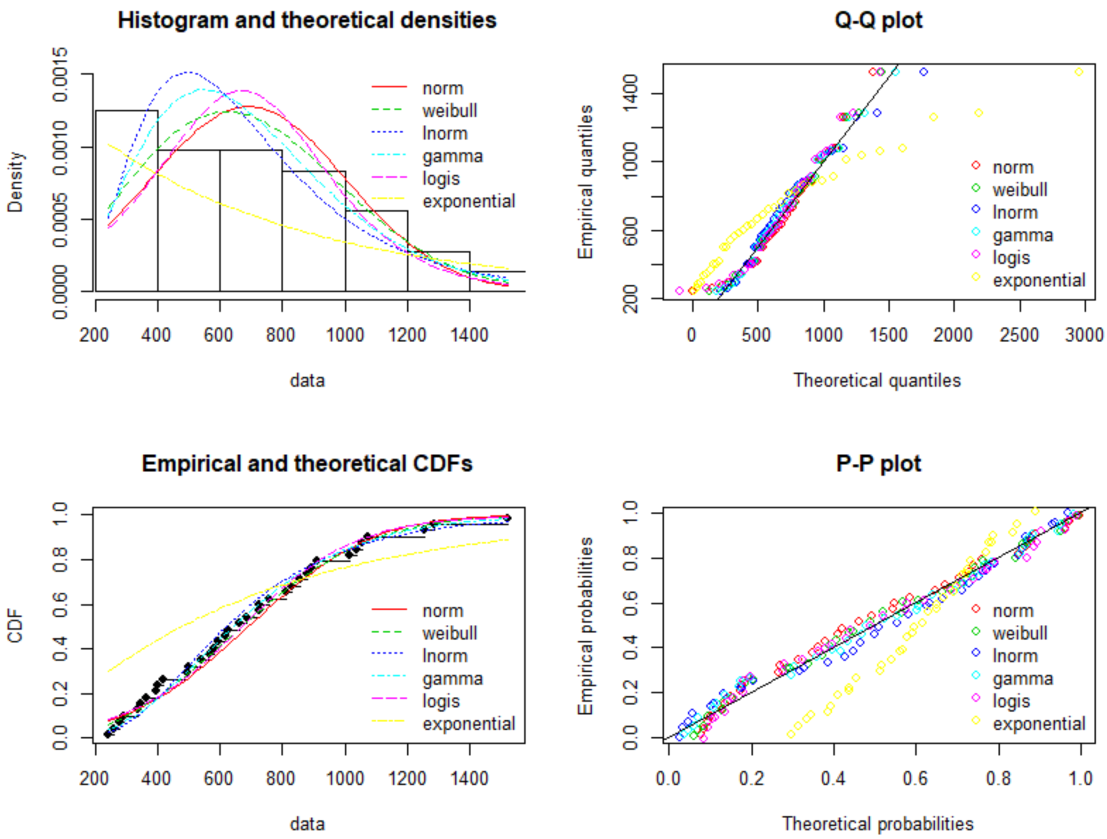


Figure 48 - Probability Distribution Fit for Eighteen-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.08512605 0.07398026 0.07364169 0.08014373 0.08583870   0.2970617
Cramer-von Mises statistic   0.04967530 0.02254950 0.04867187 0.02678646 0.03780195   0.9329924
Anderson-Darling statistic   0.39182814 0.20774679 0.31836840 0.20583573 0.35446048   4.9267630

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 519.7684 516.3112 515.7626 515.1586 520.8179    544.6819
Bayesian Information Criterion 522.9354 519.4782 518.9297 518.3256 523.9849    546.2654
```

Figure 49 - Goodness of Fit for Eighteen-Story Building

For the eighteen-story building, Log-Normal and Gamma are best-fitted distributions for an egress time. The parameter of these distributions is displayed in Table 16:

Table 18 - Best Fitted Distribution for Eighteen-Story Building

<table>
<tr><td>Log-Normal</td><td><pre>Fitting of the distribution ' lnorm ' by maximum likelihood
Parameters :
         estimate Std. Error
meanlog 6.4292989 0.07948535
sdlog   0.4769121 0.05620352
Loglikelihood: -255.8813   AIC: 515.7626   BIC: 518.9297
Correlation matrix:
        meanlog sdlog
meanlog   1   0
sdlog   0   1</pre></td></tr>
<tr><td>Gamma</td><td><pre>Fitting of the distribution ' gamma ' by maximum likelihood
Parameters :
         estimate Std. Error
shape 4.790958428 0.974226252
rate 0.006939757 0.001456138
Loglikelihood: -255.5793   AIC: 515.1586   BIC: 518.3256
Correlation matrix:
          shape   rate
shape 1.0000000 0.9348027
rate 0.9348027 1.0000000</pre></td></tr>
</table>

✓ *Nineteen-Story Building:*

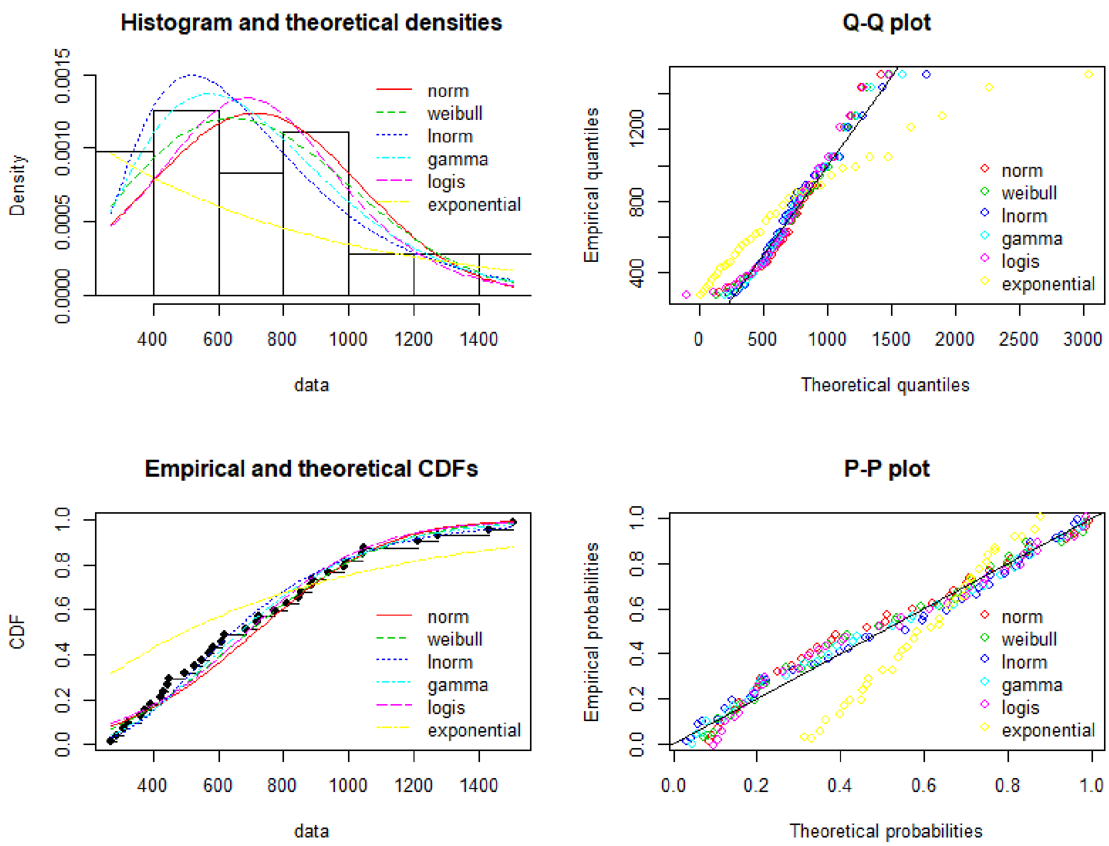


Figure 50 - Probability Distribution Fit for Nineteen-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.11184478 0.08490665 0.08542102 0.09195542 0.09683140   0.3157035
Cramer-von Mises statistic   0.07967811 0.04246491 0.04394345 0.03862831 0.06268906   0.9538447
Anderson-Darling statistic   0.57450649 0.33015382 0.27543072 0.25937925 0.51152590   5.0264460

Goodness-of-fit criteria
                                   norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 522.0287 518.2482 516.1267 516.3305 523.1902    546.8912
Bayesian Information Criterion 525.1957 521.4152 519.2937 519.4976 526.3573    548.4747
```

Figure 51 - Goodness of Fit for Nineteen-Story Building

According to the test's result, an egress time of twenty-floor building can be explained by Log-Normal and Gama distributions. The parameter of these distributions is displayed in Table 17:

Table 19 - Best Fitted Distribution for Nineteen-Story Building

Log-Normal	Fitting of the distribution ' lnorm ' by maximum likelihood Parameters : estimate Std. Error meanlog 6.4637020 0.07718658 sdlog 0.4631195 0.05457801 Loglikelihood: -256.0633 AIC: 516.1267 BIC: 519.2937 Correlation matrix: meanlog sdlog meanlog 1 0 sdlog 0 1
Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.96003592 1.006721706 rate 0.00696748 0.001456827 Loglikelihood: -256.1653 AIC: 516.3305 BIC: 519.4976 Correlation matrix: shape rate shape 1.0000000 0.9366181 rate 0.9366181 1.0000000

✓ <u>*Twenty-Story Building:*</u>

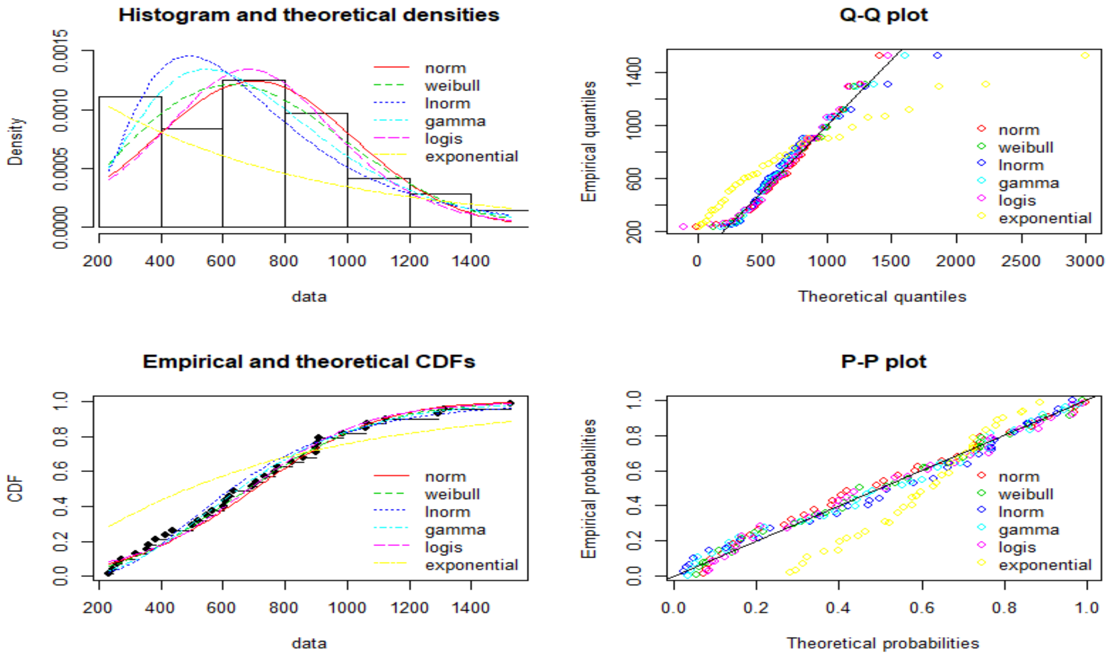


Figure 52 - Probability Distribution Fit for Twenty-Story Building

```
Goodness-of-fit statistics
                                   norm    weibull      lnorm      gamma      logis exponential
Kolmogorov-Smirnov statistic 0.07992061 0.05946702 0.08210984 0.06696794 0.08201808   0.2831578
Cramer-von Mises statistic   0.04046237 0.01954861 0.06177577 0.03121010 0.03396525   0.8897838
Anderson-Darling statistic   0.33681289 0.18240919 0.40199043 0.23037897 0.31406869   4.7268643

Goodness-of-fit criteria
                                  norm  weibull    lnorm    gamma    logis exponential
Akaike's Information Criterion 521.773 518.4241 519.1659 517.9493 522.9875    545.7353
Bayesian Information Criterion 524.940 521.5912 522.3330 521.1164 526.1546    547.3188
```

Figure 53 - Goodness of Fit for Twenty-Story Building

For twenty-story building, the best fit for an evacuation time is Gamma. The parameter is shown in the below table:

Table 20 - Best Fitted Distribution for Twenty-Story Building

Gamma	Fitting of the distribution ' gamma ' by maximum likelihood Parameters : estimate Std. Error shape 4.52680884 0.910330193 rate 0.00646197 0.001340449 Loglikelihood: -256.9747 AIC: 517.9493 BIC: 521.1164 Correlation matrix: shape rate shape 1.0000000 0.9296988 rate 0.9296988 1.0000000

6.4.2. Summary of the Probability Distribution Fitting

In summary, the result shows the three most common distributions, Weibull, Log-Normal and Gamma, which are the best fit with the behavior of an egress time. Also, the information on best-fitted distribution is summarized in Table 21:

Table 21 - Summary of Probability Distribution Fitting Test

A Number of Story	Best-fitted Distribution	Parameter		Mean of Evacuation Time (second)	95th Percentile of Evacuation Time (second)
10	**Weibull**	***Shape***	2.181933	661.2096	1234.4781
		Scale	746.616651		
	Log-Normal	***L-mean***	6.3618844	658.7893	1371.025
		SD-Log	0.5237119		
	Gamma	***Shape***	4.047306046	658.7317	1272.931
		Rate	0.006144089		

11	**Weibull**	***Shape***	2.158534	653.2932	1226.37
		Scale	737.680637		
	Gamma	***Shape***	3.790911585	651.1351	1280.39
		Rate	0.005822005		
12	**Weibull**	***Shape***	2.214054	638.7149	1183.762
		Scale	721.185427		
	Gamma	***Shape***	3.975350583	637.0535	1236.899
		Rate	0.006240215		
13	**Weibull**	***Shape***	2.287331	679.2356	1238.732
		Scale	766.751792		
	Gamma	***Shape***	4.24283096	677.3563	1292.833
		Rate	0.00626381		
14	**Weibull**	***Shape***	2.371149	672.3383	1204.949
		Scale	758.59519		
	Gamma	***Shape***	4.545018646	670.8219	1257.868
		Rate	0.006775299		
15	**Weibull**	***Shape***	2.348962	685.7716	1234.591
		Scale	773.866913		
	Gamma	***Shape***	4.330225058	684.2004	1299.005
		Rate	0.006328884		
16	**Weibull**	***Shape***	2.392518	699.6405	1248.514
		Scale	789.277556		
	Gamma	***Shape***	4.520192859	697.6488	1310.001
		Rate	0.006479181		
17	**Gamma**	***Shape***	4.693744264	707.6655	1316.159
		Rate	0.006632716		
18	**Log-Normal**	***L-mean***	6.4292989	690.3846	1357.974
		SD-Log	0.4769121		
	Gamma	***Shape***	4.790958428	690.364	1277.374
		Rate	0.006939757		
19	**Log-Normal**	***L-mean***	6.463702	711.8968	1373.978
		SD-Log	0.4631195		
	Gamma	***Shape***	4.96003592	711.8838	1305.843
		Rate	0.00696748		

20	**Gamma**	***Shape***	4.52680884	705.1434	1323.579
		Rate	0.0064197		

In summary, we measured average and 95th percentile of an evacuation time for building from ten to twenty floors using an estimated distribution from the analysis. Although there is another approach that analyzes an extreme case – maximum evacuation time, we decided to measure 95th percentile due to the small size of the building as well as a number of evacuees.

Gamma distribution is considered a universal fit for all cases. At a certain number of stories, there is no significant variation in the mean-time value among statistical distributions; meanwhile, the 95th percentile is reasonably distinctive. The further experiment with a broader range of population and evacuation rate is recommended to sufficiently capture the actual behavior of an escaping time.

CHAPTER 7

SUMMARY AND EXTENSION

In conclusion, this thesis has presented the procedure of embracing deterministic as well as stochastic methods to solve an evacuation problem. The research successfully embeds the procedure into the GMAF_MGCC program which can search for optimal layouts and validate them with the simulation module. The study has identified the relationship between the response variable, evacuation time and other factors including arrival rate, population and a number of stories.

7.1. Open Questions and Extensions

Although GMAF_MGCC successfully solves the problem of evacuation, there are some remaining issues which enable to advance. The most significant issue related to the performance of the simulation model which was studied in chapter 5.3.c. There are numerous problems which are excessively intricate and tedious that lead to a failure or a slow performance of GMAF_MGCC. Besides, the scale of this research is confined at the thirty-story building which has formed an incomplete understanding of GMAF_MGCC's efficiency.

Accordingly, prospective studies should pay attention to enhance the performance of stochastic model M/G/C/C state dependent and also explore further research on the behavior of GMAF_MGCC due to building layout over thirty stories. As well, extensive research on the effect of evacuation rate and capacity for each floor of a building structure, which is higher than twenty floors, is also recommended. Regarding fitting distribution, the future research in this area could include the fitting of some extreme value distribution to the model the maximum time of evacuation.

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