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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).

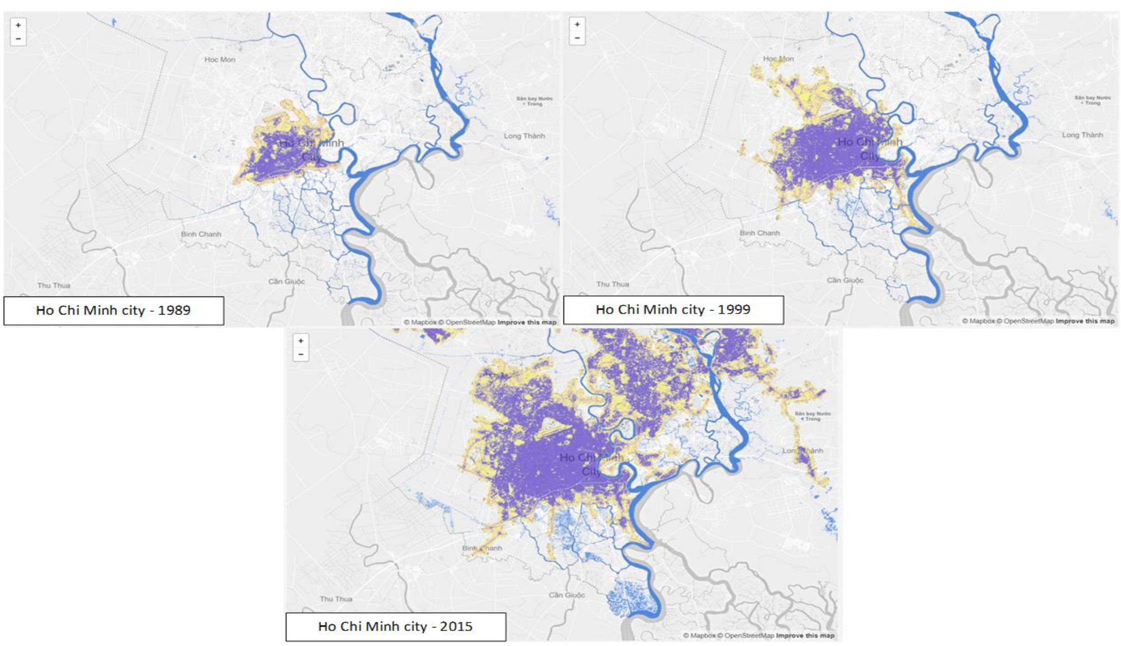



*Figure 1- The Urbanization Map of Ho Chi Minh City from 1989 to 2015*

*(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, $\lambda_{kt}$, and a set of arrival rate associate to between-flow with other activities, $\lambda_{kj}$. 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, $\lambda_{kt}$ and internal traffic flow, $\lambda_{kj}$ 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.

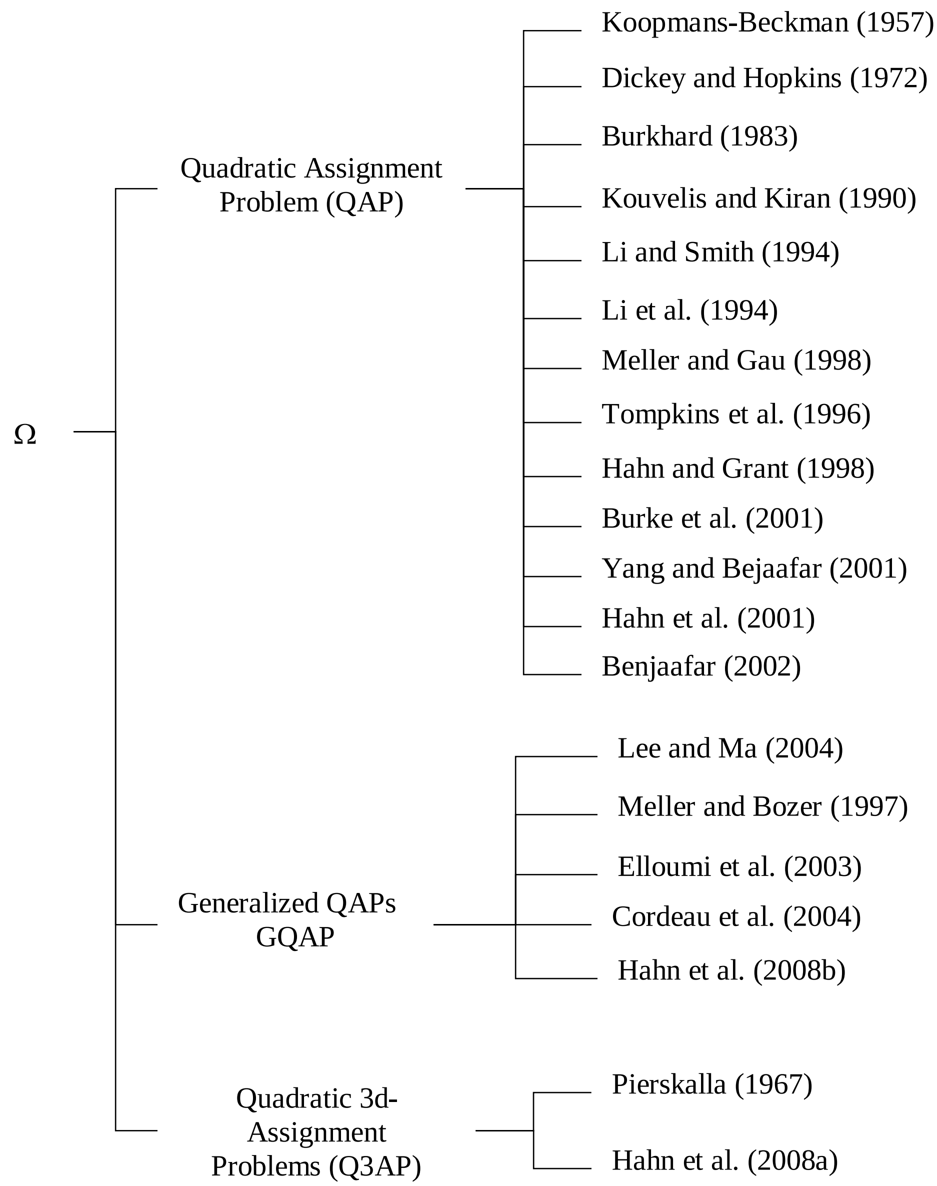



*Figure 2 – Development of Quadratic Assignment Problem Research – QAP*

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.

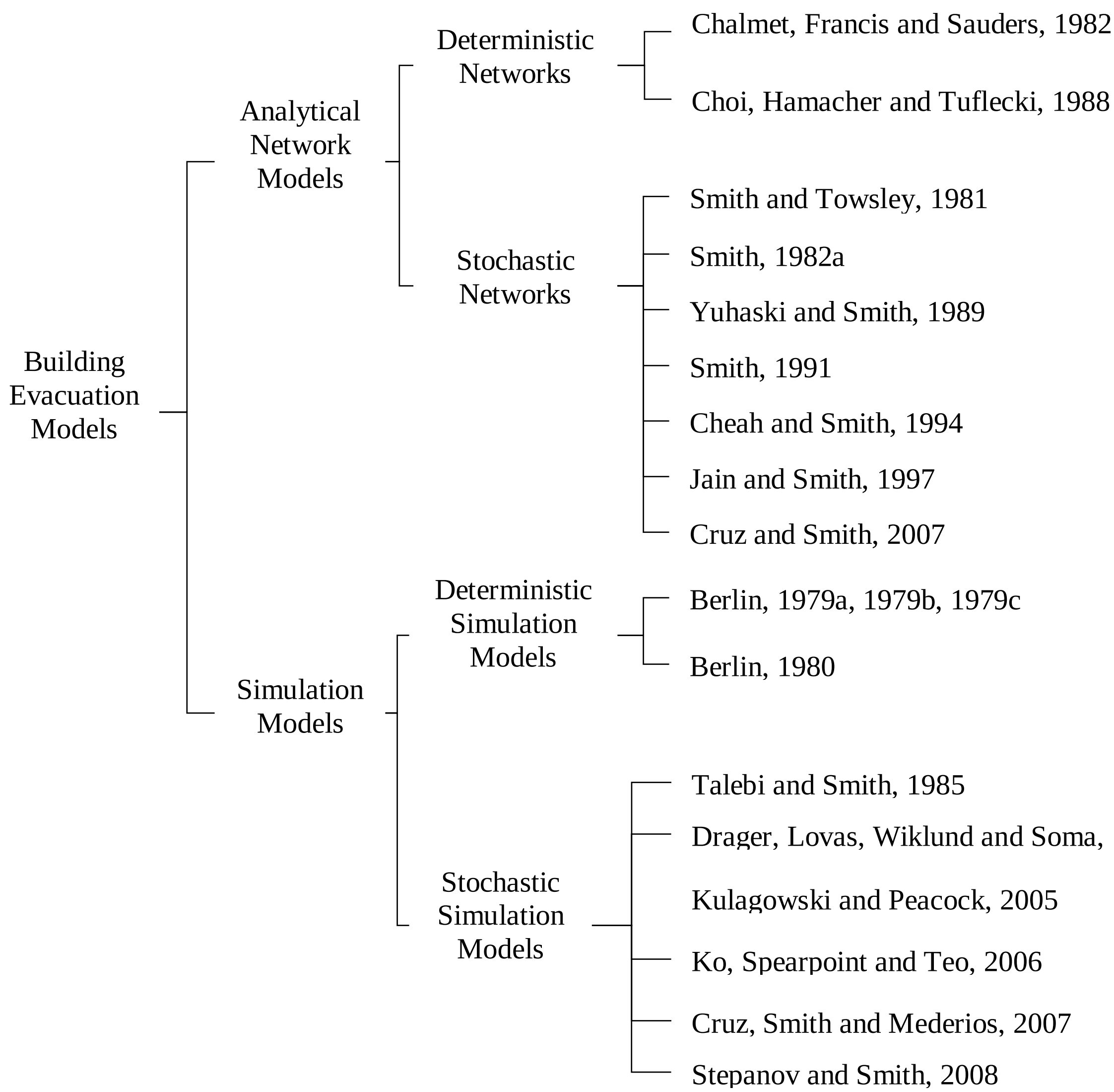



*Figure 3 – Development of Building Evacuation Problems*

# 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:

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

$$Subject\ to:$$

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

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

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

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.

$\alpha_{ikt}$: 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 $\lambda_{kt}$ and $\lambda_{kj}$ 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) $\lambda_{kj}$ into the position of $u_{kj.}$ The objective function becomes:

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

$$Subject\ to:$$

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

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

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

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.

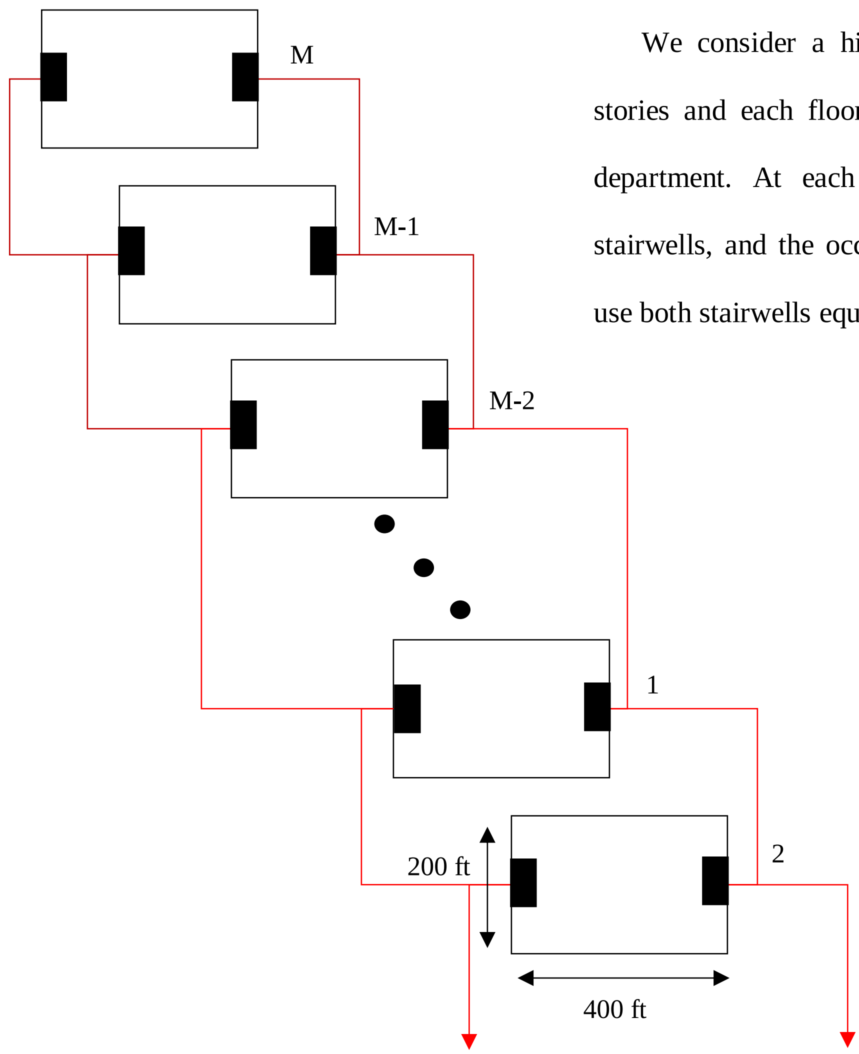



*Figure 4 – General Structure of High-rise Building*

# 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

$\gamma$, $\beta$: shape and scale parameter for exponential model

$\lambda$: 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

$\theta$: 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 $\lambda_{kt}$ and $\lambda_{kj}$ 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.

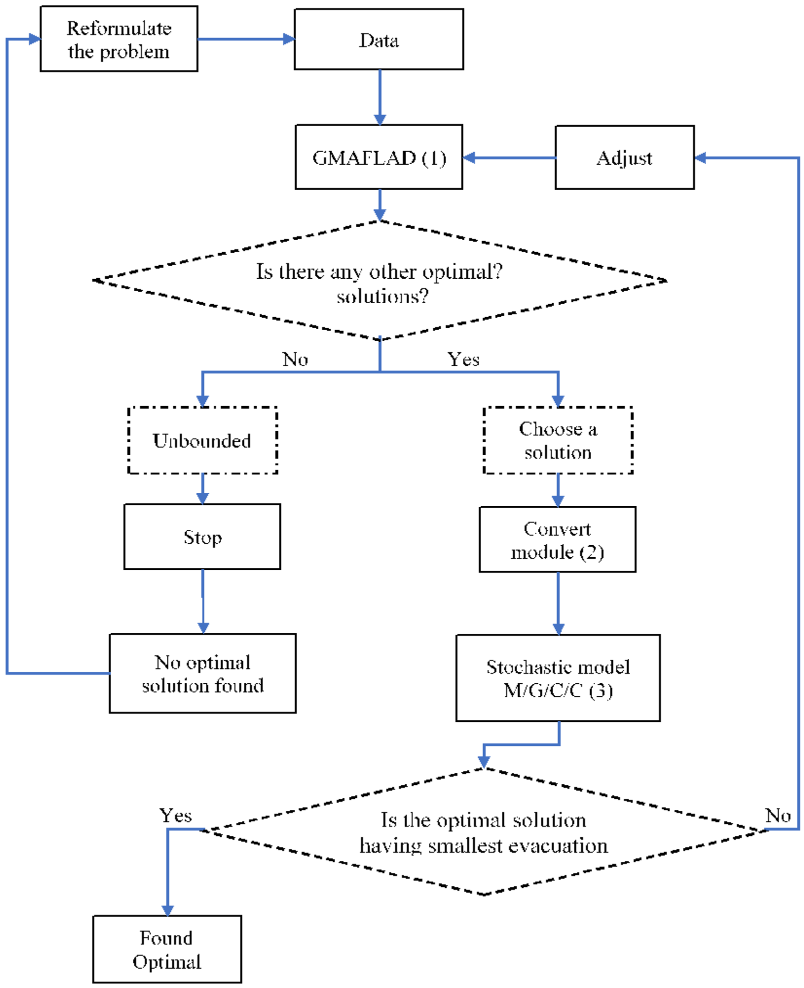



*Figure 5 - The Programming Diagram of GMAF_MGCC Software*

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).

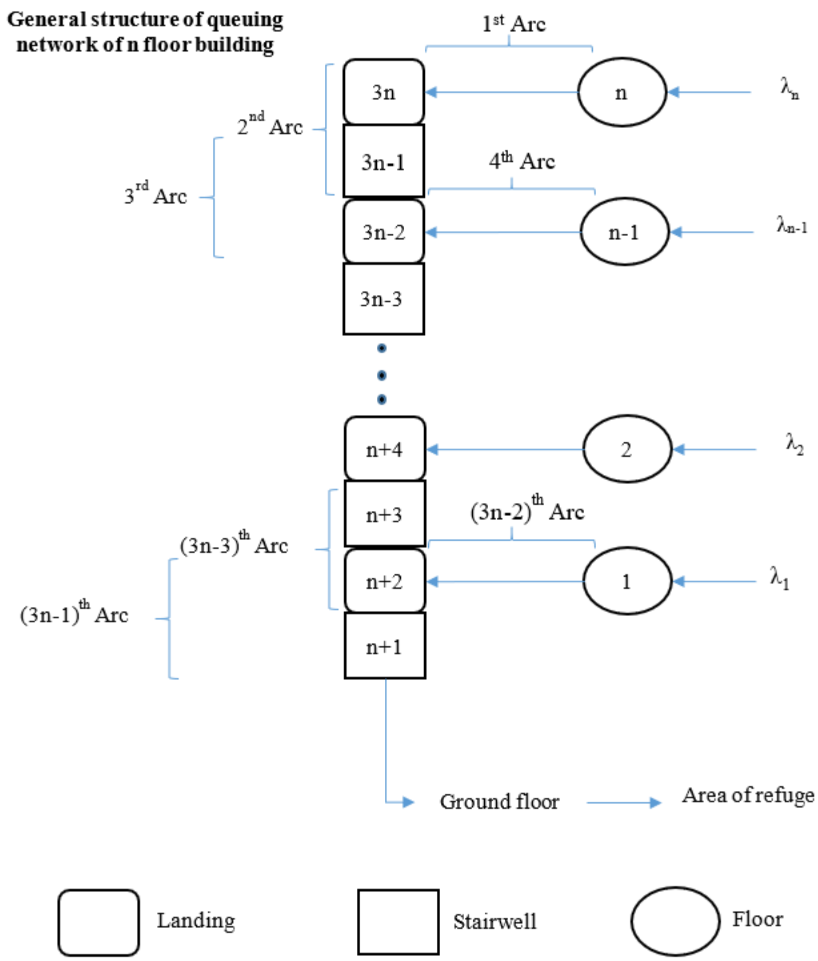



*Figure 6 - General Structure of Queueing Network of N-Floor Building*

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*

```
Pseudocode for GetNode function:
private double [] GetNodes(Problem problem, int[] alternates) {
        * Create a double array to store nodes' properties:
        result ← new double [this.node_count];
        * Get ultility value corresponding to each activity:
        for (int i = 0; i < this.node_count; i ++)
                if i < (total number of activities) {
                        Activity activity ←(Activity)problem.Activities[i+1];
                        nodeNumber ←[int node index];
                        result[nodeNumber]← activity[alternatives[i]-
1].DNumber;
                else
                        result[i] ←0;
                end if }
        end for }
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 lambda 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 }
```

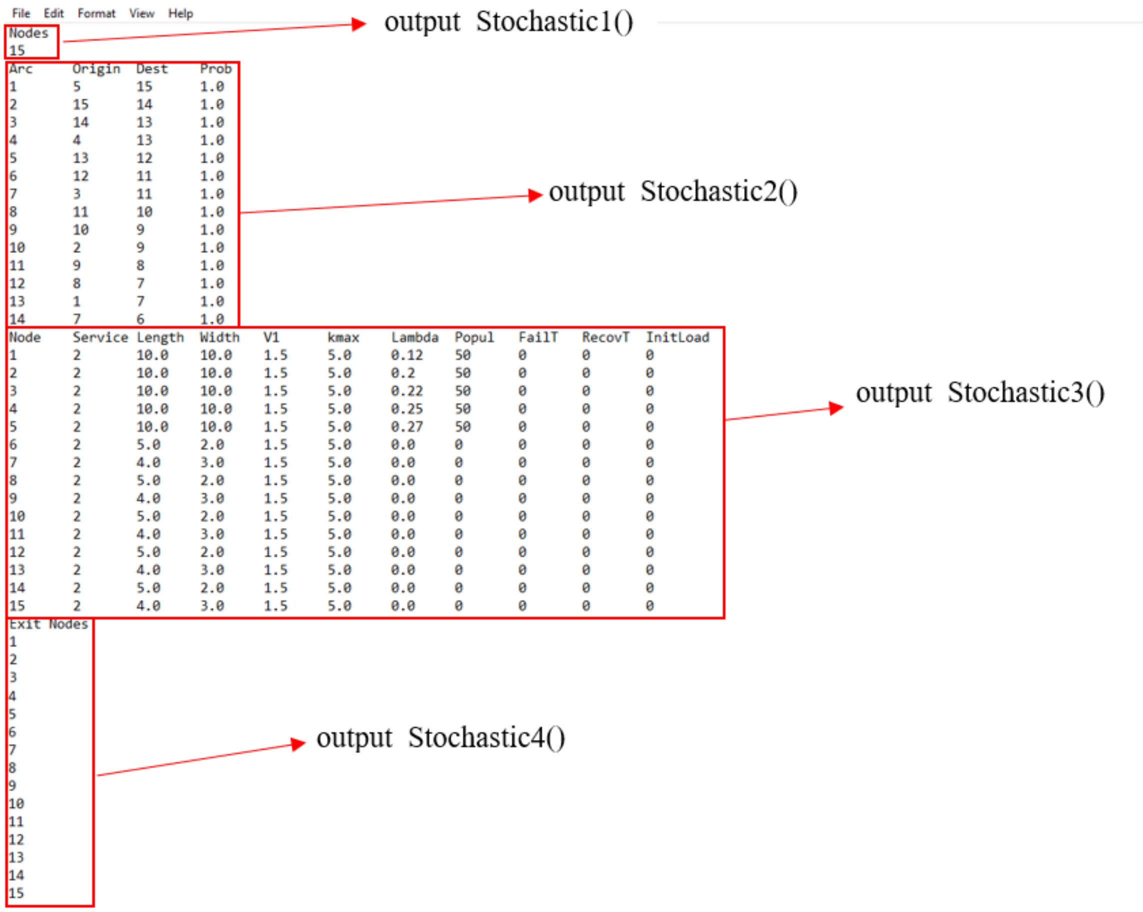
```
Pseudo-code for output_Stochastic_4 function:
private string output_Stochastic_4 {
        * Store "Exit Nodes" title into variable outputText:
        ouputText ← "\r\nExit Nodes";
        * Store exit nodes into variable outputText:
        for(int i = 0; i < this.node_count; i ++) {
                outputText ←"\r\n" + (i + 1);
        end for }
end function }
```

```
Pseudo-code for output_Stochastic_1 function:
private string output_Stochastic_1 {
        * generate the "Node" column in the input matrix:
        outputText ←"Node";
        outputText ←this.node_count
end function }
```

```
Pseudo-code for output_Stochastic_2 function:
private string output_Stochastic_2 {
        * generate "Arc", "Origin", "Dest", "Prob" column in the input matrix:
        outputText ←"\r\nArc \tOrigin \tDest \tProb";
        arc←0;
        dest ← node_count;
        * store value corresponding to each column:
        for (int i = 0; i < this.problem.Activities.Count; i++)
                origin ←this.problem.Activities.Count - i;
                prob ←"1.0";
                outputText ← "\r\n" + arc + "\t" + origin + "\t" + dest + "\t" +
prob;
                Assign data under the "Arc", "Origin
                for (int j = 1; j < 3 && i * 3 + j < node_count - 1; j++)
                        origin ←dest;
                        outputText ←"\r\n" + arc + "\t" + origin + "\t" + dest +
"\t" + prob;
                end for }
        end for}
end function }
```

```
Pseudo-code for output_Stochastic_3 function:
private string output_Stochastic_3 {
        ouputText ←"\r\nNode \tService \tLength \tWidth \tV1 \tkmax \tLambda
\tPopul \tFailT \tRecovT \tInitLoad";
        * Assign properties for each node in queueing network (including lambda):
        for(int i = 0; i < this.node_count; i ++){
                outputText ←[service], [length], [width], [v1], [kmax], [popul],
[failT], [recovT] and [initLoad];
                if (i >= this.problem.Activities.Count) {
                * Assign value of length, width and population for landing area and
stairwell:
                        if( (i - this.problem.Activities.Count) % 2 == 0) {
                                outputText ← [length], [width] and [population];
                        else {
                                outputText ← [length], [width] and [population];
                        end if }
                end if }
                outputText ←[service], [length], [width], [v1], [kmax], [lambda],
[popul], [failT], [recovT] and [initLoad];
        end for }
end function }
```

*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”.

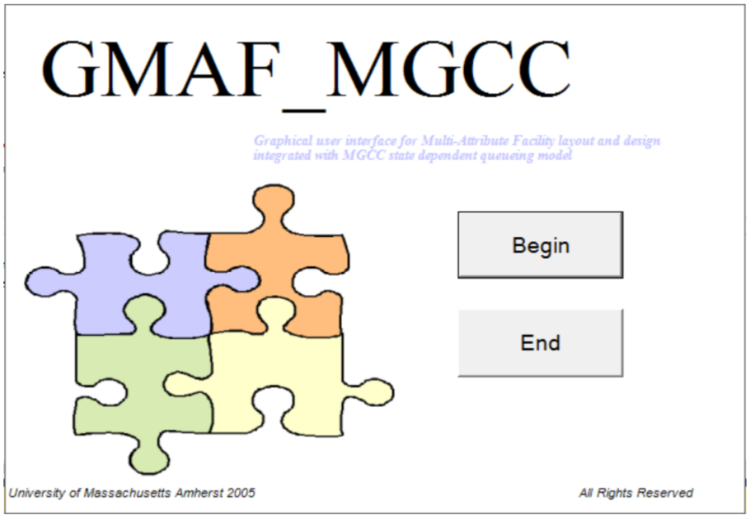



*Figure 11 – Starting Window of GMAF_MGCC*

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.

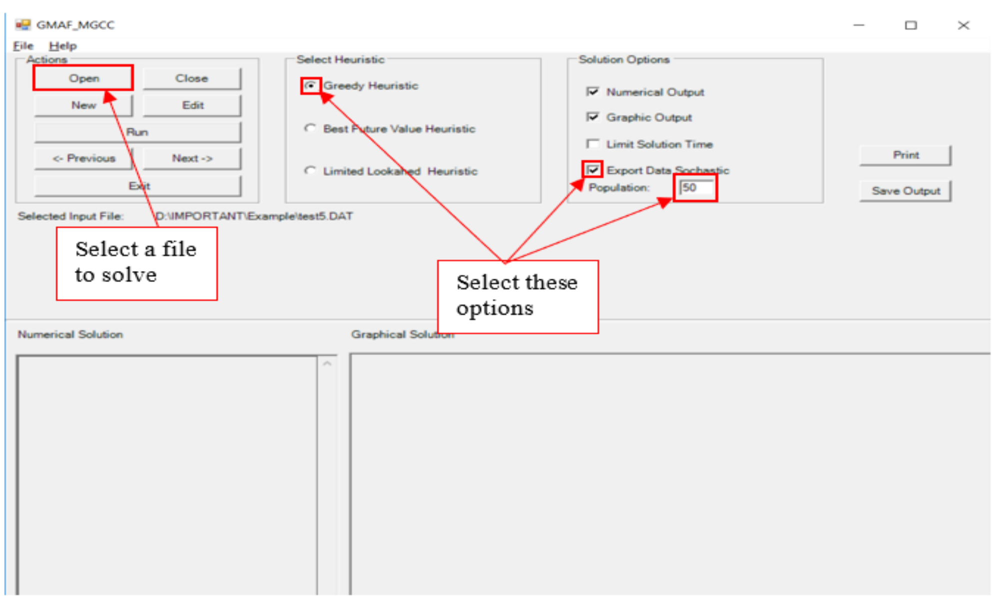



*Figure 12 - Working Screen of GMAF_MGCC*

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.

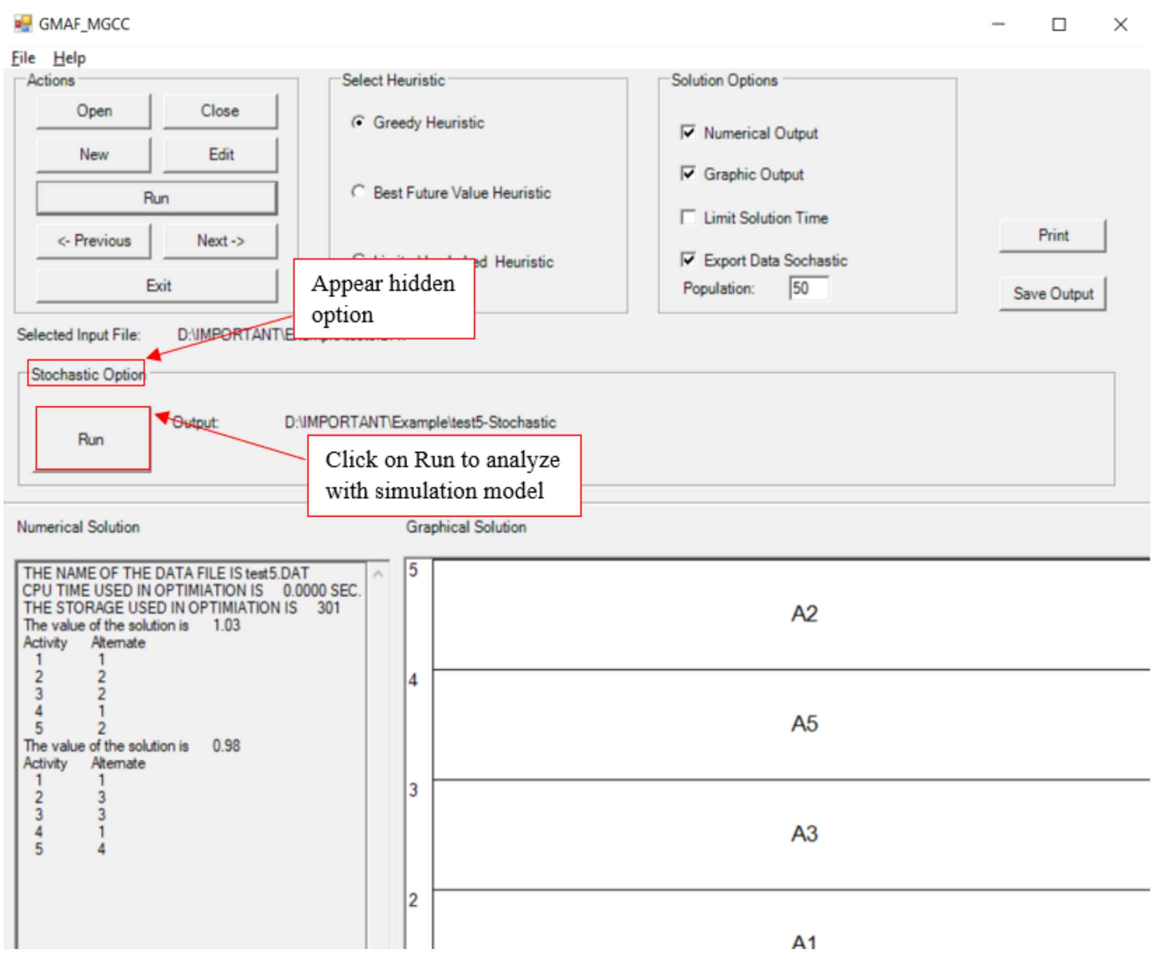



*Figure 13 - Hidden Option to Solve with Stochastic MGCC State Dependent Queuing Model*

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.

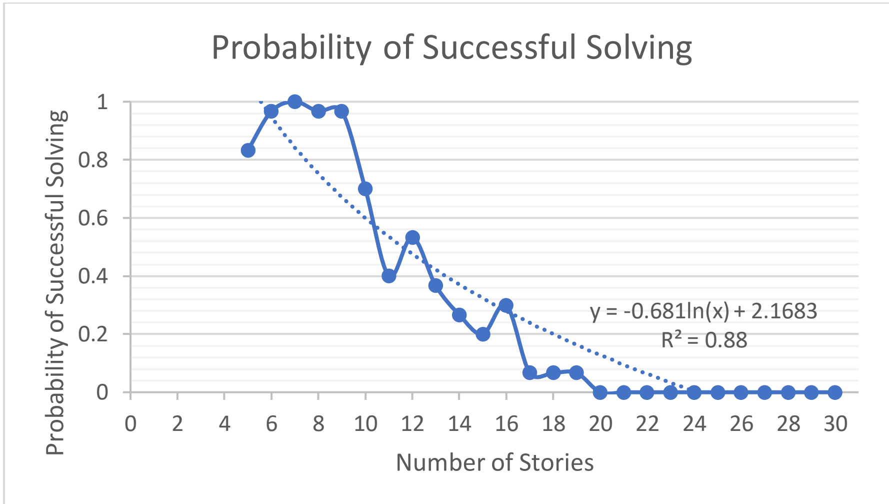



*Figure 18 - Probability of Successful Solving of GMAF_MGCC*

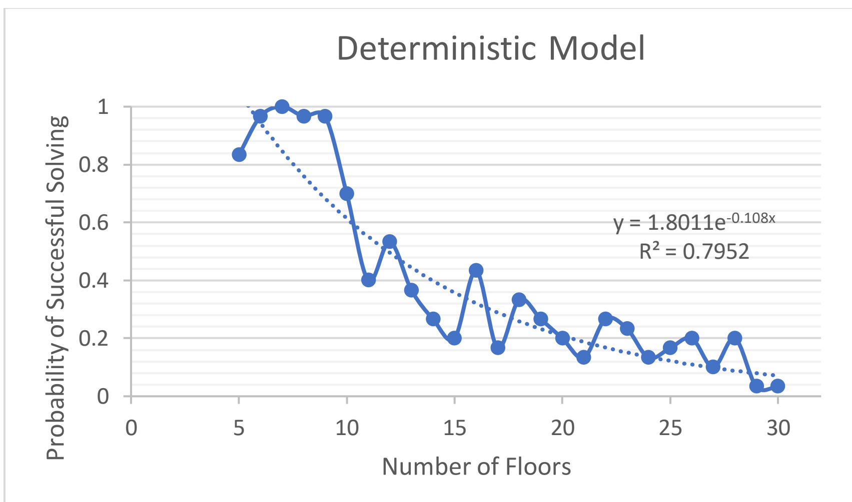



*Figure 19- Probability of Successful Solving of Deterministic Model*

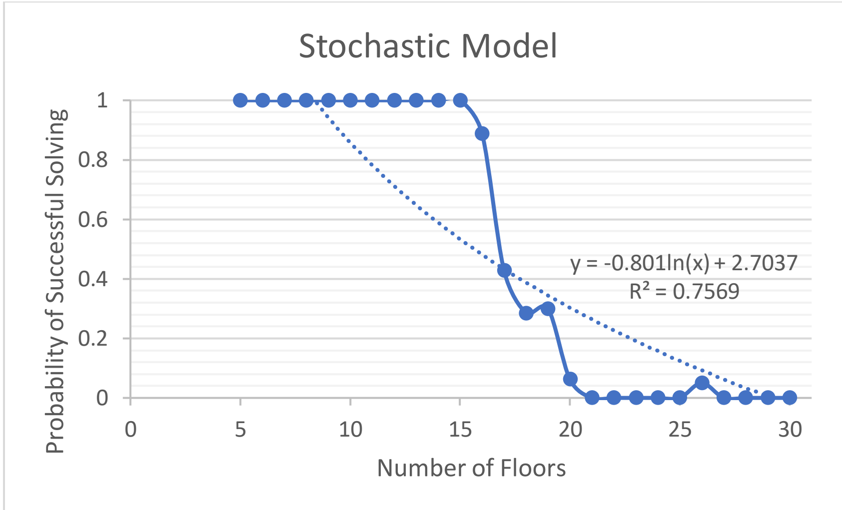



*Figure 20- Probability of Successful Solving of Stochastic Model*

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.

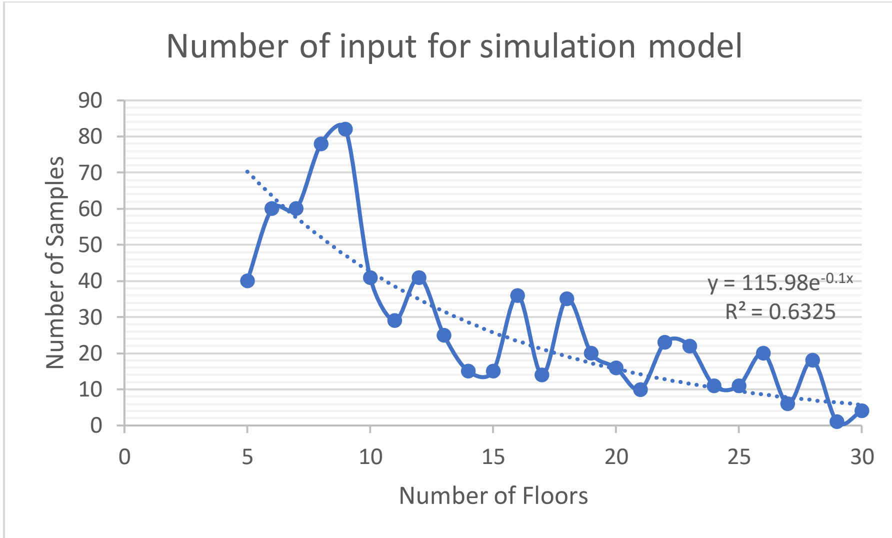



*Figure 21 – Number of Inputs for Simulation Model*

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 ($\lambda$).
- 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 |

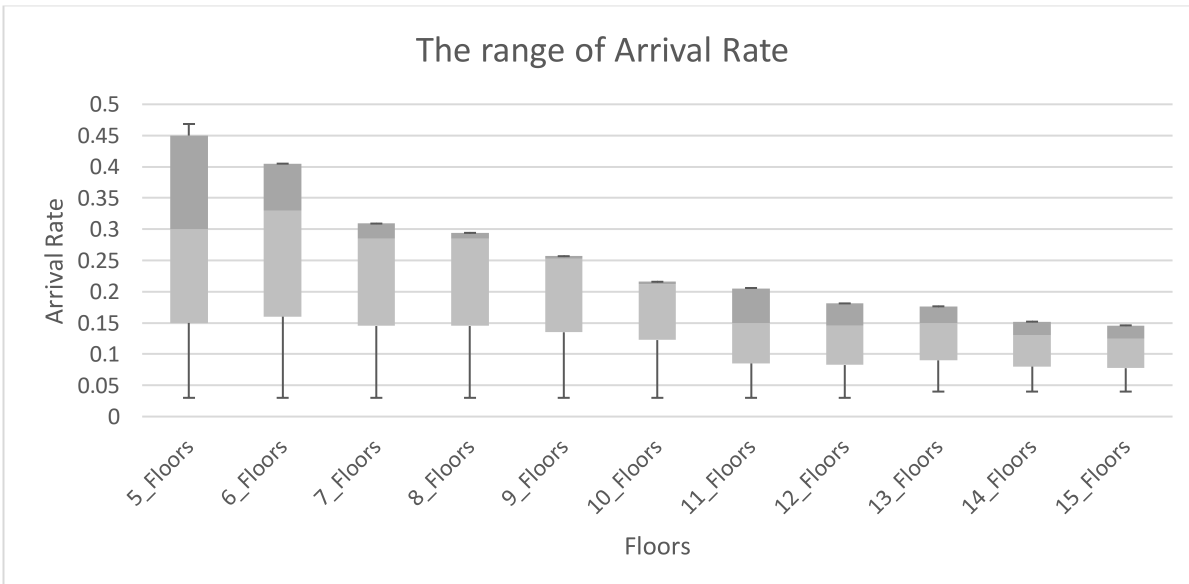



*Figure 22 - The range of Arrival Rate*

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 |

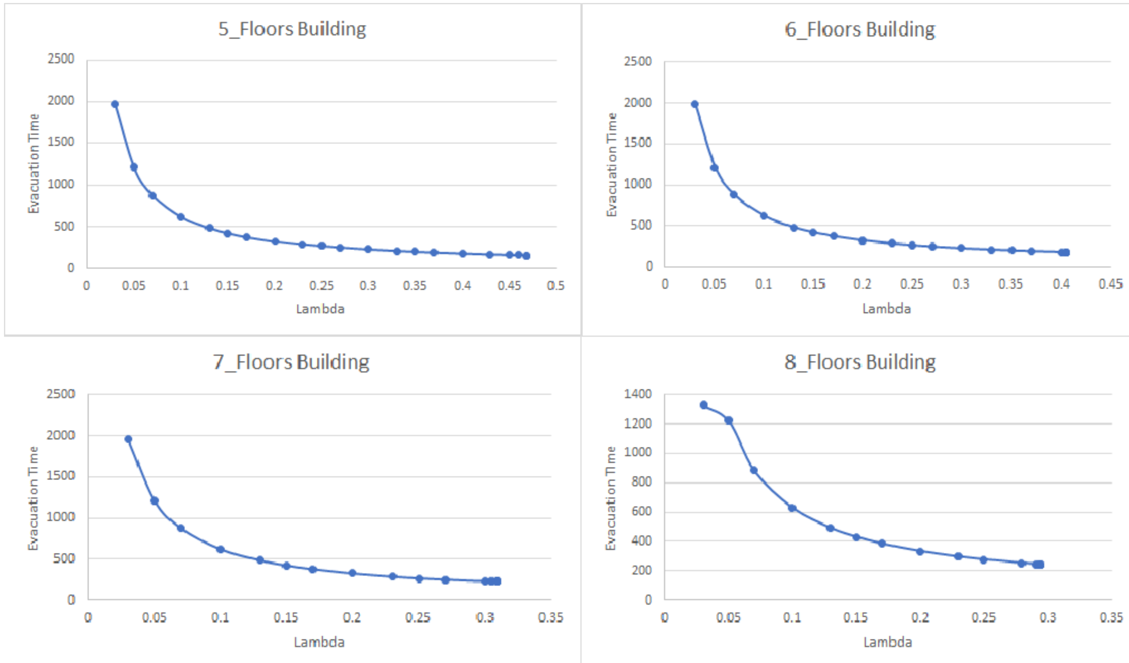



*Figure 23 – Five-Floors to Eight-Floors Building*

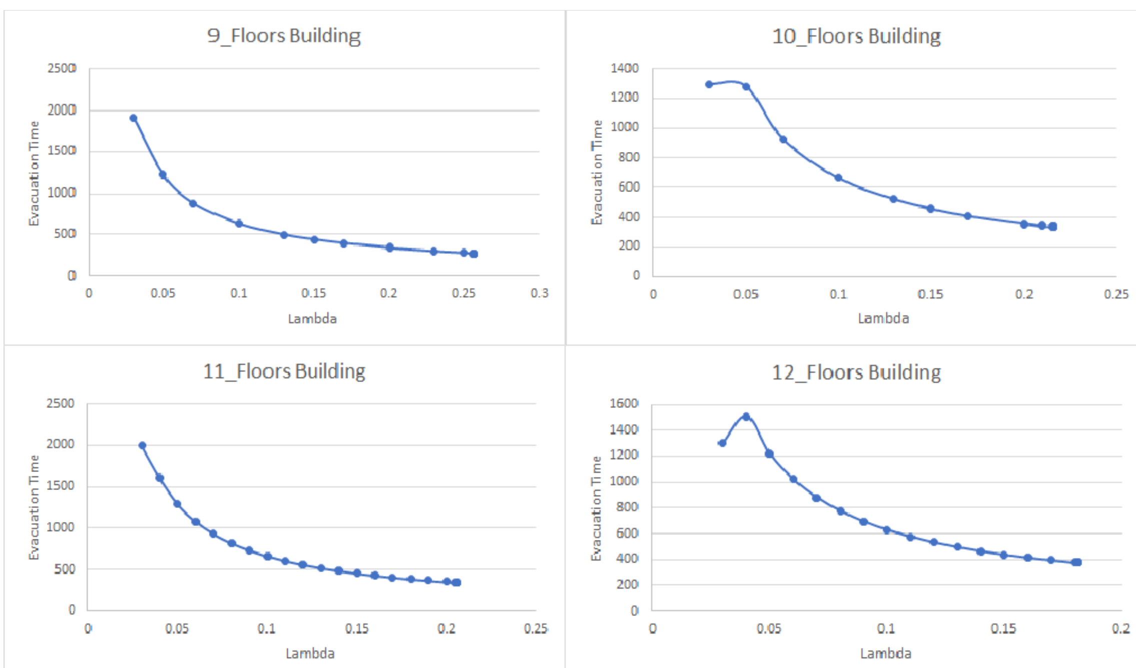



*Figure 24 – Nine-Floors to Twelve-Floors Building*

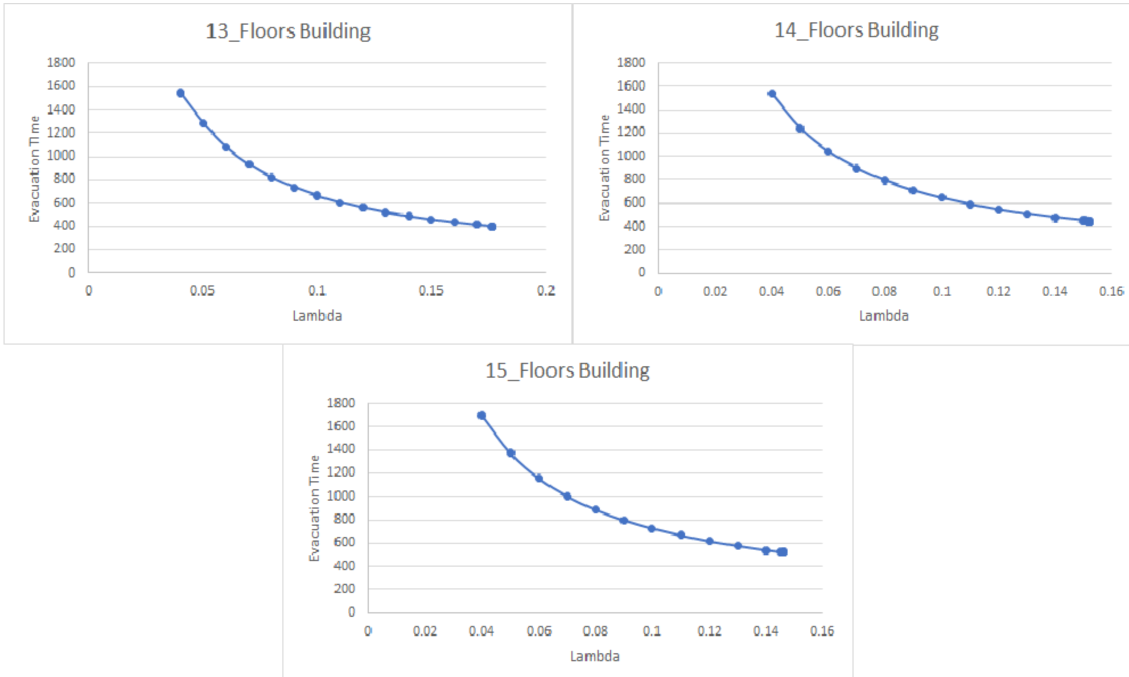



*Figure 25 – Thirteen-Floors to Fifteen-Floors Building*

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.

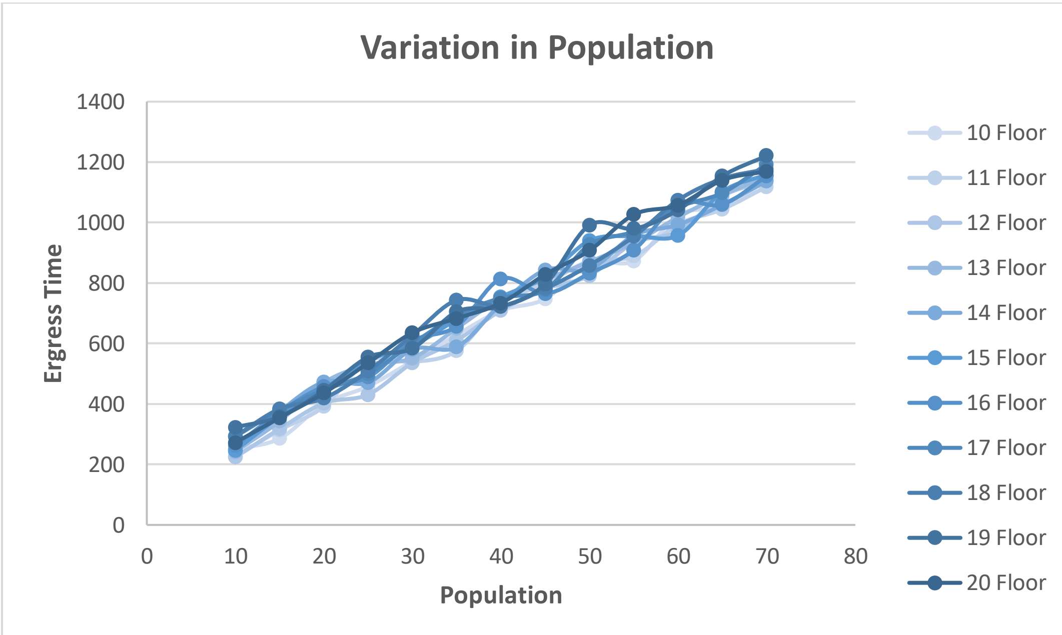



*Figure 26 - Evacuation Time with Variation in Population*

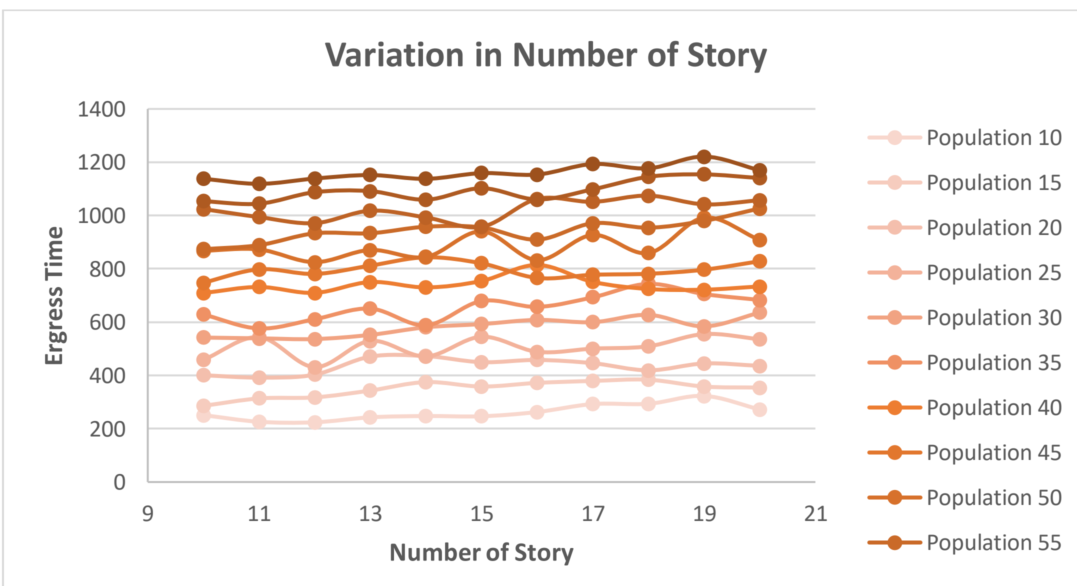



*Figure 27 - Evacuation Time with Variation in Number of Stories*

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.

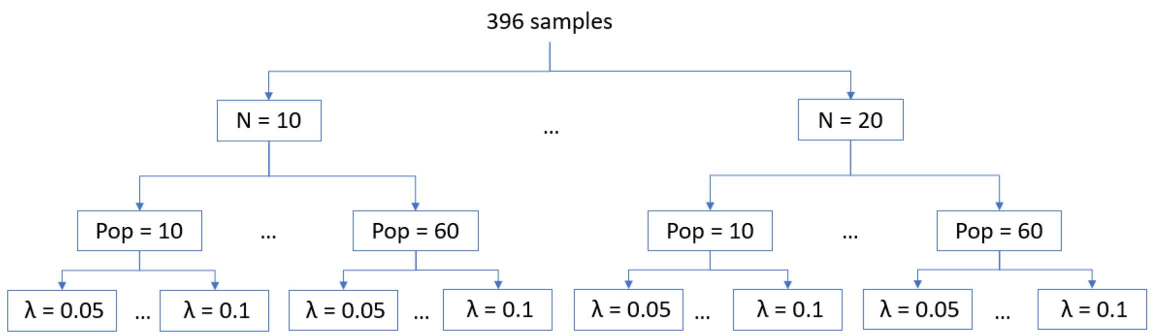



*Figure 28 - Sample Structure*

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.

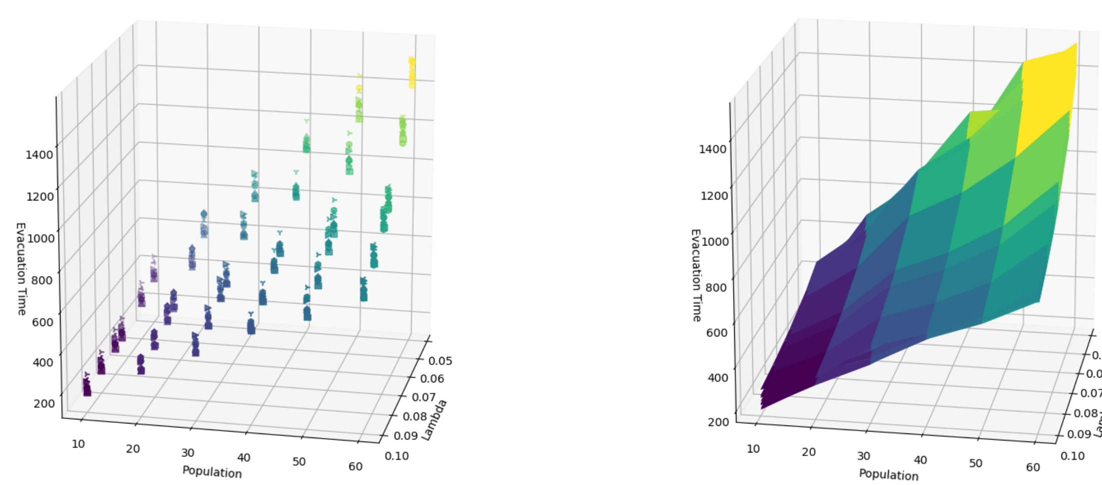



*Figure 29 - Effect of Multiple Factors on Egress Time (Dummy Variable - Population)*

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.

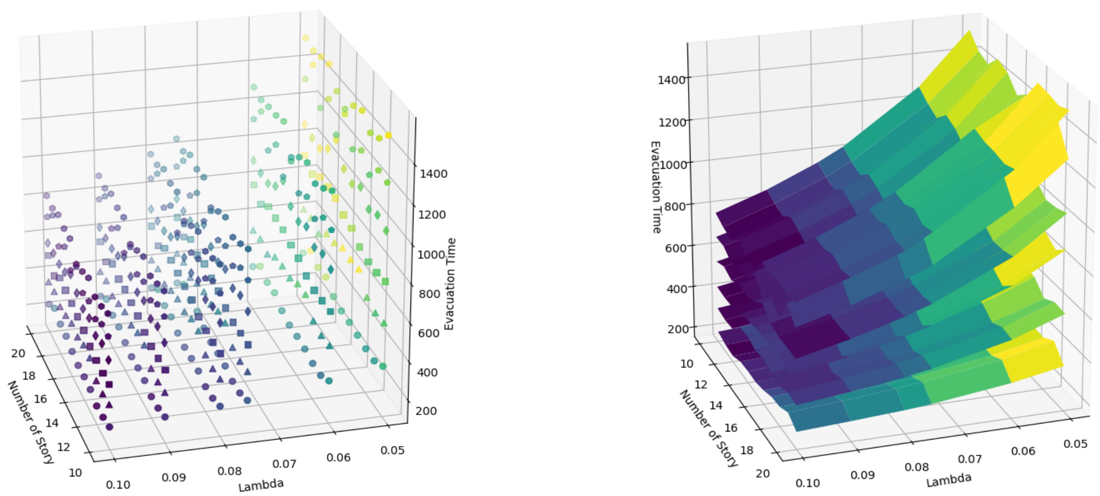



*Figure 30 - Effect of Multiple Factors on Egress Time (Dummy Variable - A Number of Stories)*

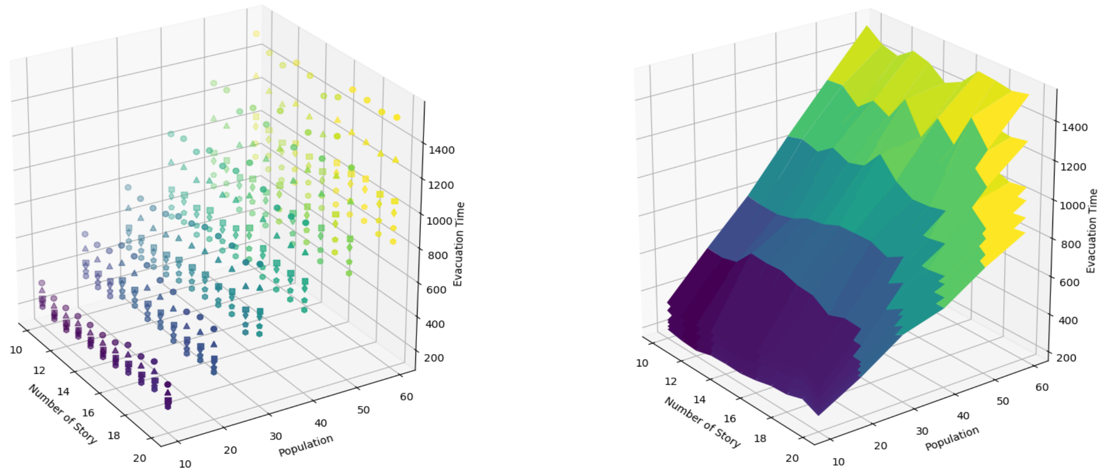



*Figure 31 - Effect of Multiple Factors on Egress Time (Dummy Variable - Lambda)*

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:*

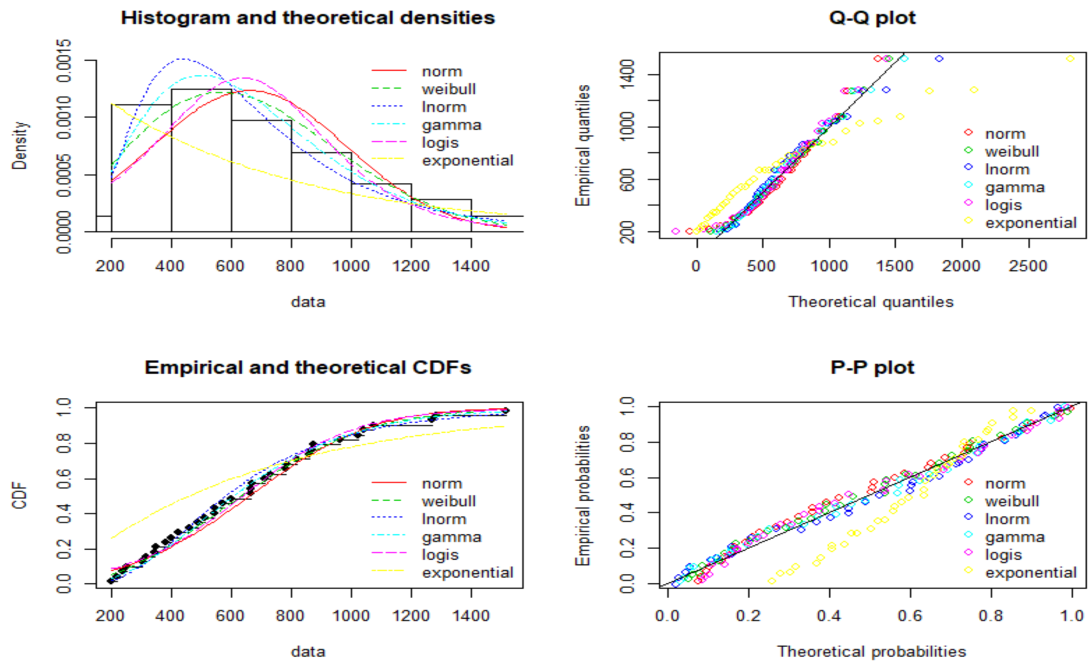



*Figure 32 - Probability Distribution Fitting Test for Ten-Story Building*

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

✓ *Eleven-Story Building:*

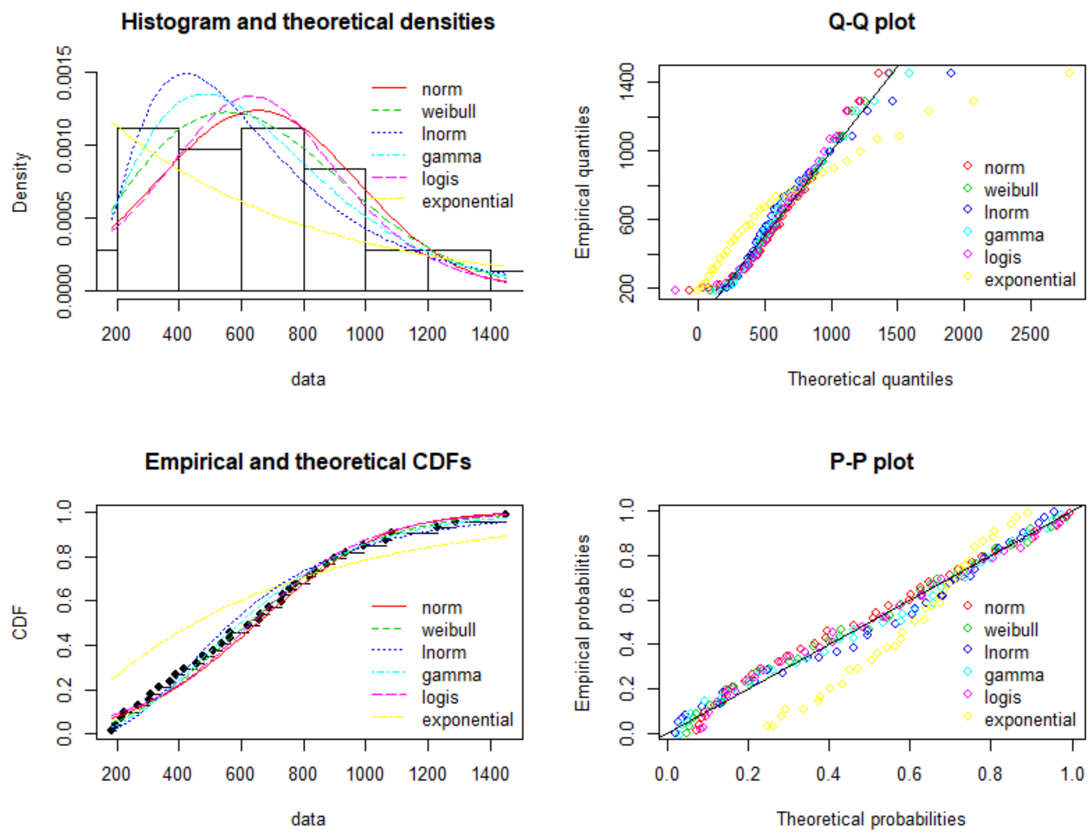



*Figure 34 - Probability Distribution Fitting Test for Eleven-Story Building*

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<br>Parameters :<br>estimate Std. Error<br>shape 2.158534 0.2808483<br>scale 737.680637 60.1355525<br>Loglikelihood: -256.9698 AIC: 517.9396 BIC: 521.1066<br>Correlation matrix:<br>shape scale<br>shape 1.0000000 0.3207907<br>scale 0.3207907 1.0000000 |
| **Gamma** | Fitting of the distribution ' gamma ' by maximum likelihood<br>Parameters :<br>estimate Std. Error<br>shape 3.790911585 0.755141274<br>rate 0.005822005 0.001202135<br>Loglikelihood: -256.9517 AIC: 517.9034 BIC: 521.0704<br>Correlation matrix:<br>shape rate<br>shape 1.0000000 0.9156888<br>rate 0.9156888 1.0000000 |

✓ <u>*Twelve-Story Building:*</u>

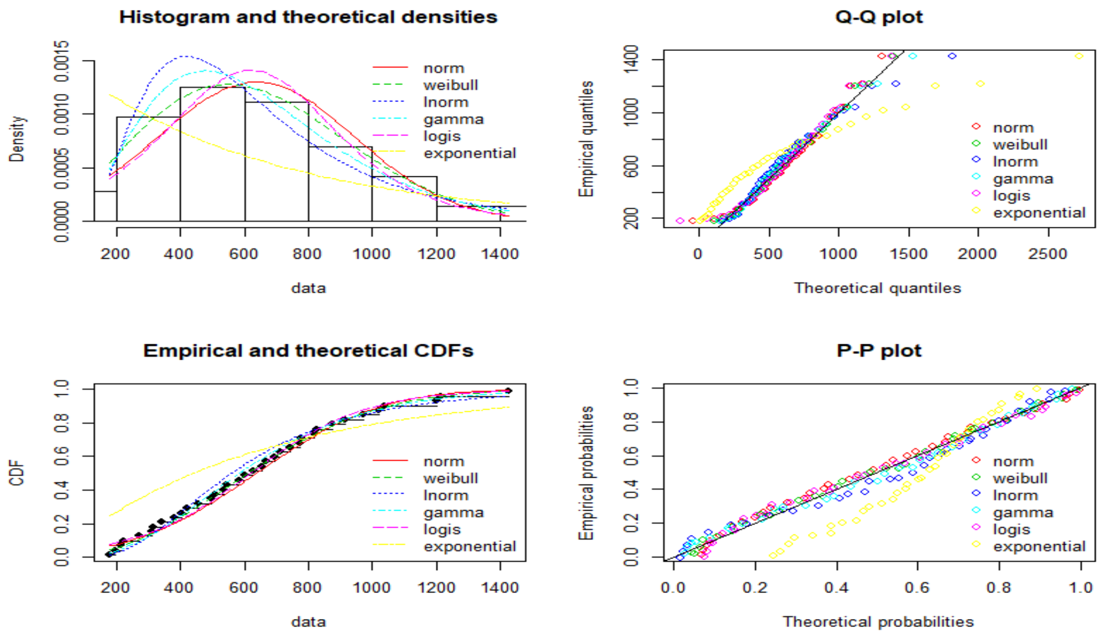



*Figure 36 – Probability Distribution Fitting Test of Twelve-Story Building*

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

## ✓ *Thirteen-Story Building:*

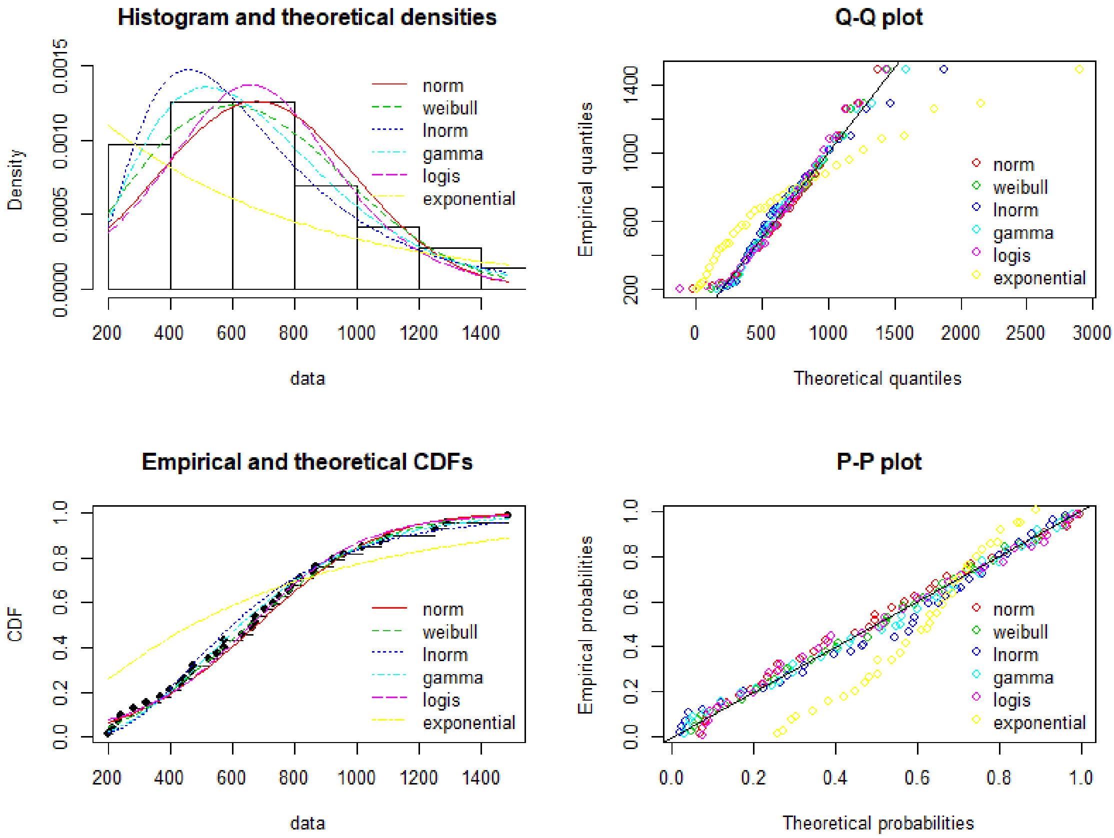



*Figure 38 - Probability Distribution Fitting for Thirteen-Story Building*

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

✓ <u>*Fourteen-Story Building:*</u>

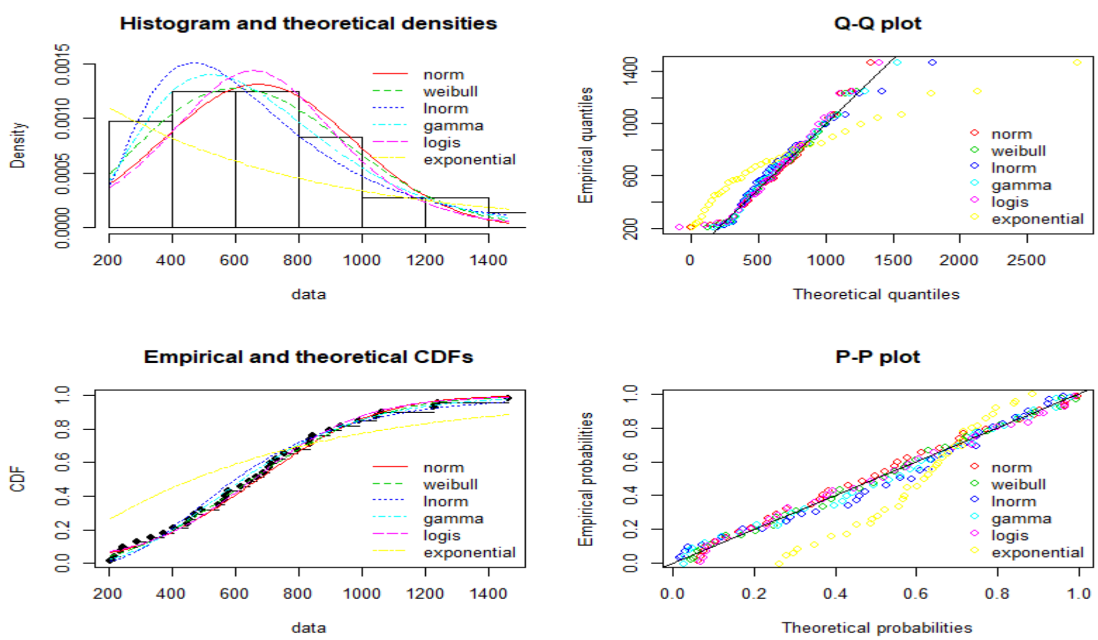



*Figure 40 - Probability Distribution Fit for Fourteen-Story Building*

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

✓ *Fifteen stories building:*

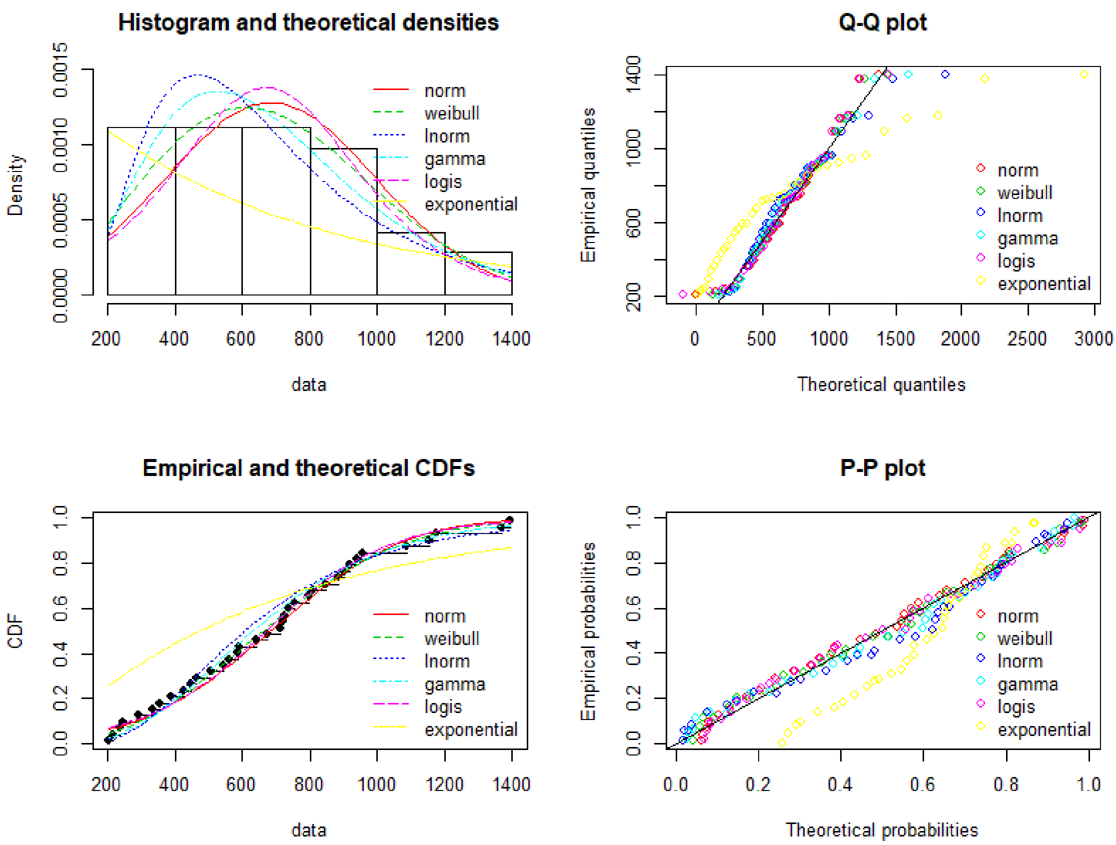



*Figure 42 - Probability Distribution Fit for Fifteen-Story Building*

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

✓ <u>*Sixteen-Story Building:*</u>

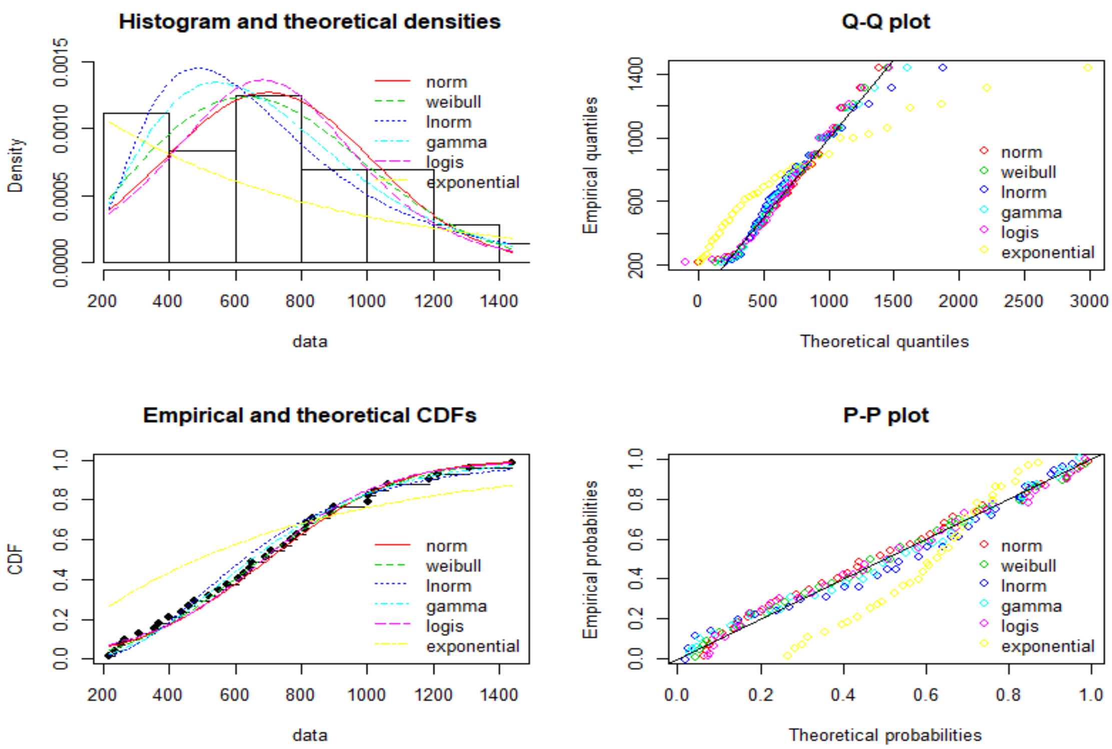



*Figure 44 - Probability Distribution Fit for Sixteen-Story Building*

```
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*

<table>
<tr><td>Weibull</td><td><pre>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</pre></td></tr>
<tr><td>Gamma</td><td><pre>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</pre></td></tr>
</table>

✓ *Seventeen-Story Building:*

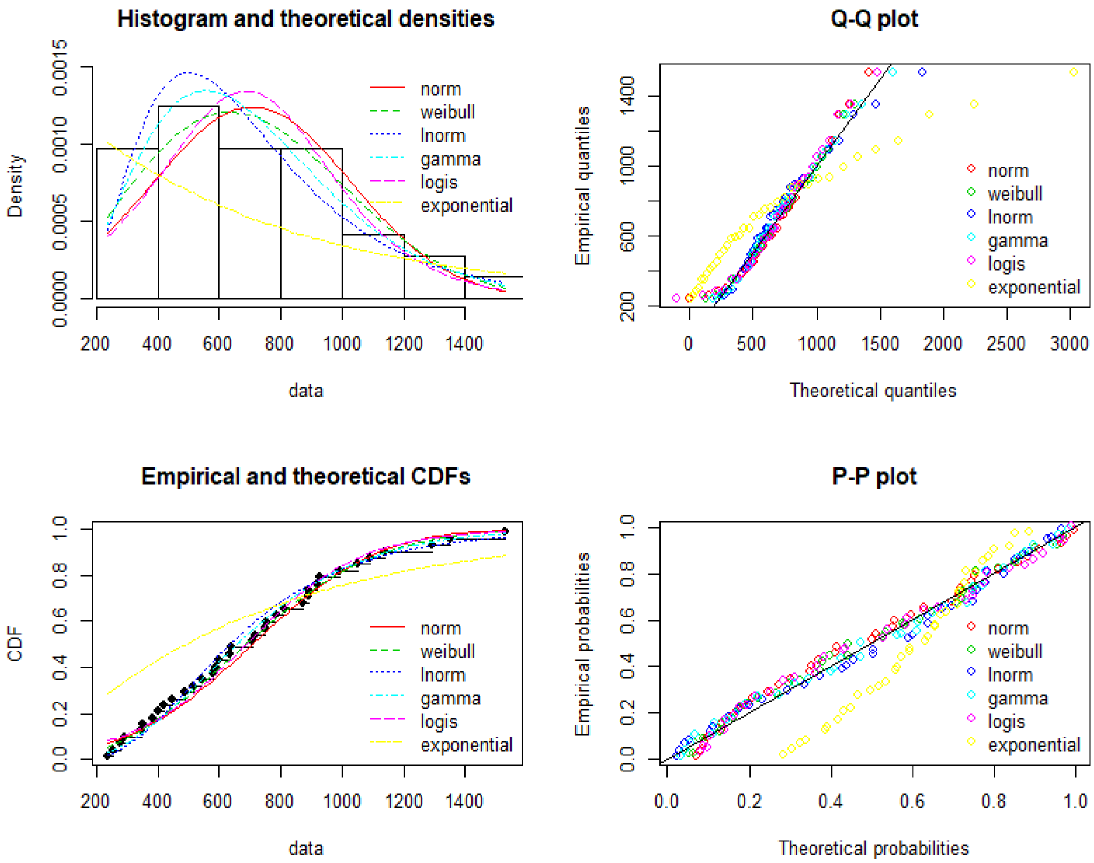



*Figure 46 - Probability Distribution Fit for Seventeen-Story Building*

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<br>Parameters :<br>estimate Std. Error<br>shape 4.693744264 0.946634135<br>rate 0.006632716 0.001378902<br>Loglikelihood: -256.7838 AIC: 517.5676 BIC: 520.7347<br>Correlation matrix:<br>shape rate<br>shape 1.0000000 0.9324138<br>rate 0.9324138 1.0000000 |

✓ ***<u>Eighteen-Story Building:</u>***

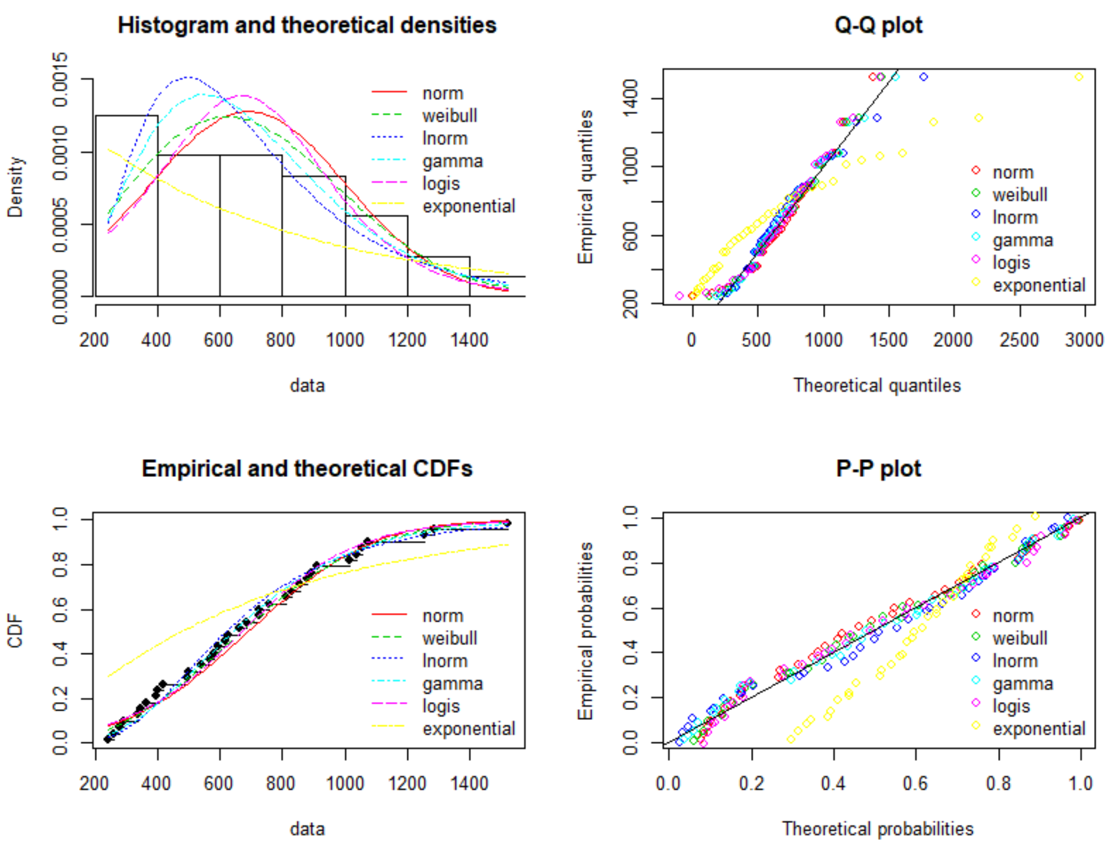



*Figure 48 - Probability Distribution Fit for Eighteen-Story Building*

```
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*

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

✓ *Nineteen-Story Building:*

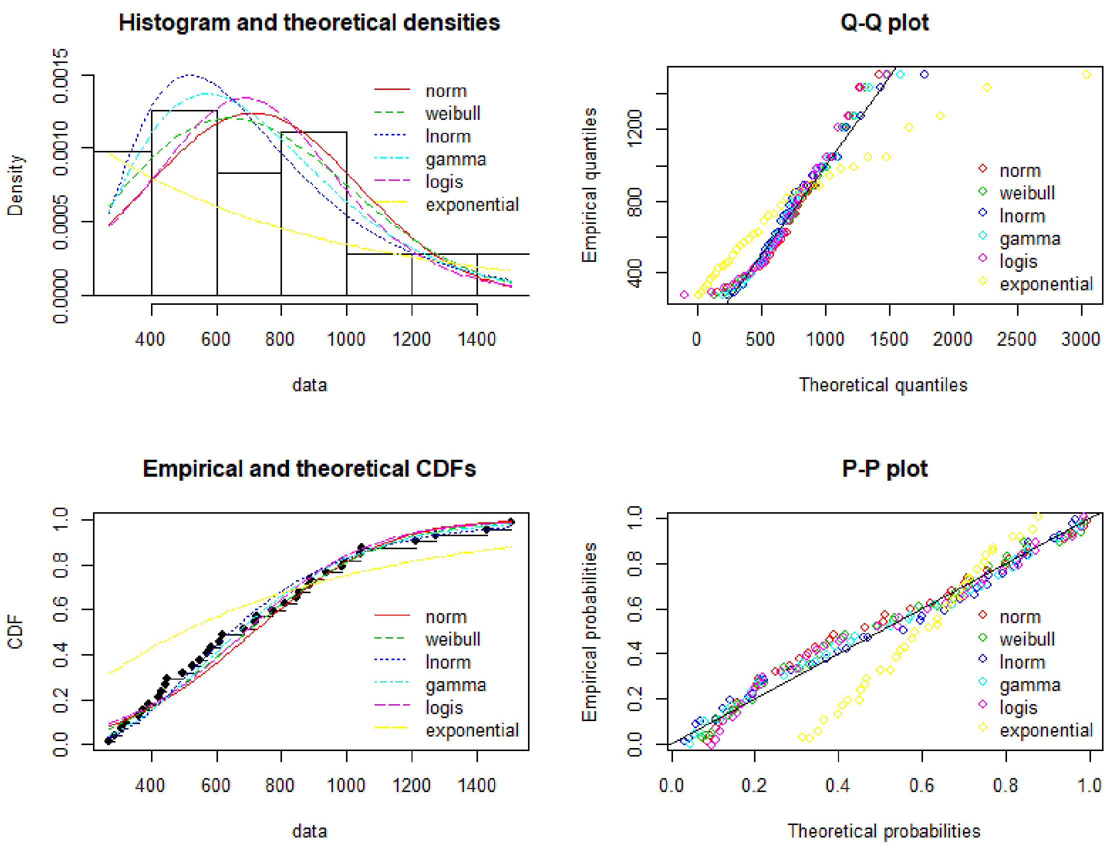



*Figure 50 - Probability Distribution Fit for Nineteen-Story Building*

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

✓ <u>*Twenty-Story Building:*</u>

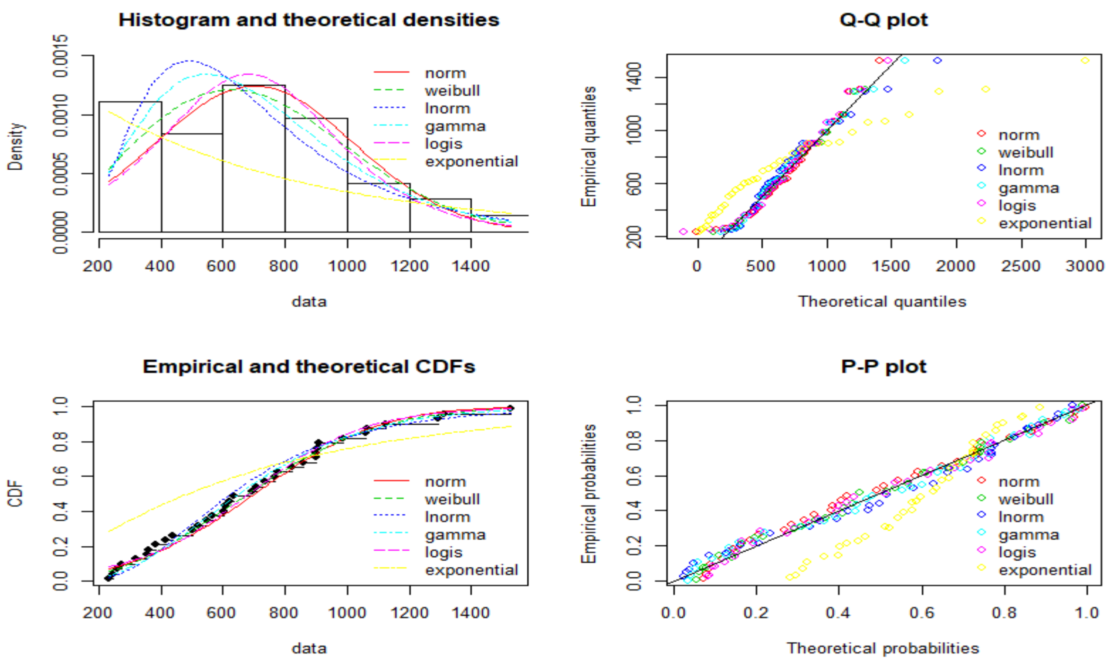



*Figure 52 - Probability Distribution Fit for Twenty-Story Building*

```
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<br>Parameters :<br>estimate Std. Error<br>shape 4.52680884 0.910330193<br>rate 0.00646197 0.001340449<br>Loglikelihood: -256.9747 AIC: 517.9493 BIC: 521.1164<br>Correlation matrix:<br>shape rate<br>shape 1.0000000 0.9296988<br>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) | 95$^{th}$ 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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