# A BUILDING EVALUATION TECHNIQUE FOR FIRE DEPARTMENT SUPPRESSION

by

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# Abstract

Building design and site features have an influence on helping or hindering fire fighting operations. Traditional studies relating to building performance evaluation for fire department operations do not address the influence of building site and architectural design on local fire department suppression techniques. These studies also do not relate fire fighting analysis to anticipated fire size. The goal of this dissertation is to develop an analytical procedure by which the size of a specified design fire can be predicted for the time at which fire fighting attack water application is likely to occur. The delays encountered due to building configuration and specified design fire conditions are incorporated in the analysis. Discrete Event Simulation is used to compute time durations for fire fighting operations. The results of this dissertation may be used as a stand alone technical analysis for any office building or as a part of a more complete building performance evaluation.

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# Chapter 1

# Introduction

## 1.1 The Problem

Architectural and site conditions for a building can dramatically affect an initial fire attack and the tactics used by the fire service to extinguish a fire. When architectural obstacles and difficult site conditions delay the initial fire attack, the fire grows and propagates causing additional property damage and greater danger to occupants and firefighters. Callery [5] describes the interactive nature of the process as follows:

> “When a fire department quickly extinguishes a challenging building fire, the firefighters usually take the credit for making a ”good stop”. Often the building deserves much of the credit. Likewise, when a fire gets away from the department, the building deserves some of the blame. The likelihood of quick extinguishment will differ for various fires of similar size at the time the first fire apparatus arrives. The change in impact is brought about by the building and the location of the fire within the building”

The fire protection, firefighting, and building construction communities currently lack a procedure to evaluate the effectiveness of building designs and site features to accommodate firefighting. This area has been relatively untouched by researchers.

## 1.2 Purpose

The goal of this thesis is to develop and introduce a procedure to evaluate the influence of building layout and site design and layout on the time to first water application and the fire size at first water application, given a specific delay for notification and response. Currently, neither the architect nor the fire officer has a credible method to make such a determination. The method described in this thesis provides architects, firefighters and engineers with a procedure to evaluate the fire size at initial agent application. The results from this procedure may be used as a stand-alone technical analysis for a specific building or as part of a more complete building performance evaluation.

The primary goals of this new procedure are:

- to determine how building and site design and layout affect the time to first water and the fire size at first water given a specific delay for notification and response.
- to provide a basis to determine if building and fire ground design and layout would indicate that the fire department must move from an offensive interior attack, aggressively trying to put out the fire in the rooms involved when they arrive or to a defensive mode, where portions of the building or even the building itself are likely to be lost and resources must be directed to protecting exposures.

## 1.3 Scope

This research will develop a routine procedure to determine the time to lay fire attack lines along a specified route within a structure and to coordinate that operation with supply water establishment. The creation of an analytical method that incorporates fire service experience to predict the fire size at the time of initial water application will provide such benefits as,

- measures that allow local fire fighting resources to compare building designs.

- fire department development of site specific operational planning for available local resources and conditions.
- comparison of design alternatives to give the local fire authorities additional ways to communicate with owners, architects and other governmental agencies about the effect of specific building features on fire suppression and occupant safety.
- an improved estimation of potential heat and smoke damage for a particular building design.
- fire service participation in the global movement toward performance based building codes with a rational, analytical method to assure that its "value added" to structural fire safety is properly recognized and an integral part of the process.

This dissertation describes a procedure to estimate the fire size at the time of first water for any building architecture and layout. Office buildings are used to demonstrate this procedure. When architectural obstacles and difficult site conditions delay the initial fire attack, the fire grows and propagates causing additional property damage and greater danger to occupants and fire fighters.

A deterministic approach to determine the time it takes for firefighters to alight an apparatus upon arriving at a fire, set up a water supply, and to move through a structure to the fire area will be developed. This approach will be able to account for the influence on time to first water depending on firefighter tactics and staffing. The ability to integrate this approach with room fire models and determine the influence of interior building environmental conditions such as smoke and heat on time to first water will also be demonstrated. Finally, the ability to determine an estimated fire size at first water application will be shown.

## 1.4 Thesis Organization

This thesis consists of five chapters. This first chapter is an introduction and orientation to the problem and contents. Chapter 2 covers the background of the problem in order to give the reader a better understanding of the basis for this work. Chapter 3 focuses on the development of the procedure and its verification. Later in the chapter, the model is expanded by the incorporation of fire conditions such as smoke and heat. Chapter 4 discusses application of the model and chapter five offers conclusions and recommendations for future work.

# Chapter 2

# Background

## 2.1 Introduction

This thesis will develop and introduce a procedure to determine how building layout and site design affect the time to first water and the fire size at first water. Conceptually, the comparison may be illustrated by the time lines describing each of these sequences shown in Figure 2.1[13], between the labels "arrival" and "first water on". These time lines describe a general building fire event in which the fire department intervenes, a concept often referred to in the fire service as "set up time". Background for the development of each of these provided in the first two sections of this chapter. A set of design fires for office spaces is also developed in the fire growth time line section, so that firefighter environmental conditions and fire sizes can be explored as the firefighter movement model is developed in later chapters.

After the firefighter operations are conceptually defined, and sample fires are developed, a method by which they will be integrated and modeled in greater detail will be explained. These remaining sections of the chapter conceptually explain how a discrete event simulation is created. The detailed development of the modeling of specific tasks is covered in Chapter 3.

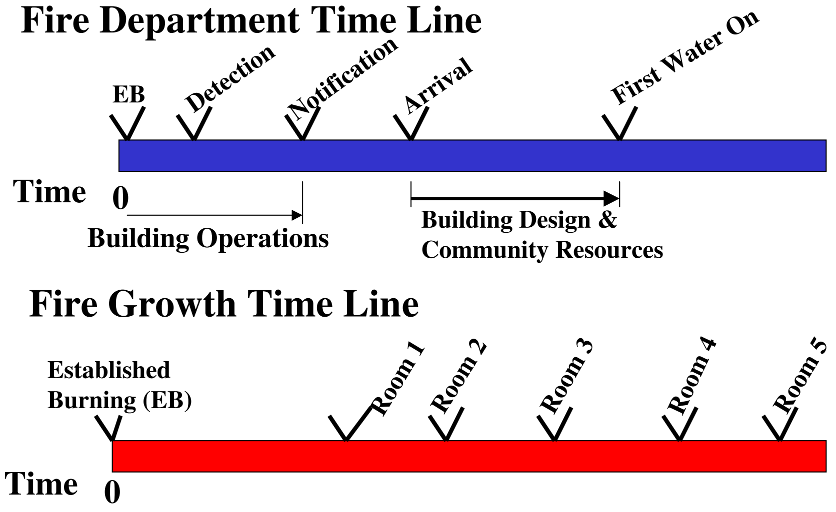

Figure 2.1: Background Description

## 2.2 Fire Department Time Line

### 2.2.1 Established Burning to Arrival

The fire department time line begins with established burning. The line then sequentially recognizes that detection, fire department notification and arrival are requisites to the time duration needed to apply to first water. The time from established burning to fire department notification is generally a function of building operations as shown in the figure. This aspect will not be developed in this work, except to note that it can be incorporated into a model either as an assigned value or as an analytical function.

Firefighter operations after arrival are integral to this study. It is necessary to acquire data on individual tasks to develop the model and whole evolutions to validate the model.

The time to fire department arrival can be estimated from statistical data of the local community.

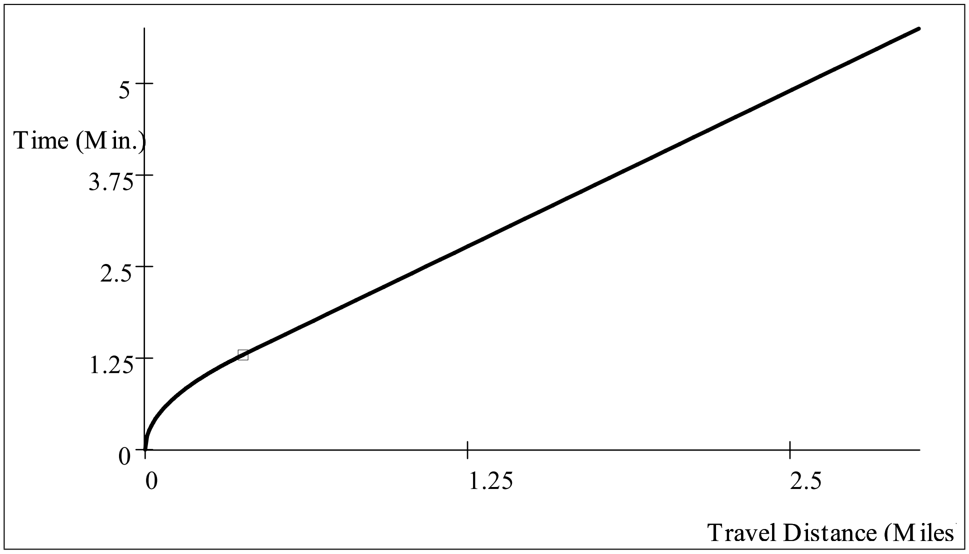

Figure 2.2: Time vs. Distance Figure From Rand Study

A variety of different techniques may be used for this analysis. On on extreme, sophisticated studies, such as the Rand Study[45] can be used to define this process. At the other extreme, simple speed and distance estimates may be used.

A direct solution to the time between fire department notification and arrival first water is shown in Figure 2.2, and is taken from the Rand Study of 1979[45]. In the Rand study it was found the following equations provide travel time estimates.

$$E(D) = \begin{cases} 2.10\sqrt{D} & \text{if} \quad D < .38 \\ 0.65 + 1.70D & \text{if} \quad D \geq .38 \end{cases} \tag{2.1}$$

where D= Odometer Distance in Miles and E(D) denotes the time required to travel between points. These equations are based on analysis of data from Trenton N.J., Denver CO,Wilmington DE, and Yonkers, NY. It can be seen that a travel distance of two miles requires about four minutes for fire department arrival according to this model. The study found that this correlation worked well for most cities.

It should be noted that the time from notification to arrival must also include alarm handling and turnout times. These time durations, combined with the transit time, provide the total response duration. These durations can vary significantly in different communities, depending upon local protocol. Consequently, this thesis will focus on the fire ground operations from arrival of the first apparatus to the time of first water application. This time duration has had much activity and little documentation that is of value to an analytical study.

### 2.2.2 Arrival to First Water (Set Up Time)

The time duration between the arrival point and the agent application point is defined as the set-up time. Establishing this time is the primary goal of this study. The time duration for this set up period will vary tremendously depending upon the site conditions, the building and the fire conditions, the number of people and the types of equipment responding, and several other related factors. When a fire department is notified of a fire emergency and the responding forces are travelling to the site, they never know exactly what they will encounter when they arrive. However, when they do arrive and begin to take action, a generalized process will unfold that portrays the range of activities that take place. Because of the potential for a large range of contingencies and conditions, one must recognize that the fire ground commander adapts decisions to meet the perceived needs of the situation. Although the organization and activities that are portrayed in our description may be related to any type or size of structure, the mental image on which the process is modelled is an architecturally designed commercial, business, or residential building.

The process of fighting a fire involves accomplishment of a number of discrete activities. One should not infer, however, that this procedure is ”step-by-step.” Rather, the activities are done when they need to be done as determined by the conditions perceived at the time. Some of the activities must be performed sequentially. Others may be performed simultaneously. In many ways, the process is similar to that of a construction project. The time durations to complete discrete activities are influenced by the manpower, equipment, and conditions that exist at the time. Some of the concepts of construction management have been used to organize the fire fighting operations necessary to control and extinguish a fire.[13]

### Arrival and Size Up

The first arrival is usually an engine company. This first-in company places itself in what appears at the time to be the most appropriate position to carry out initial activities. This positioning involves balancing several immediate and possibly conflicting needs including, gathering information about the location and magnitude of the fire, ascertaining if there are any potential life safety threats, establishing a water supply, and laying attack lines. Shortly after the first company arrives, a chief and the other companies arrive.

The fire ground commander is the senior officer at the fire scene. Initially, it is the officer of the first arriving company. However, this position is transferred when a more senior officer arrives. The fire ground commander is in responsible charge of the scene and all of the operations. The fire ground commander is placed in a position of making rapid decisions on the basis of incomplete, often inaccurate, and constantly changing information. In addition, these decisions must be made during periods of maximum distraction and emotional stress within very short periods of time. The process becomes decision making under uncertainty in a very pure form.

Experience, knowledge, and training are very important to a fire ground commander's educational background. Timely, astute decisions can make the difference between a good stop and a fire that got away. The other important element to the success or failure in limiting the fire to acceptable sizes is the influence of the building site and design features.

An initial size up becomes the basis for the fire ground commander's decisions. A size up is a mental model of the entire system that makes up the fire ground conditions at the time of arrival. A size up begins on route and becomes more defined upon arrival at the site when better information becomes available.

The goal of fire ground operations is to use the available community resources of manpower and equipment to rescue endangered individuals and to minimize the destructive damage of a hostile building fire. The size up provides the information on which to base decisions regarding the strategy and tactics to achieve that goal. An ideal size up would include the type of information described below. Obviously, time constraints of required early action preclude the collection of all of the information initially. However, when complete information is not available, the fire ground commander makes decisions based on the accumulated knowledge at the time.

- Life Safety - Are any occupants remaining in the building? Where might they be located? How certain is the information?
- Building Construction Information - In buildings of this type, will the barrier effectiveness quality contain a fire to one or few rooms or will it allow the fire to propagate easily? What is the collapse potential? Can the building construction be used to advantage to control the fire and limit its propagation? Does this building present a safety hazard to fire fighters?
- Fire. - Where is the fire? What is its size? What is burning, and what is the fuel loading? What types of hazardous materials may be present? Are they involved in the existing fire? Can they become involved if the fire extends?
- Water Supply - How many hydrants are available, and where are they located? How much fire flow is available? Are static water supplies available for drafting? Must water be supplied by tankers?
- Fire Fighting Resources. - How many engines and fire fighters are available? What other types of apparatus are present or available? Where is the equipment now placed? Should they be relocated? If additional equipment will respond, where should they be placed? Are personnel needed for a primary search and rescue or are they available for fire fighting? How many hose lines could we lay? What fire flow can be delivered internally and externally?
- Fire Attack. - Where are the building access locations? Are there any natural or man made obstacles to approaching the building from different sides? Where are the stairwells? Where are the standpipes? How do we gain access to the floor of origin? What fire attack routes are available? How clearly are they recognizable? Will doors have to be forced to gain access to

the fire location? How many? What size and how many hose lines can be stretched with the manpower available? How long will it take to lay the hose lines? Are there critical locations at which to position hose lines in order to defend people or valuable property from fire extension? Will these positions help or hinder fire attack or control? Where and how can the building be ventilated.

- Environmental Conditions - What is the time of day? What are the weather conditions? What are the site conditions that influence movement, such as mud or snow? How will the wind conditions affect fire fighting? What are the smoke, heat, and visibility conditions within the building? What are the heat and visibility conditions near the fire?
- Exposures - Are there any other external buildings exposed to the fire? Should those exposures be protected before or subsequent to attacking the existing fire? Are there internal exposures that should be protected?
- Building Services Information - What type of heating fuels are used, where are they stored, and where is the fuel shut off located? What is the electrical system and where is the shut off? Is emergency lighting available? Does the HVAC system continue operation, shut off, or shift to an emergency mode of operation at detection? Can its operation be changed to help fire fighting? Where are the controls and how is it done? Are elevators in operation or is there a recall at detection? Is there a fireman's key for emergency use? What other building services information is available that would influence life safety or fire fighting?
- Resource Augmentation. - Does standpipe water need to be augmented from the building's fire department connection? Does the building have a sprinkler system at the fire location? Would connection to the sprinkler Siamese enable the system to operate? Are additional alarms or mutual aid needed?

The more information that is available, the better the decisions can be made. However, the fire will not wait. As it continues to burn, the conditions change. The fire companies will take initial actions in accordance with a preconceived plan of operations and immediate needs before a size up is completed. This plan will be modified by the fire ground commander to reflect conditions that are evident or that change during the course of the fire.

Communications and the chain of command become essential features in fire ground operations. In many instances, communication becomes the basis for the transmission of new information about conditions inside the building to the command post. Communication is also crucial to the proper deployment of resources and to learn of the outcomes of the actions taken.[13]

### 2.2.3 Manual Suppression Coordinated Operations

While life safety may be the principal concern for the fire ground commander, the focus of this chapter is on building evaluation for its ability to limit fire extension by manual suppression. Manual suppression involves five coordinated operations. They are,

1. find the fire
2. establish a water supply
3. lay attack lines and initiate agent application to the fire
4. prevent extension of the fire to other spaces
5. extinguish the fire.

This research is concerned primarily with steps 2 and 3 above, although the methods developed can be applied to the other sections as well. Depending upon the size up, the fire ground commander may employ an interior offensive attack to extinguish the fire aggressively. Alternatively, the commander may select an exterior or interior defensive procedure to prevent fire extension to threatened exposures outside or within the building. Building and fire conditions may change over time, requiring the fire ground commander to alter tactics from an offensive mode to a defensive mode.

### Finding the fire.

Although locating the fire may seem to be a trivial problem, the process is not as easy as it at first may appear. Of course, small buildings do not usually pose much difficulty. However, in large or complicated buildings, finding the fire can be time consuming and difficult. Dense smoke obscures visibility, and a fire often is located by feeling the heat rather than by seeing the flames. Consequently, accurate information given to the fire officer can substantially reduce the time to agent application in a complicated building. Accurate information on the fire location is important not only to place the attack hose lines effectively, but also to become aware of potential life safety or property protection concerns.

### Establish a Water Supply

Another part of the process that must be evaluated is the establishment of water to supply the attack lines. Engines will carry some water in their tanks. Often, the 500 or 750 gallons is sufficient to provide enough water to extinguish a smaller fire or to start a fire attack. However, to provide enough water for a larger fire or building, there are three principal sources of water supply for a fire. These are

1. Underground public or private water distribution system with hydrants.
2. Body of water such as a lake, pond, or stream from which water can be drafted.
3. Using shuttle operations, transport water by tanker trucks (tenders) and deposit water into portable tanks at the fire scene. The water then can be drafted for attack pumper use.

The most common water supply in communities that have underground water piping is through the hydrants. Water is supplied from the hydrants through hose lines to the pumpers. The pump provides the desired pressure and delivers water to the building supply lines or standpipes. The distance of the hydrants from the building, the number of hydrants available, and the distance and number of supply lines from the pumpers to the building attack lines are considered in the evaluation of time durations and staffing needs.

If underground piping and hydrants are not available, water must be drafted from an available pond or stream to the pumper. Establishing this type of water supply can be very time consuming, and the reliability is uncertain during periods of drought or deep freezing. If these water sources are not in the vicinity of the building, alternative sources must be considered.

The third type of water supply is brought to the site by tankers. A temporary reservoir must be set up and tank trucks are used to relay the water to the pumper and delivery to supply lines. Evaluating the scheduling of tanker discharges, staffing needs, and reliability during different times of the day and seasons of the year are a part of any building evaluation that depends upon this source of extinguishing water.[13] Further description of these procedures is located in Appendix A of this document.

### Lay Attack Lines and Initiate Agent Application to the Fire

This thesis is concerned with quantifying fire department set up time. The interior tactics involved are essentially laying an attack line with the primary goals of prevent extension of the fire to other spaces, and extinguishing the fire. Callery [5] addressed this issue by developing the attack route difficulty concept. This concept identified delay sources in building designs for firefighters.

These time delay resources were:

1. Community resources
    - local fire department and its water supply
2. Environment
    - Visibility
    - Heat
    - Fatigue
3. Architectural Obstacles
    - doors

- corridors
- stairs
- corners
- large rooms
- hazards/clutter

Callery's concept describes a "building friction" as the time it takes walking through a well lit building in street clothes to the time it would take to lay a hose through a burning building in full turnout gear and equipment. Callery's theory suggested an analyst could walk a path through a building and apply a series of factors to determine the time it took to navigate the same path laying hose line in a burning building. He developed generalized process that was intended to determine these times. Variables were included to incorporate the effects of smoke and heat.

Callery's equations provided were included only to demonstrate an overall concept. It has not been validated to provide accurate quantitative output. It also does not provide for commutativity. Clearly a firefighter having to drag charged hose up a flight of stairs and then down a corridor would take more time than a firefighter moving down a corridor and then climbing a flight of stairs. The fact that when moving charged hose, A+B does not equal B+A was not considered. However, the concepts are valuable to recognize that this enormously complex process can be described.

Callery sought to develop graphs similar to Figure 2.3. These graphs presented equivalent distance vs. room location number, rooms corresponding to a particular floor plan. In Callery's work, equivalent distance is a direct function of time, so one could just as easily develop an assembly vs. time graph. For the purposes of this study, the time is more important, because it can then be compared to the time developed in the fire models, to determine how large the fire is when first water is applied. Therefore time, and not effective distance, will be plotted against building features.

Callery's conceptual results were are one would expected. The number of firefighters directly influenced the time it takes to attain a certain depth within the building. Callery's concept states the equivalent distance for 3 firefighters is much greater than that for 5 firefighters, up to a certain

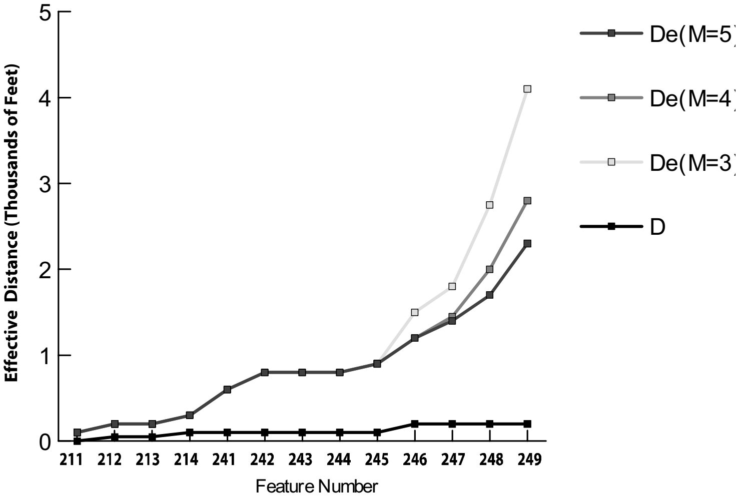

Figure 2.3: Callery Effective Distance Concept

point. Before that point, in this case the vicinity of room 245, larger staffing is not an issue. Callery did not assign actual numbers to his equations, however, the general concept is of great value.

### 2.2.4 Existing Sources of Time Data

A study recently undertaken in Australia [4] takes into account many factors of interest for the development of this model. Statistical information was gathered on individual events such as how long it takes a firefighter to travel in full turnout gear and don SCBA equipment. The large amount of data provided proved to be very useful. The data developed was not detailed in interior tactics, which are necessary for this study. In particular does not include specific information about how obstacles such as corners within the building will modify firefighter operations.

An excellent study for the validation of this model is the Louisville study of 1993[32]. It addressed the time necessary for firefighters to reach a fire in an office building. This study was a collaboration between the Louisville Kentucky fire department and NIST. The use of modern firefighting tactics and the environments encountered due to smoke and heat were all accounted for in this work.

Some studies suggest specific standard operating procedures for the setup of water supplies[10]. None was found that provided overall durations for these procedures. NFPA 1410 does provide suggested times for these procedures but source data for these numbers was unavailable at the time of this writing.[43].

Another often cited study was the 1984 Dallas study.[27]. The firefighting tactics used in this study are somewhat dated. It is common practice today in the US when attacking fires in high rise buildings to use a "high rise pack" containing about 150' of lightweight attack hose and the tools necessary for its employment. A small group of firefighters is able to get to the site of the fire and attack it quickly using this method. In the Dallas study 100' of 2.5" hose were then attached to 150' of attack hose before the evolution was considered complete. Setting up this extra 2.5" hose took considerable time and required significantly more manpower than modern tactics would. It would be possible for this study used for calibration. The additional tasks would need to be properly incorporated.

Another study commonly known as the 1969 Dallas Study dealt with staffing levels and hose laying evolutions for selected room configurations of specific buildings [16]. The influence of modern equipment and protective gear on the outcome of this experiment is unknown. In one instance designed to demonstrate the influence of staff size a very heavy hose rig was put together that was required by the designers of the evolution to be moved as a unit. Disconnecting hose from the rig so that smaller groups could move it easily was prohibited. The obvious result was that large groups of firefighters easily completed the evolution while small groups could not. In another procedure the firefighters were overly familiar with the situations they encountered in the test. Live fires were also not used or accounted for so any hindrance by smoke and heat were not represented.

Other studies use a statistical NFIRS type approach[3] in which many fires were studied and general statistical data was gathered about firefighter operations. These studies lack specific information needed to develop a deterministic time duration model. This missing data includes building dimensions, door configurations and other architectural obstacles and attack routes.

A series of studies were concentrated in Canada. A study by the Office of the Fire Marshall of Ontario concerned staffing required to handle house fires [26][25]. These studies are discussion papers of what different size fire brigades should and should not be able to do. Their justifications primarily on historical precedence and an analytical and statistical methods were not developed.

Another group in Canada is working at the NRC under Dr. David Yung. No information is available from this study.

## 2.3 Building Construction , Compartmentation, Configuration and Contents - The Fire Development Time Line

This section deals with consistencies in the development of buildings so that the fire environment can be identified. It deals primarily with consistencies in office building designs, so that estimations of heat release rate, fuel configuration and fire movement can be established, so that in turn, an interior environment for firefighting operations can be defined and evaluated, and a size of fire at first water can be ascertained. Although office buildings are used as examples, this method can clearly be adapted for other spaces.

Fitzgerald [13] describes 6 realms of fire growth within a compartment, preburning, initial burning, vigorous burning, interactive burning, remote burning and full room involvement. In practice this process can be described in the form of a fire growth curve. The fire growth curve corresponding to the occupancy can be used to determine when a room will reach full involvement, and what smoke conditions in and around the room of origin will be like using zone fire models such as CFAST[29]. The issue of what growth curve to use and when full room involvement will occur becomes a function of construction, fuel configuration and contents of the room. This section describes typical construction, configuration and contents for an office occupancy, so that the ”set up time” model can be developed. Once full room involvement has occurred, barrier integrity becomes a large factor in fire growth, and its influence on the fire that the fire department will encounter also needs to be incorporated into any model.

A comparison of fires in high-rise office buildings and low-rise office buildings shows that 60 percent of high-rise buildings that had fires were protected by sprinklers, as opposed to 20 percent for low rise buildings." [17] It was also estimated that 95 percent of all office buildings in the United States are only three stories high or less. It is clear from these statistics that the majority of office buildings are unprotected by sprinklers and therefore count only on manual suppression efforts in case of fire.

In recent years many office parks are being developed in suburban areas. These office parks require that local fire departments which may have previously handled only residential and small business fires, to be responsible for protecting larger office structures that they have no previous experience, and for which they quite possibly have insufficient resources. An analytical tool that can evaluate an office building design for its impact on fire ground operations can have important value in the changing building and technological environment that exists today.

### 2.3.1 Construction

It is arguable that building construction, compartmentation and contents are a direct function of use. Historically, in the case of office buildings, the rigid steel construction of the early 20th century resulted in relatively expensive buildings with limited available floor area. Even today buildings that used this construction tend to make use of conventional floor planning, with individual offices provided for workers.

The construction of buildings evolved in the early 1950's with the use of a building core to contain elevators and utilities to the upper floors. This core is built adjacent to large expanses of open floor area that can be readily configured to occupant needs. This cored construction is less expensive in terms of building and maintenance costs to more conventional forms.

### 2.3.2 Configuration

Office buildings share similar characteristics not just in the types of room they contain, but also in their overall layout within the building. Office building layout and design is a very important element in the determination of flame spread outside the room of origin. Both modern and contemporary office buildings share many similarities. The office as we know it today has a history of about one hundred years. Initially it was a one-person space containing a desk and chair. Depending on the status of the individual in the office it may have contained a table and chairs for guests. As industrialization spread offices grew by increasing the number of staff and the administrative structure. Office layouts evolved to accommodate more people. This evolution has included many phases which can be summarized in the general categories listed below.[28]

- Conventional Planning
- Bullpen Concept
- Executive Core
- Open Planning
- Conventional Planning

Conventional office plans consist of individual offices for everyone. These plans have the advantage of being relatively easy to design, especially with modular columns and load bearing walls. They also have the advantage that compartment fire models are readily applicable and the design fires can be modeled for the individual room type. They have the disadvantage of being relatively inefficient in terms of space.

The bullpen concept places the staff in open spaces with rigid grids of desks and aisles. Executives are segregated to one or more sides in enclosed, windowed offices. Variations on this concept were used until the late 1950's and early 1960's, always with the executives on the outside in the windowed offices. The function of the bullpen concept was to contain a large number of people in a small area, thus reducing cost. In addition, it was obvious to everyone who worked or visited a facility who had status and who did not.

A different phase started in the 1960's, where the staff was placed in the building exterior, still in bullpen type layouts. Executives were moved to individual offices within the building core. This was intended to shift some of the status away from the executives, and to therefore prevent or reduce the growing amount of turnover in staff-level personnel that was occurring during this time. The furnishings are identical to the bullpen design. The only changes are the relative positions of the workers. The differentiation in status is still obvious.

There are those in the architectural community who claim that the concept of open office planning was a direct result of the Quickborner Team, a planning and management consulting firm in Germany, that developed the concept in 1959. "Until that time, the Quickborner Team was a materials company, specializing paper and related products, furniture, equipment and filing systems for offices. It was out of frustration caused by lack of harmony between products and systems, that the Quickborner Team began to investigate interdependencies within the office. This led to the realization that all elements of the office are interrelated and should be dealt with concurrently; and this, in turn, led to the development of an approach to office planning, later to be called office landscaping"[33]. These authors claim that open office planning was not implemented in Europe until 1960, and did not reach the United States until the fall of 1967, with the remodeling of Du Pont's Freon Products division in Wilmington, Delaware.

Others in the community, while acknowledging the contributions of the Quickborner team, claim that the dynamic problem solving concept involved in open office planning can be seen in the United States in the form of Union Carbide Headquarters, as early as 1959. The Union Carbide headquarters made use of:[35]

- Partition Systems
- A furniture system that permitted desks to have interchangeable pedestals
- Integrated filing and storage systems
- Clustered Workstations with low dividers

Lighting, air conditioning, and the partition system were integrated with a 5 foot grid, keyed into the ceiling runners. The runners supported the ceiling, locked into the partitions, and acted as continuous strip diffusers. There was no need for fire stops or sound baffles, since the space above the plastic ceiling was divided into cells, each enclosing a lighting fixture.

It is clear that the Union Carbide headquarters contained most of the elements of today's open office. Open office planning is widely used today because of its low cost.

The office planning generally in use today is a combination of open office planning and conventional planning. Generally these office plans consist of full offices around the exterior of the building and open office planning in the interior. The open office plan provides low cost and flexibility. The full offices allow for proper status for the upper management.

### 2.3.3 Building Contents

In office buildings with similar functions share similar layouts and contents. They can generally be divided into the following categories.

- Small Office
- Medium Office
- Large Office
- Conference Room
- Lobby
- File Room
- Library
- Open Office Area

The rooms contained in these categories share enough characteristics that general fire models can be developed for them. The type of room occupancy, whether it be an office, library, lobby etc., has a strong influence on the type, amount, and configuration of the furniture located inside, as well as the rooms size. It will also determine, in general, what type of barriers a building will contain. They will also be important in factoring in the influence of smoke.

### 2.3.4 Building Design Fires

Multiple design fires must be introduced in order to address the full range of potential issues that may arise. Choosing a relatively large "design fire" to simulate what the firefighters will encounter has some advantages. A larger fire should produce less visibility, more heat, more smoke, more fatigue, and increased the rate of structural attack. These characteristics will make all of the buildings' architectural obstacles more difficult than they would be in a smaller fire, resulting in a conservative approach. In addition, if the resources to suppress a large fire are brought to bear in an adequate time, those same resources should be able to adequately suppress a small fire in the same rooms of a similar building. This is similar to the concept used in structural building codes for floor loading. If large loads can be handled, the smaller ones can be effectively ignored. In short, a building design that is adequate for large fires should be more than adequate for smaller ones.

Potential disadvantages in the choice of large design fires are:

- Worst case conditions may not be very useful for determining fire department intervention, as in using this methodology, there may theoretically be no building left standing when the fire department arrives.
- If an unreasonably large fire is chosen for the given scenario, the effects of smoke, heat, visibility and potential for structural collapse will be overestimated, and the potential of fire department intervention may be grossly underestimated. This can result in the recommendation of a costly redesign when none is necessary.
- Large design fires have the potential to make detection and location a simple matter, when under real conditions this is often not the case. It is important to address detection and fire location separately.

Three fire sizes will be developed. A fast fire, a medium fire, and a slow fire, in order to cover these possibilities. These fires should not be confused with the fires developed in NFPA 72. They will need a method to incorporate fire in the room of origin, but spread outside the room of origin as well.

Fires must be developed for the associated office building compartments for the type of building layout that is being studied. An associated model for the spread of fire to other compartments must also be developed.

It is important that information about smoke and heat in the burning compartments and their neighbors is available so the influence of these factors on firefighter movement can be established. For some occupancies such as office buildings, there is a large amount of generalized information available about ventilation and fire loading. Information about the building is vital to the development and integration of the overall model.

Fire models such as the zone model CFAST can be used to develop generalized design fires for individual compartment types. The output from these programs includes information on time to compartment flashover and smoke movement information outside the room of origin.

Information about different room types is provided in the work of Culver and Milke[6][9] These studies give sizes ventilation areas and fire loadings for different office building room configurations. These room types are modeled based on their contents and content layout[33]. If these categories can be effectively modeled, then any fire in an office building will be quantified. We will be choosing the more hazardous room layouts, as this is the most significant to firefighters, and measuring time for firefighter accessibility. Design layouts are included in the Appendix B for these rooms. Sizes for traditional offices can be divided many different ways. Table 2.1 shows the areas used for the design offices provided in Appendix B. This table also shows the vent areas that will be used in the development of medium and slow fires. The vent area for fast fires is taken to be the size of an open door.

For the purposes of demonstration, a set of theoretical design fires will be developed for office compartments. In order to construct such a design fire, it is necessary to obtain heat release rates for particular fire packages. This is done so that to flashover for individual rooms, and fire spread throughout buildings, can be modeled. In developing design fires we are particularly concerned with

| Type | Size | Area (Sq. Ft.) | Vent Area (Medium and Slow Fire) |
|---|---|---|---|
| Small Office | 10' x 11' | 110 | 80 Sq. ft. |
| Medium Office | 20' x 16' | 320 | 160 Sq. ft. |
| Large Office | 30' x 16' | 480 | 240 Sq. ft. |
| Conference Room | 14' x 21' | 294 | 112 Sq. ft. |
| Lobby | 11' x 14' | 154 | 88 Sq. ft. |
| File Room | 10' x 10' | 100 | 80 Sq. ft. |
| Library | 18' x 18' | 324 | 144 Sq. ft. |

Table 2.1: Office Areas and Vent Sizes

time from established burning to flashover. Established burning is defined as the point where the dominant heat transfer mode shifts from convection to radiation. Radiation feedback is assumed to occur when flames reach a height of approximately 10 inches. After this point, the fire grows much faster. The time to full room involvement is one of the most common calculations performed by fire protection engineers using computer models such as CFAST. There are a number of definitions of FRI including upper layer gas temperatures of 500 to 600 °C., or a radiative heat flux at the floor level of 20 $\mathrm{W/m^2}$.

Traditional fire zone models were used to develop the fire growth time line. Zone models describe the boundary between the hot upper layer and a cooler lower layer and most account for variations in room ventilation. A recent survey identified over 50 zone fire models in use in various countries worldwide.[40] The defacto standard in zone fire modeling in the US is the NIST model CFAST. It is commonly used in the firesafety community in the US in spite of the fact that its source code and specific documentation are not publicly available. Other zone models used include ASET, WPI/Harvard[34] and lesser known models developed by Tanaka [39] and others.

Models also have been developed to study the behavior of fire in structures such as ships and large buildings that containing ten rooms or more. The SAFE program was developed for the Coast Guard to determine the fire safety of cutters[7][14][36]. Input information was available in the form of statistical information on room dimensions, ventilation dimensions and other information pertinent to fire modeling[9]. The fire models used in the SAFE study lack the necessary detail for use in modeling fire service operations. Most notably they do not provide upper smoke and heat layer heights for burning compartments and their surroundings. Thomas' correlation and other simple flashover models also do not provide this information. The simple zone model ASET does provide layer height information but it does not allow changes in room ventilation parameters.

Estimated times for compartment flashover are developed in Appendix C and are shown in Table C.1.

### Compartmentation and Barrier Failure

Barrier effectiveness is important to fire fighting operations. In most cases, the important barrier failures will occur due to open doors and windows, and wall penetrations. These can be identified within the design fire model, so that potential fire paths can be identified once the room of origin has become fully involved. According to the Engineering Method [13] the states of a barrier at any given time are as follows.

- Barrier success which does not permit ignition in the adjacent space (B)
- Small, localized barrier failure ($\overline{T}$)
- Large, massive failure ($\overline{D}$)

A number of methods are available for the calculation of barrier failure. The most common are the Ingberg, Law, Pettersson, and Normalized Heat Load Models[11]. These methods utilize knowledge of relationships between boundary material properties and ventilation openings with the behavior of the compartment fire and its relation to the test furnace. Newton [23] concluded that the Normalized Heat Load Method was the method of choice for barrier failure. However, none of the methods was consistent through a full range of size, opening and fuel load values.

The rate of introduction of smoke into an adjacent compartment depends on pressure differences across common partition assemblies, and on their leakage characteristics. These pressure differences are caused by [12].

1. buoyancy arising from differences between internal and external ambient temperature
2. buoyancy created directly by the fire

3. effects of external wind and air movement
4. the air handling system within the building

Only the first three forces can be accounted for in zone fire models. Pressure differences generated by wind and changes in elevations, known as ”stack effect”, can be modeled in other ways.

After the fire size at first water application can be estimated with some degree of confidence, the next consideration is the relationship between fire size, available suppression resources, and the selection of offensive or defensive attack modes. These tactics will influence the water requirements for control and extinguishment.

## 2.4 Simulation

A simulation is the imitation of the operation of a real world system over time[18]

The five basic steps of problem solving are:

1. Define the problem
2. Collect Data and analyze it
3. Search for alternatives
4. Evaluate each alternative to determine which is best with respect to the performance criteria
5. Implement the selected alternative and follow up[15].

When simulating a system it is clear that the important details of the system must be accounted for. A few systems that need to be defined in order to perform an analysis. There is a *real system* separate from the people modeling it. This real system provides a source of data from which the model is to be constructed.[46] Different people usually have different ideas about the operation of the real system. These these ideas can be described in *conceptual models*. The *simulation model* may eventually become a mathematical model or a computer program that incorporates the conceptual model and is expected to be much simpler than the real system.

As shown in Figure 2.4 there are several ways to try out a system design before it is implemented.[30]

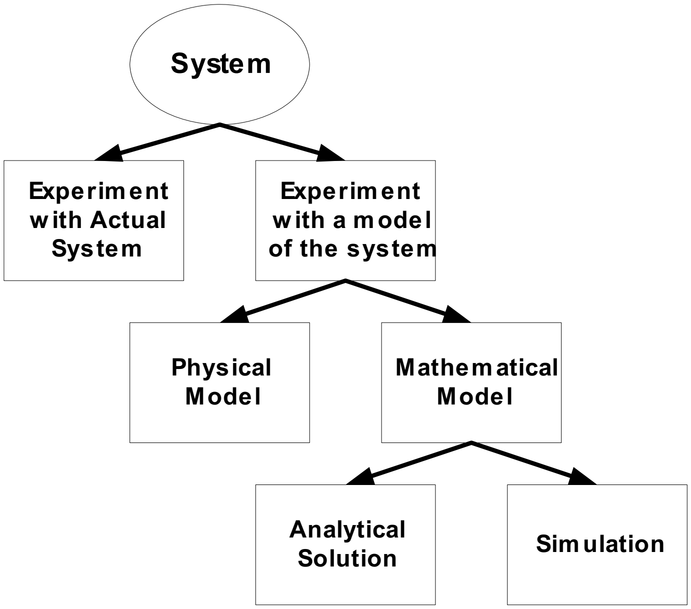

Figure 2.4: Ways to study a system (Law and Kelton, 2000)

- The policy could be tried in the real world in a controlled way so that its effects can be understood and analyzed. There are obvious problems with this approach as it pertains to firefighting. In the fire field in general experimentation can be very expensive (you need a building first to perform experiments on) and dangerous (you generally need to destroy it). This type of direct experimentation does have its place, especially when training people under controlled conditions.
- Another approach is to develop an analytical model of the system being studied. The basic problem is that the mathematics needed to represent a *very* complex system may be impossible to solve using first principles, or virtually impossible to formulate without excessive approximation. For truly complex systems the result is generally a system of differential or other equations that are difficult or impossible to solve with a closed form solution.
- The final option is to simulate the system of interest in a computer based model and them carry out experiments on that model to see what might be the best design to adopt in practice.

Computer simulation methods have been in use since the 1950s. They are based on the idea that an experimental approach can be a useful support to decision making.

The concern of this thesis is with the influence of building design on a firefighter's ability to get water onto a fire. If a proper simulation were developed, a building design could be evaluated before it is constructed or modified after it is constructed so that firefighters can get water onto a fire before the fire makes the building untenable. In other words the fire can be attacked before the firefighters move from an offensive mode to a defensive mode.

### 2.4.1 Continuous, Discrete and Mixed Simulation Approaches

Computer simulation approaches are normally classified into three groups - continuous, discrete, and mixed. It is important to note that these classifications are made by the modeler and are not distinctions that are made in the tangible system (the real world system being simulated).

#### Continuous Simulation

One popular approach is continuous simulation. The main building blocks of this approach are as follows:

- Aggregated Variables: The main concern in continuous simulation is with groups of entities instead of a concern with individual entities. For example, the smoke released from a chair is generally measured as an aggregated variable.
- Smooth Changes in continuous time: Rather than focusing on individual events, the emphasis in continuous simulation is on the gradual changes which happen as time progresses. The aim is to develop suitable equations to model the smooth changes of a variable. The lowering of the ceiling layer in a zone model is an example of a continuous change over time.
- Differential equations: Continuous models usually consist of a set of equations which define how behavior varies through time inevitably leading to a set of differential equations. In zone fire models these equations involve the accumulation of smoke and heat in the upper layer of

a room, and the leakage of smoke and heat from openings within the rooms.

### Discrete Event Simulation

Discrete event simulation (DES) is based on a number of building blocks as follows:

- Individual Entities: The simulation program tracks the behavior of each individual entity through simulated time. The entities can be individual objects (apparatus, firefighters, tools) or could be a group of objects (two firefighters moving a ladder, a group of firefighters on a hose line).
- Discrete Events: In DES each object's behavior is modeled as a sequence of events. An event is defined as a point in time when the entity changes state. For example, a firefighter may arrive on the scene of a fire, wait while another firefighter breaks open a locked door and then enter the building. The firefighter arrives (an event) and the door is broken down (another event ). The task of the modeler is to capture the distinctive logic of each of these events. The flow of simulation time in a discrete event simulation is not smooth. These intervals may be irregular as they move from event time to event time.
- Stochastic Behavior: The intervals between events is not always predictable. One example of this is that the time taken to break down the door may vary. There may sometimes be obvious and entirely predictable reasons for this (the door is made of steel vs. wood). There also may be no obvious quantifiable reason to explain things. In this case the varying intervals between events have to be modelled stochastically by using sampling models based on probability theory.

### Mixed Discrete/Continuous Simulation

In some cases both approaches are needed and the result is a mixed discrete-continuous simulation. An example of this might be a factory in which there is a cooking process controlled by known physics which is modelled by continuous equations. This is very similar to the type of model being

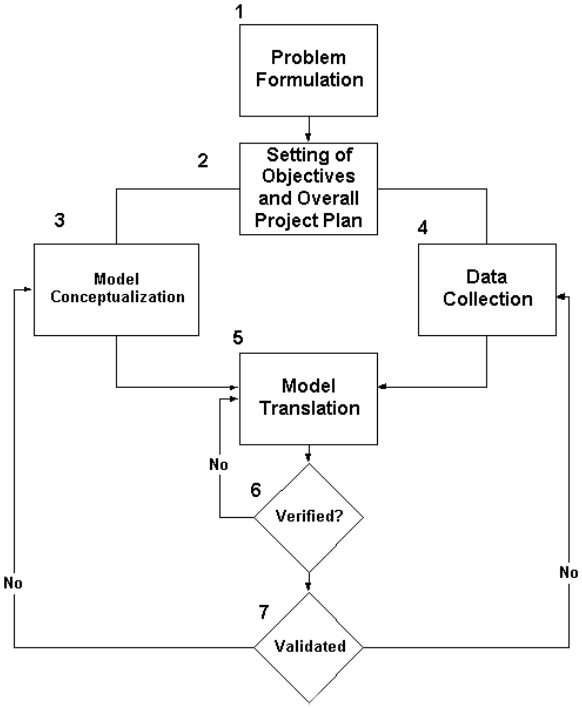

Figure 2.5: Simulation Study (Adapted from Banks, 1999)

developed here, where the physics of the fire is known and must be combined with a discrete event simulation describing firefighter movement.[30]

### 2.4.2 Steps in a Simulation Study

Figure 2.5 shows the steps in a simulation study. A detailed description of the steps in a simulation study are provided below.

**Problem Formulation.** Every study should naturally begin with a statement of the problem. If the statement is provided by policy makers, then the analyst must be sure that the problem described is clearly understood. It is also important that the policy makers agree with the analyst's formulation. There are occasions where the problem must be reformulated as the study progresses. It is generally known that there is a problem long before its exact nature is identified.

**Setting of Objectives and the Overall Project Plan.** The objectives simply indicate the questions that the simulation will answer. A statement of alternative systems and a method for evaluating the effectiveness of these alternatives should also be developed at this time if it is assumed that simulation is an appropriate method.

**Model Conceptualization.** The art of modeling is improved by the ability to simplify the essential features of the problem. A talent for selecting and modifying the basic assumptions that characterize the system until a useful approximation results is very important in this step. Model complexity does not need to exceed that required to accomplish the model's purpose. It is not necessary to have a one-to-one mapping between the model and the tangible system.

"Perhaps the best way of modelling complicated event logic is to bear in mind the *principle of parsimony.* This principle means that we need to keep things as simple as possible for as long as possible. This requires an evolutionary approach to modelling. The modeler starting with a deliberately over-simplified model. This model is gradually expanded until it is agreed to be valid for the intended use. The initially oversimplified model should represent the skeletal logic of the system. It should not be expanded until the modeler is happy with the validity of the skeleton model."[30]

One way of trying to ensure parsimony is to try to capture the essential system logic within some type of network diagram. Such diagrams can be drawn on-screen or described textually to a computer program which will itself generate the computer-based model from the diagram in some cases. Most commercial programs that do this lack flexibility. These models may force the system to conform to the program instead of forcing the program to conform with the system.

**Data Collection.** The objectives of the study indicate the kind of data that needs to be collected. As the model complexity changes the required data elements may also change. Data collection can take up a large portion of the total time to perform a simulation so it is advisable to begin collecting data as early as possible.

**Model Translation.** The model needs to be translated into a computer recognizable format. This step will be necessary whether the modeler chooses a general purpose simulation language or a special-purpose simulation software.

**Verification** This step refers to the computer program in the form in which it is translated. In this step it is simply determined if the program is working properly as written and their are no computer logic errors.

**Validation** Validating a model is the determination of whether the model is an accurate representation of the system it is attempting to describe. This is essentially calibrating the model. The model behavior and the actual system behavior are compared to improve the model.

The simulation model building shown in Figure 2.5 can be divided into two phases. Phase 1 consists of steps 1 and 2 (Formulation and Setting of Objectives). The initial statement of the problem is usually relatively unclear and the initial objectives may have to be reset. As a result the objectives may need fine tuning also.

Phase 2 consists of steps 3, 4, 5, 6, and 7 (Conceptualization., Data Collection, Model Translation, Verification and Validation) as shown in the Figure. A long period of interplay is required among these steps for the model to be developed correctly. This is the work that is being done in this study.

Two other phases of modeling are not shown here because they were not included in this dissertation. Phase 3 consists Experimental Runs, Production Runs and Additional Runs. This phase must have a well developed plan for experimenting with the simulation model for a particular building. A discrete event stochastic simulation is a statistical experiment and proper statistical analysis is required. This phase was only performed for test cases in this dissertation.

Phase 4 is the implementation phase. It involves Documentation and Implementation of the changes that the model specifies for a particular study (in this case a particular building). This step depends on the successful completion of every other step in the process.[18].

In this case only Phases 1 and 2 were performed. This entailed developing steps one through seven. A general model was developed and validated.

### 2.4.3 Components and Organization of a Discrete Event Simulation Model

Simulation describes a problem, process or system in terms of mathematical variables. Discrete event simulation is the processing of a repetitive set of instructions. The instructions define how the values for variables can change in relation to changing conditions. Conditions change because of the occurrences of events. A firefighter entering a staircase can be considered and event. A firefighter attaching hose to a standpipe can be considered another event. As each event occurs a set of computations is performed pertaining to it.

A **dynamic** and **discrete** event simulation model performs a repetitious sequence of instructions similar to the following:[15]

1. Determine what event type will occur next.
2. Set a simulation clock variable equal to the time of the next event
3. Update any statistical variables where required
4. Perform the actions (computations) associated with the most current event
5. Schedule a time for the next occurrence of that event type

Simulation modeling is an experimental technique and applied methodology which seeks

- to describe the behavior of systems
- to construct theories or hypotheses that account for the observed behavior
- to use these theories to predict future behavior or the effect produced by changes in the operational input set.

There are two approaches to discrete simulation: event-driven and process driven. Under event driven discrete simulation the modeler has to think in terms of the events that may change the status of the system used to describe the model. The status of the system is defined by the set of variables (measures of performance) being observed (e.g. number in a queue, status of a server, number of servers). Under the process driven approach the modeler thinks in terms of the processes that the dynamic entity will experience as it moves through the system.

Fire protection is generally concerned with the latter. In this case, the person at the nozzle can be considered as a dynamic entity. It is not a concern if individual resources are standing idle, as long as the overall process is running as fast as it can and these resources are available when needed in the process. This is much different than a business model where idle resources usually appear to be costing the client money. In firefighting, speed is of the essence. If some resources are idle, this may be acceptable.

The following components will be found in most discrete event simulation models.

**System State:** The collection of state variables necessary to describe the system at a particular time

**Simulation Clock:** A variable giving the current value of simulated time.

**Event List:** A list containing the next time when each type of event will occur

**Statistical Counters:** Variables used for storing statistical information about system performance.

**Initialization routine:** A subprogram to initialize the simulation model at time zero

**Timing routine:** A subprogram that determines the next event from the event list and then advances the simulation clock to the time when the next event will occur.

**Event routine:** A subprogram that updates the system state when a particular type of event occurs (there is one event routine for each event type)

**Library routines:** A set of subprograms used to generate random observations from probability distributions that were determined as part of the simulation model.

**Report Generator:** A subprogram that computes estimates (from the statistical counters) of the desired measures of performance and produces a report when the simulation ends.

**Main Program:** A subprogram that invokes a timing routine to determine the next event and then transfers control to the corresponding event routine to update the system state appropriately. The main program may also check for termination and invoke the report generator when the simulation is over.

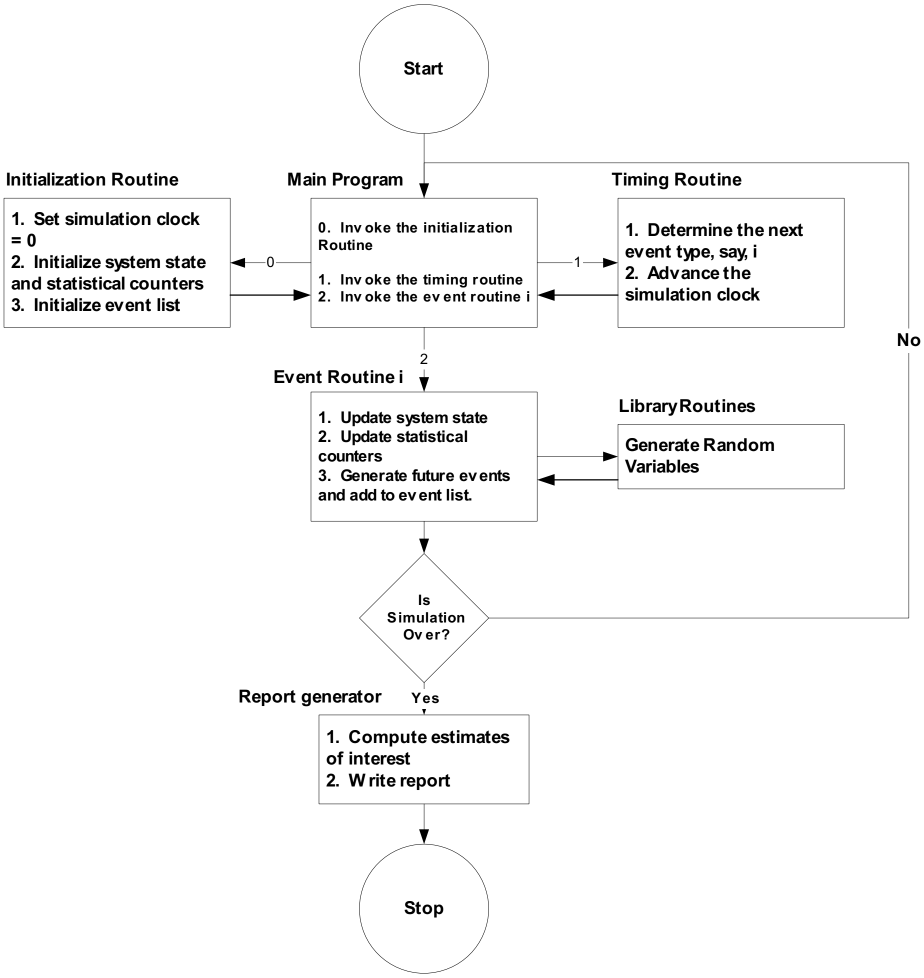

Figure 2.6: Components of a Discrete Event Simuation Model (Law and Kelton, 2000)

The flow of control among the components of a DES model are shown in Figure 2.6. At time zero the main program runs an initialization routine that sets the simulation clock to zero and initializes the system state statistical counters and the event list. Control is passed back to the main program when the initialization procedure is finished. The main program then invokes a timing routine to determine which event will happen next. If an event i is the next to occur the simulation clock is advanced to that time and control is returned to the main program. The main program then invokes event routine i. Typically three types of event occur:

1. The system state is updated to account for the fact that event i has occurred.

2. The statistical counters are updated, so that information about system performance can be gathered.
3. The time of future events is generated and this information is added to the event list.

A pseudo-random number stream is a sequence of numbers which would behave exactly as a stream of random numbers. An algorithm is used that produces a sequence with no discernible pattern. All values covered by the range of the random numbers occur equally often. In statistical terms, the sequence of numbers must be independent and uniformly distributed.[30]. This is usually achieved by a two stage sampling process which uses pseudo-random numbers. The two stage process is as follows

1. Generate 1 or more pseudo-random numbers
2. Convert these into samples needed by some suitable algorithm

A truly random number stream is a sequence of numbers produced by a device that is believed to be random. One example is a roulette wheel. Truly random numbers are almost impossible to generate at the rate which a computer program needs them. Millions of random numbers may be needed by a program. Another important consideration is that the numbers cannot be repeated.

After all of the processing has been completed either in event routine i or in the main program a check is made to determine if the simulation should now be terminated. If it is time to terminate the simulation the report generator is started from the main program. It computes estimates from the statistical counters of the desired measurements and develops a report based on these numbers. If it is not yet time for program termination control is passed back to the main program and the main program/timing routine, main program/event routine cycle routine are repeated until the stopping condition is satisfied.

The typical organization and actions of a discrete event simulation program are shown above. The approach shown above is called the event-scheduling approach. Another approach to DES is called the process approach. This instead views the simulation in terms of the individual entities involved. The code written describes the experience of a typical entity as it flows through the system. Even when taking this approach the simulation that is occurring in the background is identical to the event scheduling process that is described above.[21] The concern of this model is a series of events, and therefore the event scheduling approach is more appropriate. An example of where the process approach would be more appropriate is in an evacuation model, where hundreds or even thousands of people may be modeled, each having different processing rates when they arrived on different surfaces, or encountered different obstacles.

### 2.4.4 Software

Computer software plays an essential role in the development and the use of computer simulations and is available to support the following elements of simulation.

- Statistical analysis of input data: In a discrete simulation elements of the model will be calculated by taking samples from probability distributions. Therefore the modeler needs to consider which distributions are appropriate for the system being considered. This requires the modeler to collect data and to try to fit it to an appropriate distribution. Some programs available for doing this are Unifit and Simstat.
- Simulation model programming: Many programs are available for writing discrete event simulations. These include Simscript and GPSS/H as well as libraries in general purpose languages such as C or Pascal.
- Statistical output analysis: It is not always easy to interpret the results of simulation. This is especially true when one includes a large number of stochastic elements. The resulting output may need careful statistical analysis. There are tools to support this task and some are specifically for simulation modelling, such as Simstat and Stat::fit [8]. Others are the more generally available packages such as GPSS and SAS.[30]

### Choice of Discrete Event Simulation Model

The simulation engine is the portion of the simulator which performs the actual simulation. This is distinct from those parts of the tool which are concerned with presenting a friendly interface to the user. Several factors make GPSS/H a favorable choice in designing simulation systems. These include ease of learning, automatic output, compactness and low cost. "In addition GPSS has, due to its long history, has the great advantage that there are many program examples and much literature available, including over a dozen text books. The availability of well documented programs is important for the novice, when doing a project work, since he is them more likely to find a text book example to build upon" [37] There is also reason to believe that GPSS, with its more than 35 years tradition is better debugged than other simulation languages.

GPSS (General-Purpose Simulation System) is a process-oriented simulation language, originally developed for the modeling of queuing systems. GPSS models do not require external routines. The model environment consists of more than 60 statements represented by block diagrams. The activities to be performed are called *transactions* and their attributes are called *parameters.* The resources performing the services are called *facilities* or *storages.* They can be a single server or a group of parallel servers. [19]

There are many other discrete event simulation programs available. These include programs such as ARENA, Simscript, SIMPACK, UltraSAN and others. These programs have been developed over the years both commercially and by universities.

### Data Acquisition and Fitting

The verification that a population can be represented by some specified probability density function a common one in DES. The chi-square goodness-of-fit test is one possible statistical test to use under these conditions. The chi-square test requires at least a moderate sample size of about 15 with much larger sample sizes preferred. The Kolmogorov-Smirnov one-sample test was also developed for verifying a population distribution and can be used with small samples.

The objective of the Kolmogorov-Smirnov one-sample test is to test the null hypothesis that a the sample values of a random variable are likely to have been sampled from a specified probability distribution; the null hypothesis function must specify both the population distribution function and its parameters. The alternative hypothesis is accepted if the distribution function is unlikely to be the underlying function; this may be indicated if either the density function or the specified parameters are incorrect.

The test statistic is denoted as KS. It is the maximum absolute difference between the values of the cumulative distributions of a random sample and the probability distribution function specified in the null hypothesis. The Kolmogorov-Smirnov one-sample test may be used for small samples and is generally more efficient than the chi-square goodness of fit test when the sample size is small. The test is applicable for comparisons with continuous distributions.[1, p 253]

## 2.5 Discussion

Office buildings share similar characteristics not just in the types of room they contain, but also in their overall layout within the building. Office building layout and design is a very important element in the determination of flame spread outside the room of origin. Both modern and contemporary office buildings share many similarities.

In order to determine the influence of fire on manual suppression we must have a concept its size when a fire department arrives. The size of the fire will affect:

- Firefighter Visibility
- Heat experienced by the firefighter
- Fatigue experienced by the firefighter
- Rate of Structure Attack which could result in structural collapse

A set of design fires has been developed in Appendix C.

In order to develop a model of firefighting it is necessary to know the concepts and principles involved in firefighter intervention in a fire. Without a solid foundation in this area it will not be possible to develop an accurate and useful model. DES allows the integration of tactics using a common base of data. Broadly speaking the obstacles encountered across the world will not vary but variations in tactics for handling these obstacles do occur. It is extremely important to note these variations as they have direct influence on the design of the DES model.

One example is the use different tactics in setting up initial attack lines. One example from Australia:[41]

”Most metropolitan fire trucks have a hose reel drum on each side of the truck with 450 foot of 1 inch diameter preconnected high pressure rigid wall hose (operates at about 400 -450 psi). This will deliver about 40 US GPM and is often the first attack deployed whilst larger diameter hose is laid.

Most brigades carry 1 1/2 inch lay flat hose but not all use this as first attack. Australian Fire Brigades opted to use 2 inch diameter lay flat hose as attack hose rather than the 1 3/4 used by many US and other international fire department. Two brigades in Australia use 1 1/2 inch lay flat hose as first attack hose (after the first high pressure hose reel option) but this is really one nozzle operator whereas 1 3/4 is two nozzle operators and a good discharge quantity. Whereas many US brigades use 5 inch hydrant to truck feeder hose, in Australia many brigades still rely on multiple parallel 2 1/2 inch hose feeds.”

Another example is the preconnection of attack hose. Most departments in the US preconnect sections of attack line. In this way a large amount of hose can be pulled directly off of the pumper directly to the fire without taking the time to make connections. A notable exception to this rule is the Fire Department of New York (FDNY). FDNY connects each section of hose individually. They have the staffing to do this and find it a more flexible method.

Tactical variations must be accounted for in order that the model be as accurate and complete as possible.

In all known previous studies firefighter activity has been timed directly. This study was an attempt to simulate time. In order to properly simulate the time it takes firefighters to perform their tasks Discrete Event Simulation will be used.

DES is used to model real world processes that can be decomposed into a set of logically separate events. Each event in the process is assigned a time duration, usually based on an associated statistical distribution. The result of each event is a message passed to one or more other events. On arrival at this other event, the content of the message may result in the generation of new events at some specified future logical time. In this way, variations in time for individual events are combined to determine an overall process time. Using DES, it is possible to model the variability of events as well as any ”waiting” for other tasks that are performed concurrently by other firefighters. This ability is important in that it could be used to model variations in firefighter staffing.

The use of DES offers a number of advantages:

1. Many variations on the same system can be studied, without having to actually construct the system.
2. A simulation study can help in understanding how the system operates rather than how individuals think it operates
3. Insight can be obtained about the interaction of variables.
4. Insight can be obtained about the importance of variables.[18]

# Chapter 3

# Model Development

The goal of this dissertation is to develop a model to evaluate a building based on local fire department practices and resources. This chapter describes both how a model of setup time can be structured as well as how data for each of the events can be gathered so that a final realistic quantitative result can be obtained. It deals specifically with the elements called "Model Conceptualization", "Data Collection" and "Model Translation" described in 2.5 of the previous chapter. These elements will first be developed setting up a water supply and then a model of interior attack.

## 3.1 Model Conceptualization

Figure 3.1, adapted from Nunnemacher[24], demonstrates conceptually how two firefighters setting up a water supply in a forward hose lay. A pump apparatus arrives at a hydrant, and Firefighter2 alights the truck and wraps a supply line from the hose bed around the hydrant. The apparatus is driven by Firefighter1 to the proximity of the fire, extending hose from the bed as it moves. When the apparatus has moved a sufficient distance from the hydrant, Firefighter1 unwraps the hose from the hydrant and prepares the hydrant to supply water to the pump apparatus. Firefighter2 alights the truck at a position closer to the fire and sets up the pump for operation. When both firefighters have completed their tasks, the water supply is ready for use in attacking the fire.

Nunnemacher's conceptual diagram is necessary to define the operations about which data will be collected. It is important to note that Nunnemacher had experience with both fire protection engineering and firefighting. Without this experience, he may not have been able to develop a relevant flow chart.

It should also be noted immediately that the DES model of firefighter operations must incorporate parallel processes. When parallel processes occur, either process could be take the longer depending on conditions. The number of tasks performed by each firefighter and the variance involved in those tasks will influence the final outcome of each event

### 3.1.1 Model Events and Description

Initially the model was developed based to determine time to set up a water supply. Forward and reverse hose lays, as described in Appendix A were used to collect data on the individual events described in Appendix D. These events included the following activities:

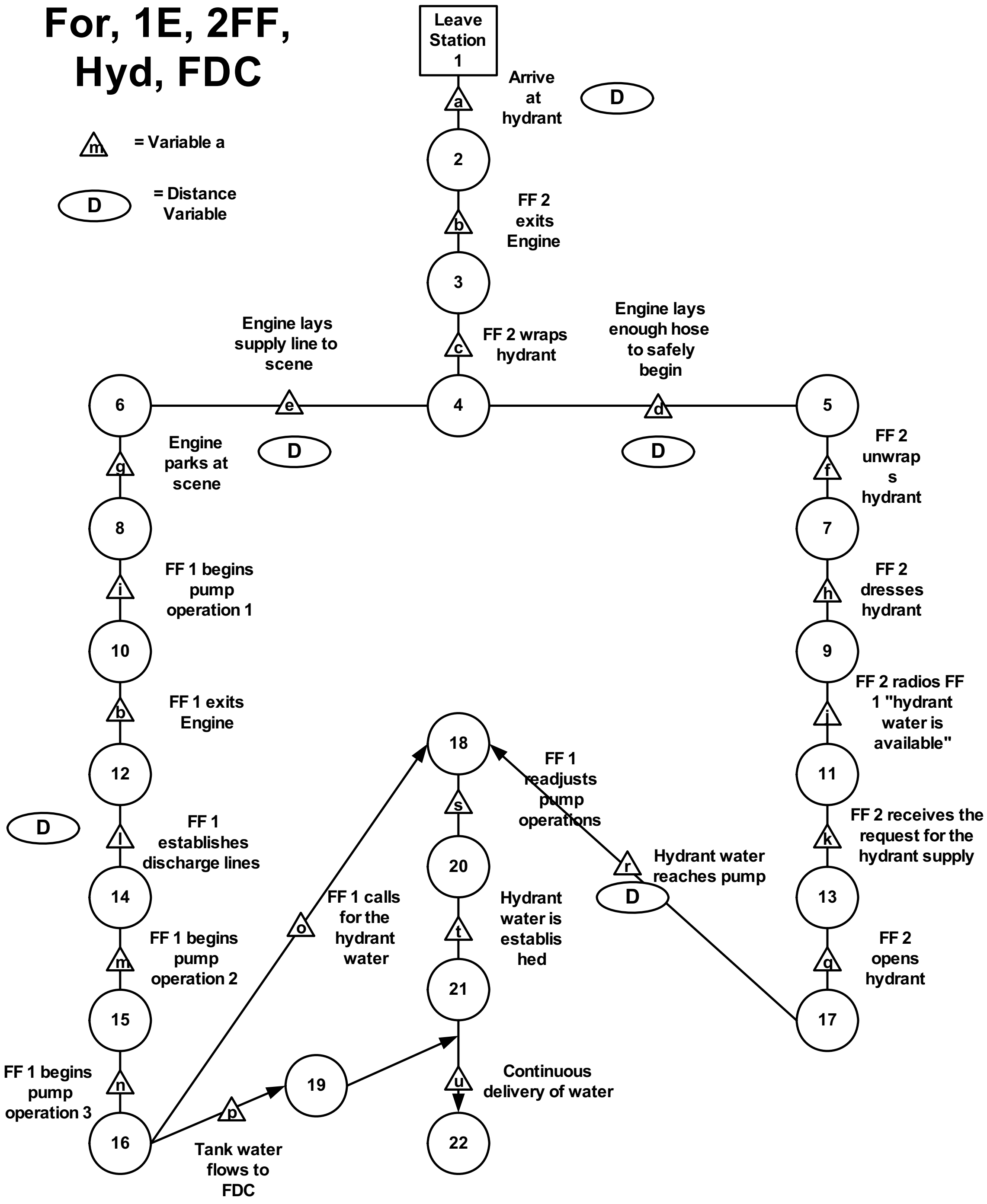

Figure 3.1: One Engine, 2 Firefighters, Hydrant to FDC

- Alight Truck
- Bring 2.5 in. Hose to Side of Truck
- Call and Receive Water
- Chock Wheels
- Clamp Supply Hose
- Connect Hose to Hydrant
- Connect Hose From Bed
- Connect LD hose to suction port
- Connect Nozzle
- Disconnect Hose From Bed
- Don SCBA
- Drop Supply Line (50')
- Extend 50' Attack
- Extend 150' Attack
- Extend 50' 2.5 in. Line - FF
- Extend LD hose
- Get Hose From Mattydale
- Pull Hose off Bed (100')
- Mount Truck
- Open Hydrant
- Pull Hose off Bed (100')
- Pump Operation 2
- Pump Operation 3
- Pump Runs Away
- Remove Ladder
- Remove LD hose
- Remove Tool
- Straighten Hose
- Take Hydrant
- Unchock Wheels
- Unclamp Supply Hose
- Wrap Hydrant

These events were chosen because they can be used to assemble models of water supply operations such as the forward and reverse hose lays.

## 3.2 Data Collection

Data for individual tasks was obtained by videotaping evolutions at the Stow Firefighting Academy in Stow Massachusetts. Examples of some of the video captured are shown in Figures 3.3 and 3.4. Over one hundred evolutions were witnessed and over fifty evolutions were video taped including forward hose lays, reverse lays and combinations. The use of video tape allowed the duration for individual tasks to be determined and for the tasks themselves to be more precisely defined. It

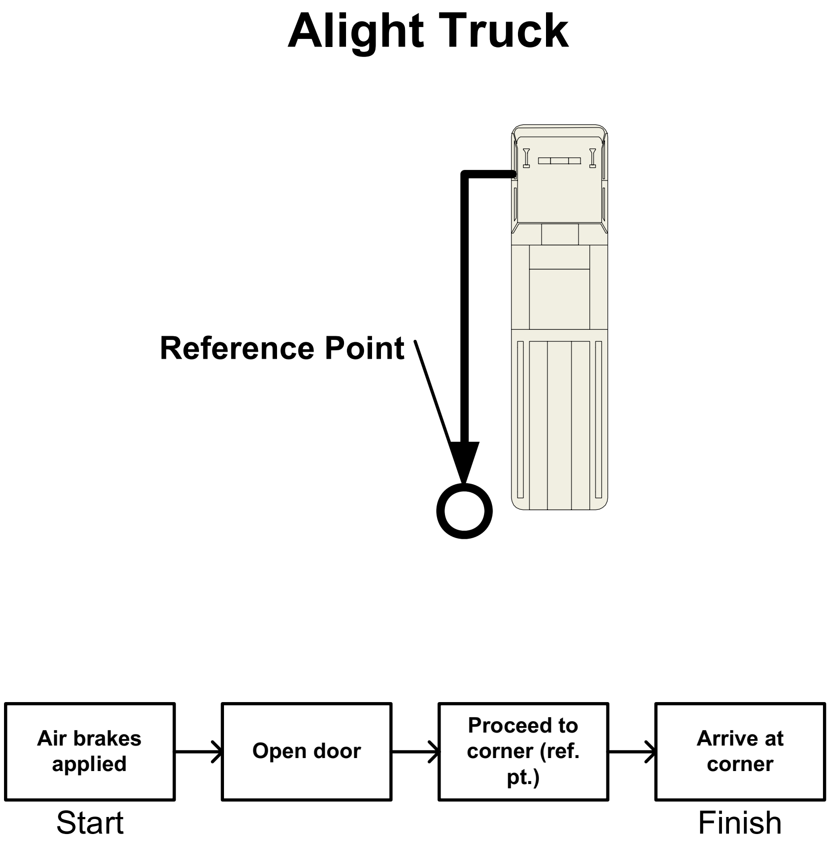

Figure 3.2: Alight Truck Experimental Design

also has the advantage that it is clear to all exactly what process is being modeled. Video was played back on a large screen television to insure that all details are properly accounted for.

To model a particular task as a discrete event that task must first be defined. It must have a definite start time and completion time. To illustrate the level of detail necessary for collected data, Figure 3.2 describes the process for alighting (dismounting) an apparatus. The entire procedure is clearly defined, and has a distinct start and finish. The time durations may be established for the complete event based on this figure.

The use of the particular reference point is defined because the firefighter will have to pass through this particular location to clamp a supply hose extended during either a forward or a reverse lay. Similar actions must define the other events, as is demonstrated in Appendix D. This allows the data provided to easily be incorporated with data collected in other efforts.

In addition the identified events will be used to develop more advanced models to determine time for interior attack and ultimately fire size for interior attack. For example the extend hose times can be used in interior and exterior operations.

For setting up water supplies, distances were correlated to the lengths of the attack hose and supply hose being used. Standard Operating procedures themselves were used to help correlate the events, as they defined the order of operations, and what each firefighter was doing in the course of the evolution.

Figure 3.3: Firefighters Removing Ladder from App.

The use of video tape allowed repeated playback of relatively complex exercises. This allowed the movement of each firefighter to be tracked individually so a large amount of data could be compiled. A video record of collected data also allows tactical differences between jurisdictions to be easily noted so that data to be more easily discussed and shared. The data collected is summarized in Table 3.1

| Descriptive Statistics | Minimum | Mean | Std. Dev. | Maximum |
|---|---|---|---|---|
| Alight Truck | 3 | 11.1 | 4.4 | 25 |
| Bring 2.5 in. Hose to Side of Truck | 4 | 8.3 | 3.3 | 15 |
| Call and Receive Water | 8 | 24.3 | 14.5 | 55 |
| Chock Wheels | 4 | 6.7 | 2.0 | 13 |
| Clamp Supply Hose | 14 | 25.1 | 8.4 | 40 |
| Configure Pump | 8 | 13.7 | 5.7 | 28 |
| Connect Hose From Bed | 5 | 31.5 | 16.4 | 61 |
| Connect Hose to Hydrant | 13 | 26.4 | 10.4 | 59 |
| Connect LD hose to suction port | 9 | 16.0 | 8.0 | 44 |
| Connect Nozzle | 13 | 26.5 | 10.4 | 49 |
| Disconnect Hose From Bed | 12 | 28.5 | 10.3 | 58 |
| Don SCBA | 38 | 67.2 | 20.4 | 136 |
| Drag Hose From Bed | 4 | 8.8 | 3.6 | 15 |
| Drop Supply Line (50') | 11 | 20.4 | 5.8 | 39 |
| Extend 150' Attack | 28 | 41.0 | 15.0 | 77 |
| Extend 50' 2.5 in. Line - FF | 16 | 21.3 | 5.1 | 36 |
| Extend 50' 2.5 in. Line - Pumper | 11 | 17.8 | 4.0 | 26 |
| Extend LD hose | 4 | 13.8 | 5.8 | 27 |
| Remove Hose From Mattydale | 16 | 25.0 | 13.2 | 65 |
| Mount Truck | 7 | 10.7 | 2.6 | 17 |
| Open Hydrant | 16 | 29.1 | 6.1 | 38 |
| Pull Hose off Bed (100') | 28 | 56.5 | 16.2 | 96 |
| Pump Operation 2 | 26 | 104.2 | 46.7 | 242 |
| Pump Operation 3 | 15 | 47.7 | 26.7 | 135 |
| Pump Runs Away | 8 | 12.8 | 4.2 | 25 |
| Remove Ladder | 16 | 29.8 | 8.0 | 56 |
| Remove LD hose | 11 | 18.2 | 5.9 | 29 |
| Remove Tool | 7 | 21.5 | 8.9 | 43 |
| Straighten Hose | 7 | 14.4 | 9.9 | 48 |
| Take Hydrant | 124 | 162.3 | 27.5 | 215 |
| Unchock Wheels | 6 | 9.0 | 2.4 | 15 |
| Unclamp Supply Hose | 21 | 36.7 | 12.1 | 58 |
| Wrap Hydrant | 15 | 20.8 | 5.3 | 30 |

Table 3.1: Summary of Collected Data (Normal Mean)

Figure 3.4: Apparatus Stops at Hydrant

## 3.3 Model Translation

The model needs to be input into a computer in a format the computer can manipulate. This format needs to take into account not only proper sequence of events, but also that each task is correlated properly in the model. These correlations must be mathematically repeatable so that distributions can be used within the Discrete Event Simulation model. In this particular case, each event must be translated into a function that the GPSS/H software can make use of.

### 3.3.1 Representations of Collected Data

A large number of tasks can be plotted on a histograms such as that shown in Figures 3.5 and 3.6. The two histograms show the time it takes individual firefighters to clamp a hose and alight a truck respectively. The first histogram contains 12 data points and the second 102. An explanation of how the exact start and end points was determined for each data point in these histograms is contained in Appendix D. A histogram is a good starting point in developing a model, in that it can show whether a distribution is skewed. In the case of both the clamp hose histogram as well as the alight truck histogram, both are skewed to the right. This skew suggests that a normal distribution (a bell curve with the arithmetic mean at the highest point) may not be the best representation of this task.

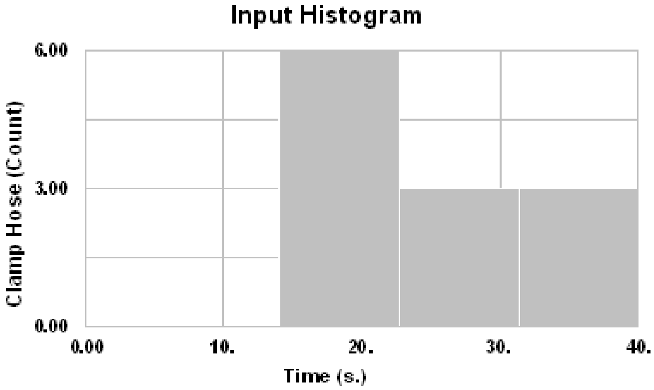

Figure 3.5: Histogram - Clamp Hose

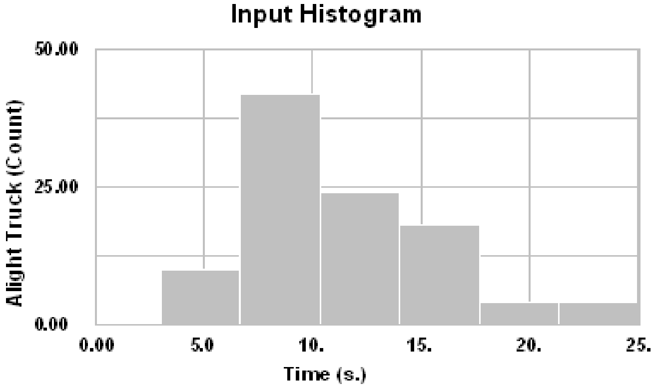

Figure 3.6: Histogram - Alight Truck

A mathematical description provides a more compact way to describe and reproduce the distribution and is the most desirable form to obtain. In Simulation Modeling and Analysis, Law and Kelton suggest that a lognormal distribution is a good distribution to choose to model the "Time to perform some task". While the a posteriori knowledge of other researchers provides a good basis for suggesting a lognormal distribution would provide the mathematical model needed, other tests can be used to reinforce this assumption. One method to identify the appropriateness of a particular distribution is the Kolmogorov-Smirnov, or K-S test. This test is particularly valuable in for this study because it can be used to draw conclusions from small test samples, even samples as small as the 12 points contained in the clamp supply hose sample.[1]

### 3.3.2 The K-S Test for Fitting Collected Data

Statistical distributions were developed for each task and the Kolmogorov-Smirnov (K-S) test was used to insure that a lognormal distribution accurately and adequately described the task duration data. The Kolmogorov-Smirnov (K-S) is a goodness-of-fit test. It is used to test whether a particular population conforms to a particular theoretical distribution. The requirements of the K-S test are as follows:

- Randomness: Sample scores (X) must be randomly drawn from the population.
- Independence: Sample scores must be independent of each other.
- Scaling: The categories must be ordinal, interval, or ratio.

These requirements are listed in approximate order of importance. Violations of the these three requirements are "fatal". Even slight violations of the first two requirements can introduce large errors in the computation of the values used to establish the statistical correlation (p-values).

The Null Hypothesis for the K-S test is that the distribution of a population of interest is the same as a theoretically derived distribution. When the K-S statistic is less than the calculated statistic, the fitted distribution provides a good representation of the observed task duration data. For the task duration data collected at the Massachusetts Firefighting Academy, the lognormal distributions provide a good fit at a level of significance of 0.05. The .05 level of significance is commonly used as a basis for determination of fit.

The procedure described above will be demonstrated by using it to develop a distribution for the time it takes to clamp a hose. While mundane, it is a critical task for firefighters because the ability to clamp off a hose allows it to be pressurized while still allowing the unpressurized side to be moved and connected to other hoses.

The K-S test uses the following six steps:

1. State the null and alternative hypotheses in terms of the proposed probability density function and its parameters. In this case the null hypothesis is "Is it safe to conclude that the sample is drawn from a lognormal distribution with a mean of 25.1 and a standard deviation of 8.3?"
2. The test statistic is the maximum absolute difference between the cumulative function of the sample (Fs) and the cumulative function of the probability function specified in the null hypothesis (Fx). The cumulative function for the sample (Fs) can be determined by rank-ordering the sample values. The step function that results can be used to determine the maximum absolute difference (KS) with the computed Fx(x) at any value of X. The sample cumulative function can be computed as :$F_x(x) = \begin{cases} 0 & x < x_1 \\ \frac{1}{n} & x_i \leq x_{i+1} \\ 1 & x > x_n \end{cases}$
3. The level of significance is set. In this case 0.05 was used.
4. A random sample is obtained and the sample cumulative probability function computed. Then the value of the test statistic should be computed.
5. The critical value is determined by the level of significance and the number of data points.
6. The null hypothesis is rejected if the computed value is greater than the critical value.

This procedure was carried out as shown in the Table 3.2. The null hypothesis is with a level of significance of 0.05, is it safe to conclude that the sample is drawn from a lognormal distribution with a mean of 25.1 and a standard deviation of 8.3.

| **Rank** | **X** | $\mathbf{X - Min(X)}$ | $\mathbf{F_s(x_i)}$ | $\frac{\mathbf{(Rank-1)}}{12}$ | $\mathbf{ln(x)}$ | **Dist.** | $KS$ $\frac{I}{\mathbf{n-f(x)}}$ | $\mathbf{KS - f(x)} - \frac{(I-1)}{n}$ |
|---:|---:|---:|---:|---:|---:|---:|---:|---:|
| 1 | 14 | 0 | 0.08 | 0 | 0 | 0 | 0.083 | 0 |
| 2 | 19 | 5 | 0.17 | 0.08 | 1.609 | 0.1204 | 0.046 | 0.037 |
| 3 | 19 | 5 | 0.25 | 0.17 | 1.609 | 0.1204 | 0.13 | -0.046 |
| 4 | 19 | 5 | 0.33 | 0.25 | 1.609 | 0.1204 | 0.213 | -0.13 |
| 5 | 21 | 7 | 0.42 | 0.33 | 1.945 | 0.2713 | 0.145 | -0.062 |
| 6 | 22 | 8 | 0.5 | 0.42 | 2.079 | 0.3501 | 0.15 | -0.066 |
| 7 | 23 | 9 | 0.58 | 0.5 | 2.197 | 0.4256 | 0.158 | -0.074 |
| 8 | 24 | 10 | 0.67 | 0.58 | 2.302 | 0.4957 | 0.171 | -0.087 |
| 9 | 28 | 14 | 0.75 | 0.67 | 2.639 | 0.7099 | 0.04 | 0.043 |
| 10 | 32 | 18 | 0.83 | 0.75 | 2.89 | 0.8351 | -0.002 | 0.085 |
| 11 | 40 | 26 | 0.92 | 0.83 | 3.258 | 0.9442 | -0.027 | 0.11 |
| 12 | 40 | 26 | 1 | 0.92 | 3.258 | 0.9442 | 0.056 | 0.027 |
|  | 25.08 |  |  |  | 2.309 |  | 0.212 | 0.111 |

Table 3.2: KS-Statistic Calculation for "Clamp Hose" Event

The KS test proves that the equation describes the information adequately.

The largest absolute deviation (called the maximum deviation D) is the test statistic. For small samples ($n < 35$) a table of critical values of D may be consulted to determine if there is sufficient evidence to merit rejecting the Null Hypothesis. Since $n = 12$ in this case, for a level of significance alpha of 0.05, the critical value is 0.375. Since the calculated KS statistic is 0.212, the lognormal assumption cannot be rejected.

In this case therefore, the “clamp hose” distribution can be described by a lognormal distribution. The KS statistic calculation matches exactly that calculation made with Stat::Fit[8] distribution fitting software, which drew the same conclusion, and which produced the graph shown in 3.7 and 3.8. The software was particularly valuable in that it helped automate the calculation of the KS statistic for all of the distributions obtained, particularly those such as the alight truck distribution that contained over 100 data points.

The Stat::Fit software was used to do correlations for all of the data collected. All of the distributions passed the test as lognormal distributions, and these results are summarized in Appendix D. Many of the distributions did not pass the K-S test as normal distributions, including the ”Alight

Truck" distribution shown.

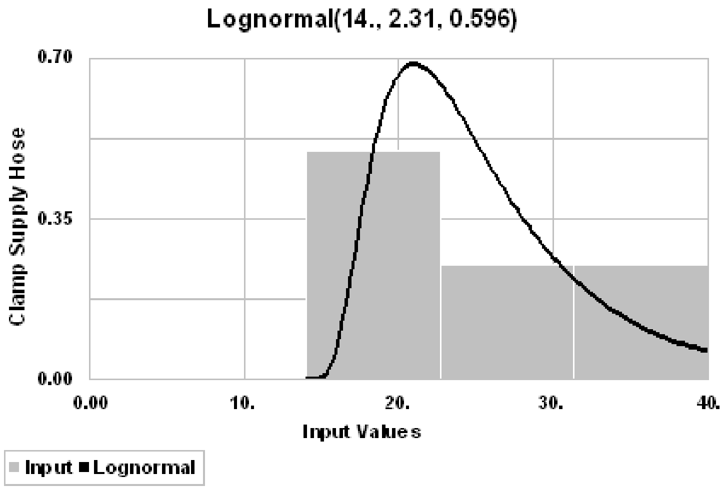

Figure 3.7: Fitted Distribution - Clamp Supply Hose

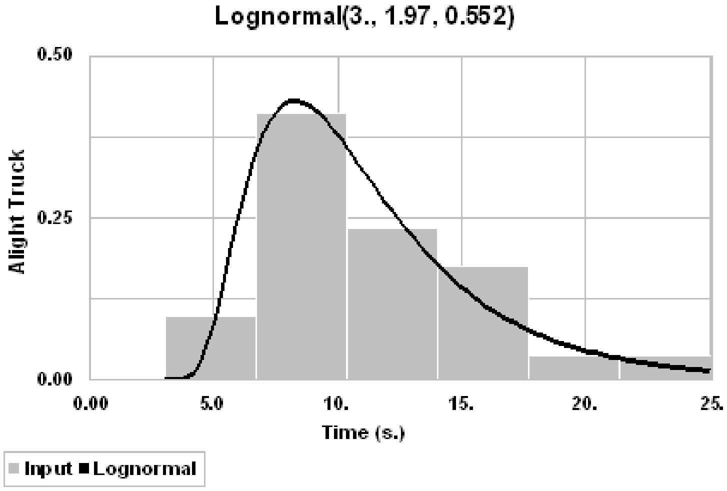

Figure 3.8: Fitted Distribution - Alight Truck

### 3.3.3 Use of Generated Distributions within the DES Model

It was assumed that the task data collected and used to generate the distributions was random. This assumption is necessary, and is best summarized best summarized from this quotation from a paper by Pidd:

> The idea of random sampling is to ensure that a set of samples is produced that is representative of the distribution from which they were taken and within which set no pattern is evident. This is usually achieved by a two stage sampling process which uses pseudorandom numbers. A truly random number stream is a sequence of numbers produced by a device which is believed to be random - for example a roulette wheel, which some people find curiously interesting. Truly random numbers streams are not used in discrete simulations because most such devices are slow (millions of random numbers may be needed) and also they cannot be repeated - an important consideration, as will become clear shortly. A pseudo-random number stream is a sequence of numbers which behave exactly as a stream of random numbers would be expected to behave but which is produced by a well-understood mathematical process.. Thus, when the sequence is examined, there is no pattern in the sequence and all values covered by the range of the random numbers occur equally often. In statistical terms, the sequence must be independent and uniformly distributed with a dense coverage of the range of values.[30]

The two stage process described by Pidd is as follows.

- Generate 1 or more pseudo-random numbers.
- Convert these into the samples needed by some suitable algorithm.

The computer program used to generate the random numbers used in this study is GPSS/H. This program makes use of a random number algorithm originally proposed by Lehmer, which is one of the most commonly used random number algorithms in computing and its origins will not be repeated here. The algorithm is deterministic, which means that the random numbers resulting from its use are reproducible, and are therefore considered not truly random, but pseudorandom. This actually has advantages, as it makes finding mistakes in simulations such as this one easier. The important fact is that for statistical purposes, the numbers produced by the program appear

| UPPER LIMIT | OBSERVED FREQ | PERC. TOT. | CUM. PERC. | DEV. FROM MEAN |
|---:|---:|---:|---:|---:|
| ... | | | | |
| 6 | 1 | 10 | 10 | -1.7081 |
| ... | | | | |
| 9 | 1 | 10 | 20 | -0.7654 |
| 10 | 1 | 10 | 30 | -0.4512 |
| 11 | 1 | 10 | 40 | -0.137 |
| 12 | 2 | 20 | 60 | 0.1773 |
| 13 | 1 | 10 | 70 | 0.4915 |
| ... | | | | |
| 15 | 2 | 20 | 90 | 1.1199 |
| ... | | | | |
| 17 | 1 | 10 | 100 | 1.7484 |

Table 3.3: Alight Truck Equation Output - 10 Data Points

random, so that the simulation will produce the proper output.

The Stat:Fit used to perform the K-S test was also used to convert the distributions developed from collected data into input expressions that were used in GPSS/H. The following equation will produce a lognormal number stream describing the alight truck sequence described in the previous section. This equation in effect combines the two steps described previously by Pidd by calling on GPSS/H's internal random number stream. The equation is described as follows:

3+RVLNOR(1,8.33,24.8)

The first number merely describes an arithmetic offset. The arithmetic average is provided separately so that the equation can be normalized, and the log function will operate properly. The first number in parenthesis is the number of the random number stream provided by GPSS/H. The second is the lognormal mean, and the third is the variance. With this equation GPSS/H can simulate a firefighter alighting a truck thousands or even millions of times. This can then be combined with other tasks as described later.

The results are shown for calling it 10, 100, and 1000 times in Figure 3.9. It can be seen that after many numbers are called, the distribution begins to look like the full mathematical distribution for "Alight Truck" shown in Figure 3.10.

| UPPER LIMIT | OBSERVED FREQ. | PERC. TOT. | CUM. PERC. | DEV. FROM MEAN |
|---:|---:|---:|---:|---:|
| ... | | | | |
| 6 | 5 | 5 | 5 | -1.0933 |
| 7 | 4 | 4 | 9 | -0.9004 |
| 8 | 15 | 15 | 24 | -0.7075 |
| 9 | 8 | 8 | 32 | -0.5147 |
| 10 | 10 | 10 | 42 | -0.3218 |
| 11 | 7 | 7 | 49 | -0.1289 |
| 12 | 16 | 16 | 65 | 0.064 |
| 13 | 6 | 6 | 71 | 0.2569 |
| 14 | 4 | 4 | 75 | 0.4497 |
| 15 | 9 | 9 | 84 | 0.6426 |
| 16 | 5 | 5 | 89 | 0.8355 |
| 17 | 4 | 4 | 93 | 1.0284 |
| 18 | 1 | 1 | 94 | 1.2213 |
| 19 | 1 | 1 | 95 | 1.4141 |
| 20 | 1 | 1 | 96 | 1.607 |
| ... | | | | |
| 23 | 1 | 1 | 97 | 2.1856 |
| ... | | | | |
| 27 | 1 | 1 | 98 | 2.9572 |
| ... | | | | |
| OVERFLOW | 2 | 2 | 100 | |

Table 3.4: Alight Truck Equation Output - 100 Data Points

It can be seen in Figures 3.10 and 3.9 that with an increasing number of data points, the GPSS/H distribution approximates the histogram developed from the collected data. As more data points are generated, the curves will more closely approximate each other.

The model output will consist of a distribution of answers for the particular task being studied. For example, the overall task of setting up a water supply using a forward hose lay may present a distribution of frequencies of times. These frequencies will be dependent on the number of firefighters, the locations of the firefighters relative to the apparatus, and other physical factors.

The model outputs can also be applied to the interior of buildings by making the assumption that firefighter tasks would take the same time indoors as they would outdoors, if interior conditions such as smoke and heat were taken into account in the firefighters posture (creeping, crawling, etc).

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| UPPER LIMIT | OBSERVED FREQ. | PERCENT OF TOTAL | CUM. PERCENT | DEV.FROM MEAN |
|---:|---:|---:|---:|---:|
| 5 | 11 | 1.1 | 1.1 | -1.2568 |
| 6 | 45 | 4.5 | 5.6 | -1.0665 |
| 7 | 79 | 7.9 | 13.5 | -0.8762 |
| 8 | 99 | 9.9 | 23.4 | -0.686 |
| 9 | 99 | 9.9 | 33.3 | -0.4957 |
| 10 | 127 | 12.7 | 46 | -0.3054 |
| 11 | 89 | 8.9 | 54.9 | -0.1152 |
| 12 | 89 | 8.9 | 63.8 | 0.0751 |
| 13 | 70 | 7 | 70.8 | 0.2654 |
| 14 | 58 | 5.8 | 76.6 | 0.4556 |
| 15 | 45 | 4.5 | 81.1 | 0.6459 |
| 16 | 49 | 4.9 | 86 | 0.8362 |
| 17 | 36 | 3.6 | 89.6 | 1.0264 |
| 18 | 20 | 2 | 91.6 | 1.2167 |
| 19 | 10 | 1 | 92.6 | 1.407 |
| 20 | 13 | 1.3 | 93.9 | 1.5972 |
| 21 | 5 | 0.5 | 94.4 | 1.7875 |
| 22 | 9 | 0.9 | 95.3 | 1.9778 |
| 23 | 11 | 1.1 | 96.4 | 2.168 |
| 24 | 3 | 0.3 | 96.7 | 2.3583 |
| 25 | 10 | 1 | 97.7 | 2.5486 |
| 26 | 1 | 0.1 | 97.8 | 2.7388 |
| 27 | 6 | 0.6 | 98.4 | 2.9291 |
| 28 | 1 | 0.1 | 98.5 | 3.1194 |
| 29 | 2 | 0.2 | 98.7 | 3.3096 |
| OVERFLOW | 13 | 1.3 | 100 | |

Table 3.5: Alight Truck Equation Output - 1000 Data Points

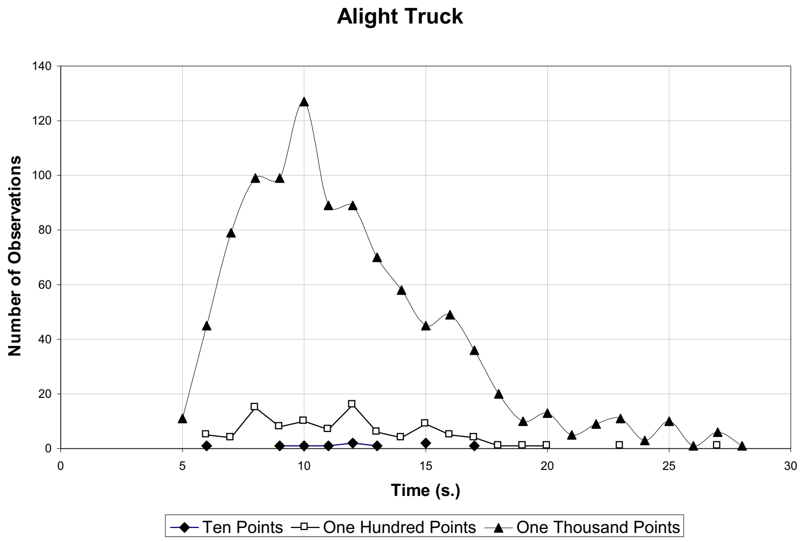

Figure 3.9: Alight Truck - Observations Generated with GPSS

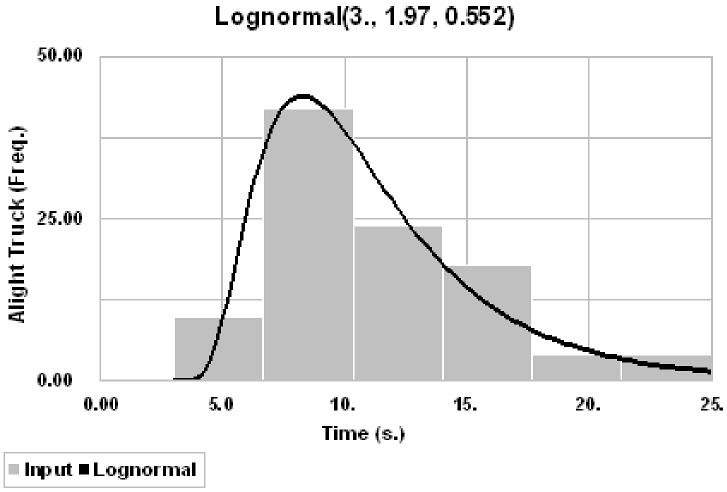

Figure 3.10: Alight Truck - Curve Fitted to Collected Data

### 3.3.4 Case 1 - Development of the Forward Hose Lay Model

When an underground water supply is not available, the water must be obtained from other sources. Drafting water from surface sources and transporting water in tank trucks must be done in this situation. Fire departments generally have standard operating procedures to set up water supplies. Using standard operating procedures for establishing water, in conjunction with knowledge of the site will enable an evaluation of the time it takes to establish a reliable, continuous water supply. The standard operating procedures outline a series of tasks that need to be performed. Experiments can be developed to determine the duration of these tasks. Depending on whether the experiments are run in parallel or in series will tell us how long it will take to set up a water supply, depending on factors such as the number of firefighters available, the location of water supplies, and weather conditions. The operational plan for two firefighters setting up a water supply from a fire apparatus is shown again in Figure 3.11.

In this case however, it is shown with distributions representing each of the tasks. It shows the parallel tasks of ”taking” a fire hydrant (setting up a hydrant to supply water), and setting up a supply line to a apparatus that is positioned closer to the fire. There are two main possible critical paths, one at the hydrant, and one that forks through the pumper apparatus operations. It is unclear which of the paths will be critical, and it is possible that merge bias will be an issue here. Generally in larger cities the fire hydrants are located a certain distance apart (in Worcester, MA the distance is 500'). Therefore in a city the maximum distance a apparatus should have to move is about half of the hydrant spacing. Based on the numbers provided, the critical path is unclear in this case, and DES should be used. In remote areas volunteer firefighters will probably be utilized. Since the arrival times of individual firefighters may be different, depending on policy, again, it appears that DES is the proper method.

To use GPSS/H to perform a discrete event simulation, these distributions can be input into a block diagram and put into GPSS is demonstrated in 3.12. Each block represents a distribution similar to the 3+RVLNOR(1,8.33,24.8) "Alight Truck" distribution described at the beginning of the chapter. The program begins and generates one value for each of the blocks described which represent a task distribution. The program will then sum these numbers to come up with an overall time for the evolution.

In the case of a parallel task, as Match block will be used, as shown in Figure 3.12. In this case, the parallel tasks for that particular loop will be added, and the highest number will be taken and used, so that the longest time is considered. Because a different random seed is used for all the tasks, and because thousands of random numbers can be generated and added, and overall distribution for the overall task can be generated.

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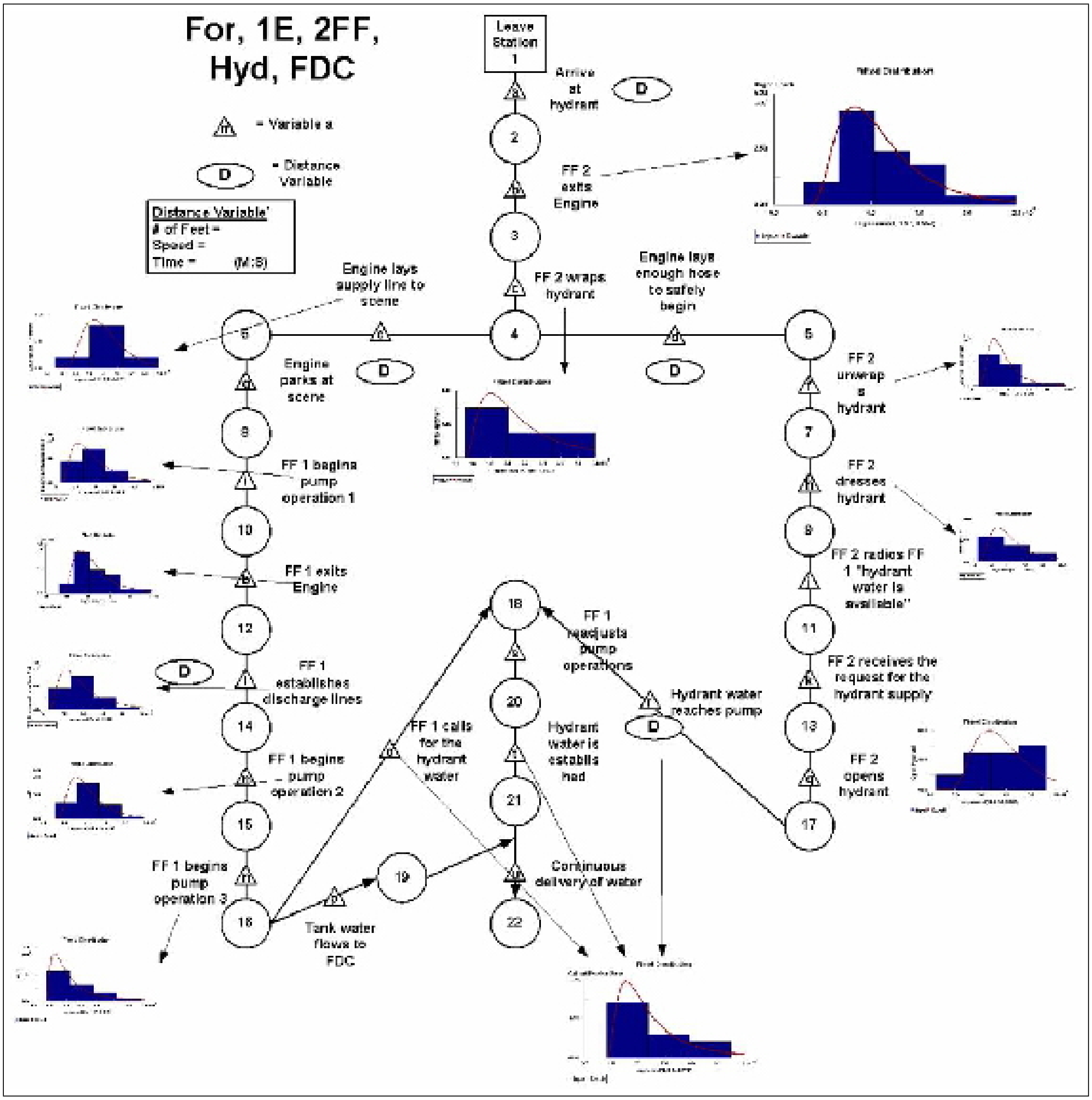

Figure 3.11: Flow Chart - One Engine, 2 Firefighters, Hydrant to FDC

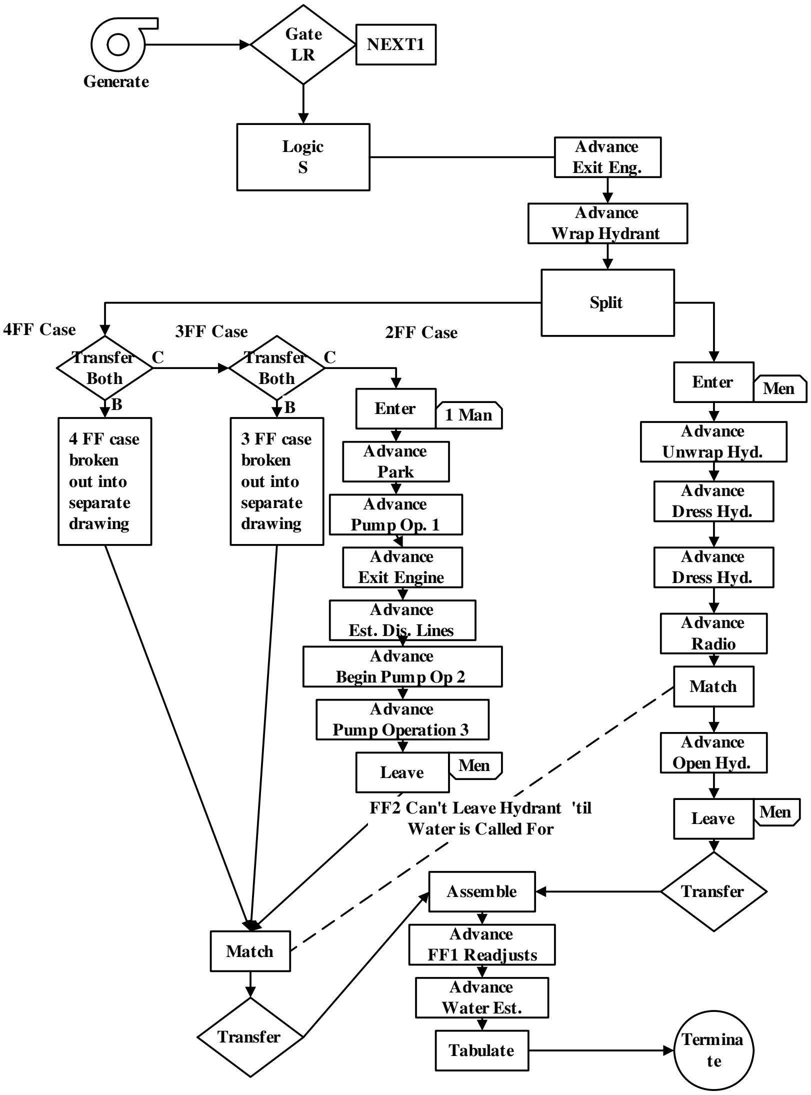

Figure 3.12: GPSS Flow Chart - Forward Hose Lay

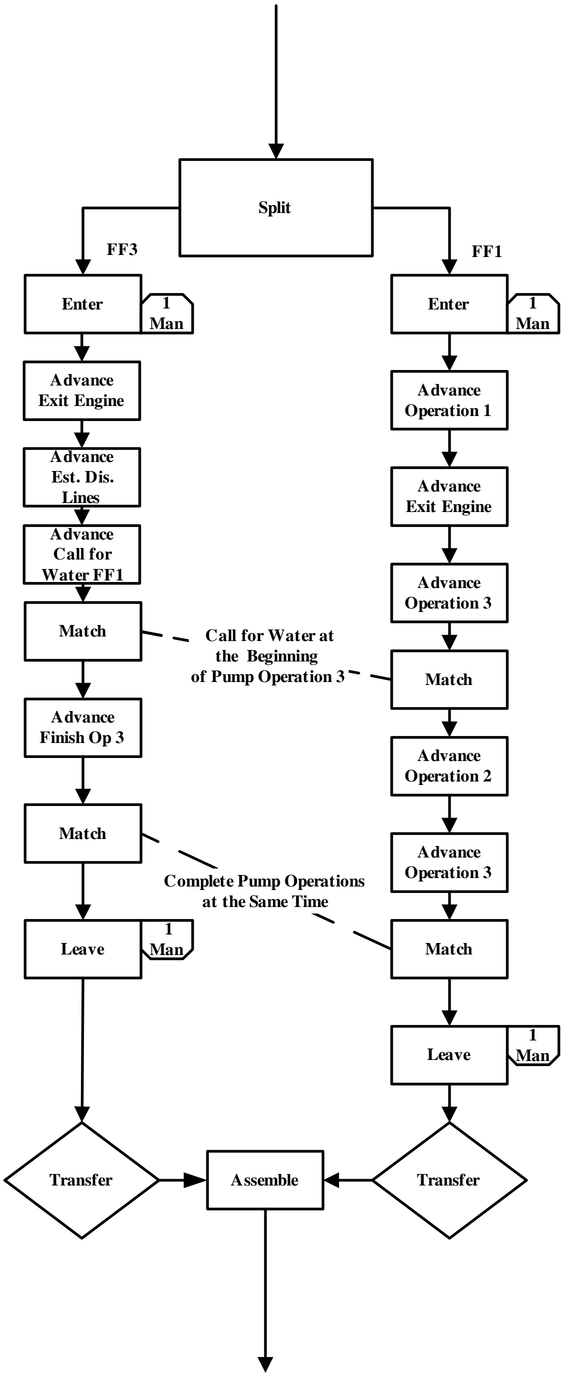

Figure 3.13: Flow Chart - Three FireFighter Breakout

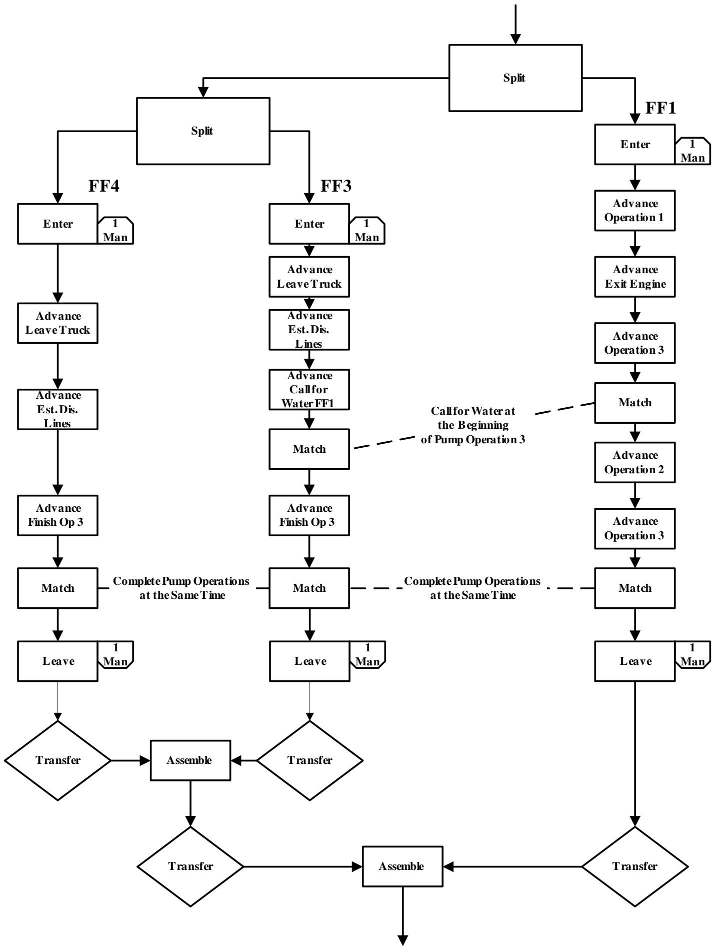

Figure 3.14: Flow Chart - Four Firefighter Breakout

The GPSS code that was developed for the 2, 3 and 4 firefighter hose lays is included in Appendix F.

### 3.3.5 Case 2 - Development of the Reverse Hose Lay Model

A reverse hose lay involves setting up a staging area and then moving a pump apparatus to the water supply. The nozzle operator relies on tank water until a permanent water supply can be established. Often the nozzle operator will run out of tank water before a permanent line is established.

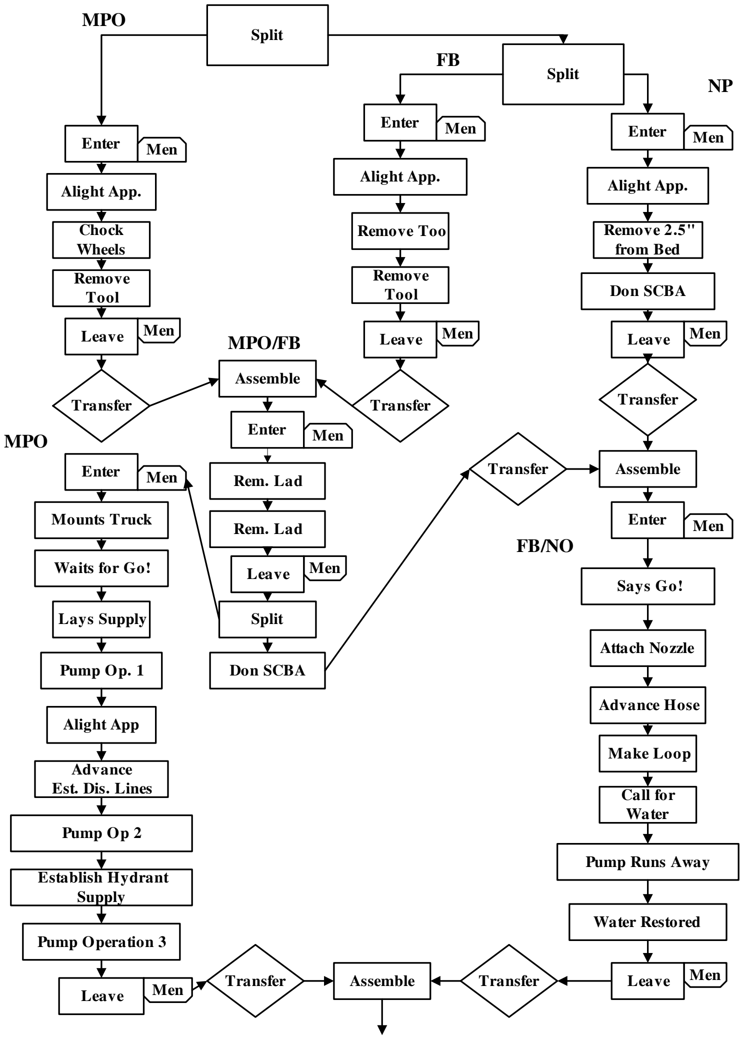

Figure 3.15: Flow Chart - Reverse Hose Lay - 3 Firefighters

A flow chart of a reverse hose lay is shown in Figure 3.15.

The input model developed from these diagrams is included in Appendix F.

## 3.4 Model Verification and Validation

Model verification is simply making sure that a simulation runs and properly represents the input logic. Model validation is the determination that a model is an accurate representation of a real system.[18] In order to validate a model it is necessary to obtain information concerning entire fire department training procedures from start to finish. Common training procedures are forward hose lays and reverse hose lays. In a forward lay, a hose is extended from a water source, a pump apparatus is set up closer to the fire, and an attack hose is extended from the pumper. In a reverse hose lay a hose and firefighters are dropped off at or near the building from the pump apparatus, and the apparatus is then moved to the water source to set up a continuous hose stream. The model developed will be compared to the results of NFPA 1410 which summarizes typical times for forward and reverse hose lays.

For interior tactics the model will be compared to the results of the Louisville Study published in 1994[32], as it is the best source of time and motion data available for comparison purposes

Output for two and three firefighters for this forward hose lay are shown in Figures 3.16,3.17, and 3.18

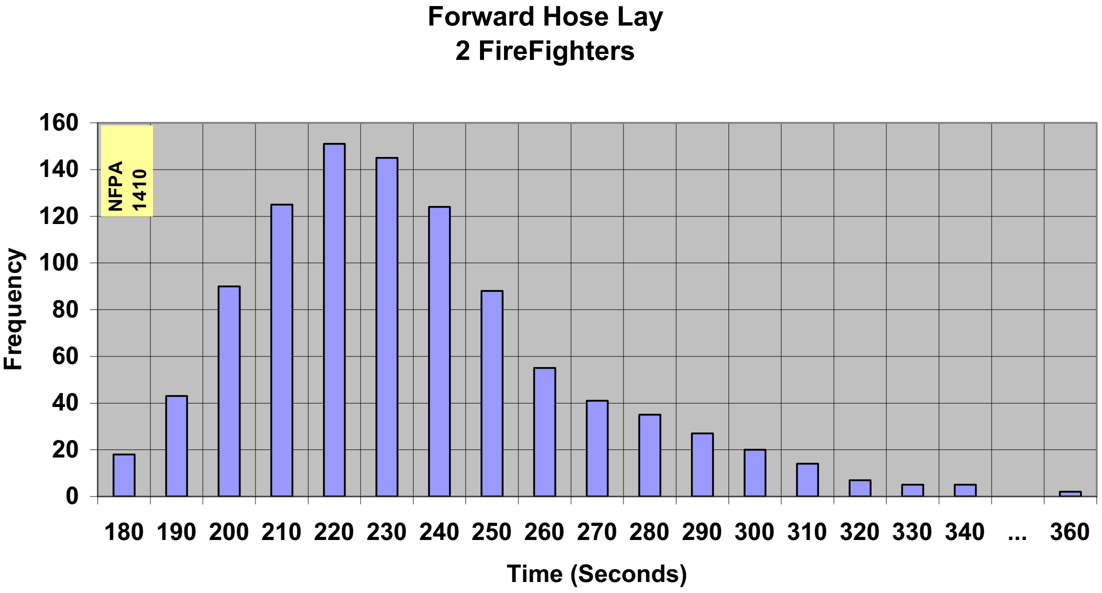

Figure 3.16: Output - Forward Hose Lay Results - Two Firefighters

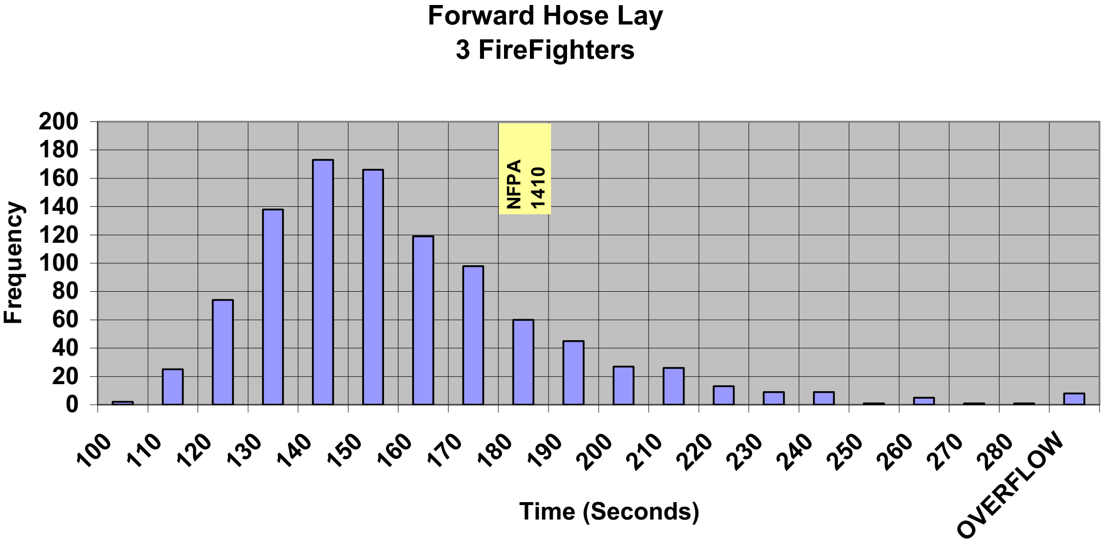

Figure 3.17: Output - Forward Hose Lay Results - Three Firefighters

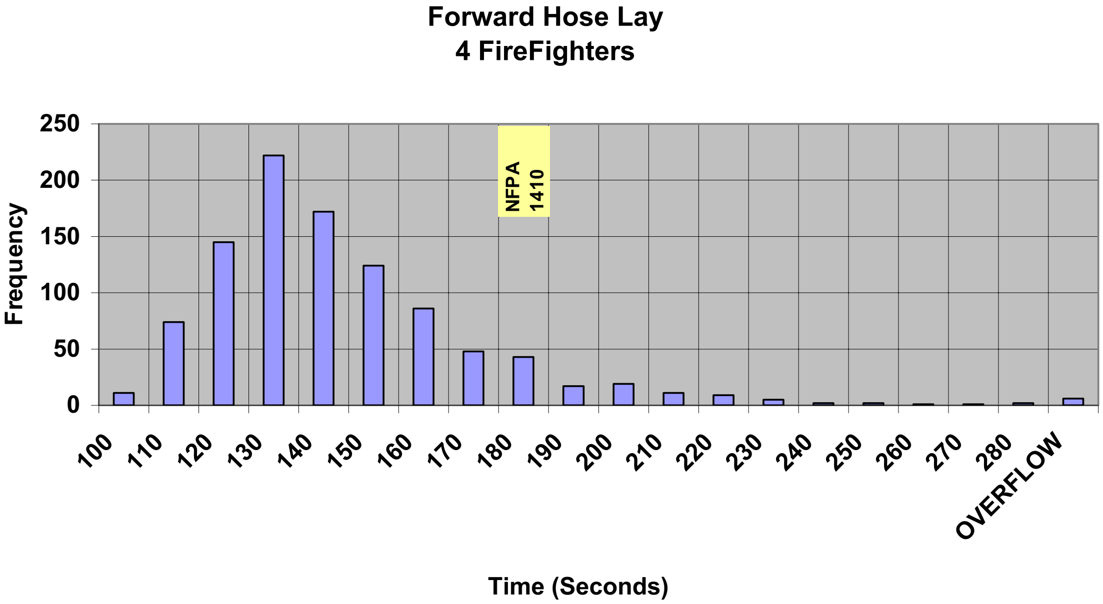

Figure 3.18: Output - Forward Hose Lay Results - Four Firefighters

The average value for the reverse lay simulation was about 250 seconds with a standard deviation of about 40 seconds. This compares somewhat favorably with the NFPA 1410 recommended time of 4 minutes. NFPA 1410 recommends a staffing level of 4 firefighters.

With four firefighters the following results shown in Figure 3.20 were obtained. The average was determined to be 200 seconds with a standard deviation of 30. This agrees much better with the NFPA recommendations. The fourth firefighter helped the MPO (motor pump operator) set up the water supply.

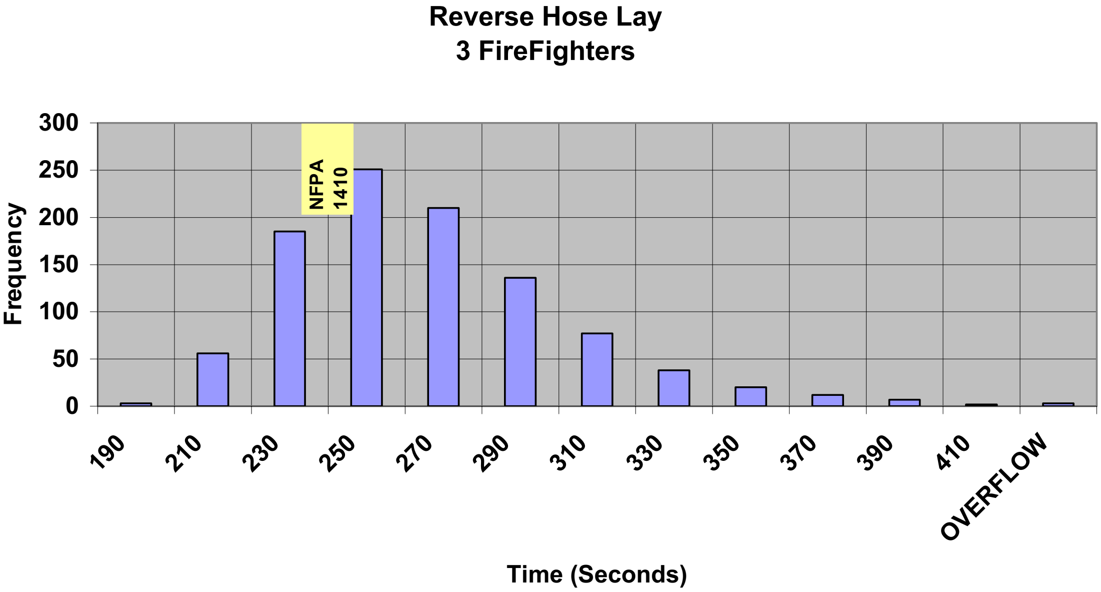

Figure 3.19: Output - Reverse Hose Lay - 3 Firefighters

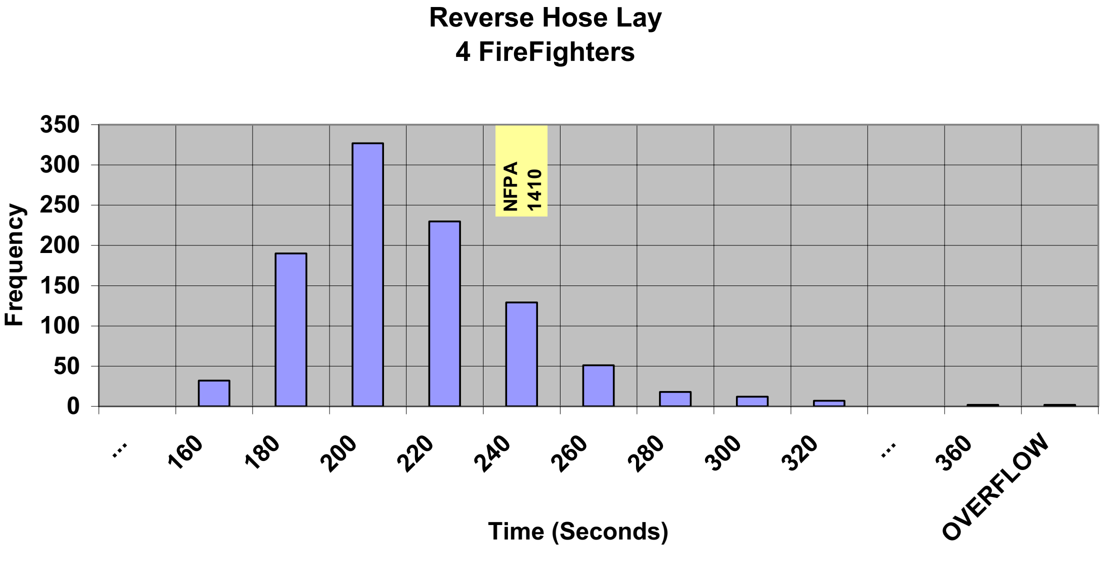

Figure 3.20: Output - Reverse Hose Lay - 4 Firefighters

## 3.5 Expansion of the Model to Interior Attack - Conceptualization

When the model is expanded to building interiors, it is assumed that the firefighters are responding directly to building conditions. Architectural features such as those described by Callery become very important, as due internal building conditions such as smoke and heat. All must be accounted for when developing a model for an individual building. In this paper fire conditions will be developed using the models described in the appropriate appendices.

The modeling of exterior and interior operations will depend greatly on how individual events are defined, and the ease at which the events can be combined. The events used in a particular model depend on available equipment, staffing, and the tactics used by the fire department being simulated. Other important factors are standard operating procedures and how staffing is utilized within these procedures. Internal and external site information must be obtained so that the obstacles that these can provide are accounted for.

Fire department tactics are a large variable. It was important that individual events be defined so tactical variations can be incorporated without substantially changing the model. The individual events must have distinct, well defined start and finish points in order that experiments can be run to gather the data. Obtaining data for both water supply and attack are key elements.

As with the other models developed within this thesis, specific information about the fireground being modeled is essential for the model to be conceptualized. The demonstration model developed here is an adaptation of a study done by the Louisville fire department in 1993[32]. This study was a joint effort between NIST and the Louisville Kentucky Fire Department simulating a fire on the 17th floor of a high rise occupancy. NIST modeled heat release for this simulation and developed information on smoke layer height. This test had particular credibility because of the input NIST had in determining hose conditions would be simulated and because firefighters were not given advance warning of the location and time of the exercise. Other studies were considered but

| Time | Event |
|---|---|
| 0 | Security Guard Dials 911 |
| 45s. | Fire Department Dispatched |
| 4 min. 15 sec. | Fire Department Enters Building |
| 10 min. 15 sec. | First Firefighter on Fire Floor (via stairs) |
| 11 min. 35 sec. | First Attack Line in Position |

Table 3.6: Louisville/NIST Test Results

were contemporary enough or lacked authenticity. The time for fire department response is shown in Table 3.6.

Firefighters needed to alight the apparatus, don SCBA, get a high rise pack and advance to the stairs. Using the elevator lobby stairway, the first-arriving company reached the 17th floor approximately 6 minutes after arriving at the building. The firefighters then connected the hose to the standpipe and advanced up the final set of steps to the fire floor. They then extended the attack hose roughly 50 feet to the workstation

## 3.6 Interior Attack Data Collection

To model the Louisville Study, information was necessary about interior attack. Data on interior firefighting tactics can be much more difficult than for exterior operations. Collecting task data on exterior operations has no structures blocking firefighters operations. As a result, data can be recorded using video tape or stopwatches. This is not the case in interior attack. Not only is there structural blocking of firefighter operations but the smoke and heat produced by the fire also results in difficulty collecting data.

### 3.6.1 Data from AFBIM

A large body of data was also available from the Australian Fire Brigade Intervention Model (AFBIM)[4]. Data used in this model is shown in data obtained from the AFBIM are shown in the

Appendix E. The graphs shown were developed from histograms included within the text of the model documentation. This data was used to expand the model in areas where videotaped data was unavailable. This data included information on stair climbing that was not readily obtainable from video tape of exterior tactics.

Unfortunately, the raw data from the Australian tests could not be obtained. The more rigorous statistical tests, such as the K-S test, require raw data in order to be run. Each data point for each distribution is required to use the K-S test to prove that the distribution corresponds to a lognormal distribution. Unfortunately the data from the Australian tests was only available in the form of histograms, which summarize the data in the form of bins as demonstrated for the data obtained from the Massachusetts fire academy in Figures 3.5 and 3.6 The data obtained from the histograms supplied from the Australian tests was insufficiently random to produce meaningful results using the K-S test.

However, the good fit of the Stow data to lognormal distributions, and the experience of other researchers supports the assumption that the data from the AFBIM would conform to a lognormal distribution as well. It was possible to compare graphs of the histogram data from the AFBIM to assumed lognormal distributions directly. This was done by converting the Normal descriptive variables into Lognormal descriptive variables using the equations described in the next section. The arithmetic mean and standard deviation that were provided can be converted into parameters that are useful into developing a lognormal distribution. A lognormal distribution can be expressed as shown in the equation below [1]:

$$f_x(x) = \frac{1}{x\sigma_Y\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu_Y}{\sigma_Y}\right)^2\right] for 0 < x < \infty \tag{3.1}$$

Lognormal distributions could be developed using the arithmetic means and standard deviations developed using the following correlations:

$$\sigma_Y^2 = \ln\left[1 + \left(\frac{\sigma_X}{\mu_X}\right)^2\right] \tag{3.2}$$

$$\mu_Y = \ln(\mu_X) - \frac{1}{2}\sigma_Y^2 \tag{3.3}$$

These two relations can be inverted as follows:

$$\mu_X = \exp\left(\mu_Y + \frac{1}{2}\sigma_Y^2\right) \tag{3.4}$$

$$\sigma_X^2 = \mu_X^2\left[\exp\left(\sigma_Y^2\right) - 1\right] \tag{3.5}$$

The AFBIM data was validated using visual means, that is by graphing it adjacent to a mathematical representation of the data as a lognormal distribution and comparing their appearances. In most cases this assumption was a good one (see Appendix E). In this way the Australian data was able to augment the data collected from Stow, particularly in the areas where the Stow data was lacking, such as in the climbing of stairs.

## 3.7 Interior Attack Translation

### 3.7.1 Representations of Collected Data

It can be seen in the previous sections that there has been a relatively large amount of data collected for setting up water supplies. The amount of data collected for interior tactics is relatively small. As reported by Callery[5], firefighter movement is impeded by six obstacles. These are, corridors, rooms, elevators, stairs, turns, and doors. Data must be sometimes be adapted to handle each of these obstacles.

### Corridors and Rooms

An estimation of walking speed can be used to determine how long it takes to navigate a corridor. This data is readily available from the AFBIM. It is shown in Figure 3.21 taken from Appendix E.

The same estimation can be used with a firefighter pulling uncharged hose due to its light weight. For moving charged hose, this process becomes more complex for multiple assemblies, as detailed in the previous chapter. Data collected about strait hose pulls from the previous section summarize in Table H.1 was used here.

The problem of when a firefighter will be walking vs. crawling is another one that has been addressed. It is possible to correlate the actions of a firefighter as he moves through a building to the smoke conditions within the building. Firefighters are commonly taught "if you cannot see your feet, you should not be standing on them". However, if there is no smoke within a section of a building, a firefighter should be able to navigate that building unimpeded, and as smoke builds up, speed will slow so that obstacles can be readily avoided The distinctions between these areas normally are somewhat vague.

Normally, a firefighter would naturally prefer to walk through a building. The fire can be reached quickly, and it is less strenuous than creeping or crawling. Crawling through a building offers firefighters a number of advantages when visibility is limited. It prevents firefighters from falling through holes burned in the floor, falling through stair or elevator shafts, or running into objects in front of them. It also offers some protection from heat, as warm air from the fire will rise and stratify above him, and if he is located in the air nearer the floor he will be cooler. Creeping is an "intermediate" mode sometimes used when smoke and heat precludes walking, but crawling can be avoided. It is a sort of "duck walk" that is faster and less strenuous than crawling. Creeping has been described by Callery [5] as reducing speed from walking by a factor of two and crawling by a factor of four. These factors can be used in this model.

### Elevators

Direct correspondence with Otis Elevator Company described how elevators are used by firefighters.[42] Specifically, Otis reported:

> There isn't any data we have from previous studies, probably because building floors, building conditions, and elevator speeds can vary greatly. I can provide some information that may be of help. In most every building the elevators have been programmed with Special Emergency Operation (SES). This means that in the event of a fire, the elevators should return to the main floor level and open the doors. After this is complete, the elevators will not run except for Firefighters who can initiate a keyed switch in the car and gain complete operation of the elevator (like Independent Service with Manual Operation of the doors for the firefighter safety). Therefore capturing the elevator should take very little time because they should be able to choose from any elevator. After that you can figure the elevator will travel past all floors at about 4 seconds for every floor the car passes. If a firefighter wants to check a certain floor for smoke or fire as they travel upward, then you need to factor 20-25 seconds for every floor they wish to check.

The information provided by Otis corresponded well with information provided in other research.[38]

### Stairs

The data obtained from the AFBIM was invaluable for determining firefighter movement up stairs. Data for this area is extremely limited. It is summarized in Figure 3.22 taken from Appendix E. Figures E.15 and E.16 provide data for moving hose up stairs as well.

### Turns

Callery discussed modeling turns in his method. Times are easy to estimate when using uncharged hose . A firefighter walks with attack hose over his shoulder. Speed can again be estimated using the speed of a firefighter walking in turnout gear. This data is readily available in the AFBIM, and adaptable for use in a discrete event simulation. Charged hose is a different matter, and more advanced methods will need to be developed to model its use.

**Doors**

Doors are difficult to evaluate in testing. One reason is the expense of having to destroy the door. A simpler and more reasonable method was employed to obtain data. An experienced firefighter (30 years) was presented with pictures of various door configurations and asked what methods he would use and how long it would take to bypass them. The pictures used are shown in Appendix G. His estimates are shown in Table 3.7.

It should be noted that doors with a large amount of glass area lose a large amount of strength when the glass is broken. This is due to the high compressive strength of glass. It should also be noted that paneled doors are easily opened if one is able to knock one of the panels out. The wood door with wood frame shown was deemed to be the toughest door as it is very well made. The firefighter surveyed felt that power tools would be the only way in.

The Australian study yielded the data on breaching doors listed in Tables 3.8 and 3.9

They also listed times to gain entry with keys.

The results of both studies compare well. The Australian study did not list methods utilized. The firefighter interviewed to obtain the data in Table 3.7 believed it was necessary to give multiple methods. This was because he believed that sometimes equipment was not readily available but the time necessary to acquire is more than the time that would be saved using it.

### 3.7.2 Fire Movement

Information about the influences of fire movement was provided by NIST during the Louisville simulation, so there is no need for the previous fire modeling to be utilized here. What happens to the firefighters during each step of the evolution was determined by NIST. Utilization of these fires

| Type of Door | Procedure | Minimum | Maximum | Average |
|---|---|---|---|---|
| Glass Door, Metal Frame | Impact | | | 60 |
| | Pry | 60 | 120 | 90 |
| | Power | DNA | | |
| Metal Door, Metal Frame, No Window | Impact | 120 | 420 | |
| | Pry | 60 | 120 | |
| | Power | | | 60 |
| Metal Door, Metal Frame, Small Window | Impact | 120 | 420 | 300 |
| | Pry | 120 | 180 | 150 |
| | Power | 60 | 120 | |
| Wood Door, Wood Frame, Panels | Impact | <60 | <60 | <60 |
| | Pry | DNA | | |
| | Power | DNA | | |
| Wood Door, Metal Frame, No Window | Impact | | | 60 |
| | Pry | | | 60 |
| | Power | DNA | | |
| Wood Door, Wood Frame, Small Window | Impact | DNA | | |
| | Pry | DNA | | |
| | Power | 60 | 120 | 150 |
| Wood Door, Metal Frame, Large Window | Impact | | 60 | <60 |
| | Pry | | | 60 |
| | Power | DNA | | |
| Wood Door, Wood Frame, Glazed | Impact | | | 60 |
| | Pry | | | 60 |
| | Power | DNA | | |

Table 3.7: Time to Force Entry (seconds)

| Door Type | Time (s.) |
|---|---|
| Inward opening, side hung door | 30 |
| Outward opening, side hung fire door | 180 |
| Outward opening, side hung solid core door | 90 |
| Inward opening, hollow core door | 15 |
| Outward opening, hollow core door | 45 |
| Glass Door | 15 |
| Roller security, steel door | 220 |
| Chained Gate | 45 |

Table 3.8: Time to Force Door (s.)

| Door Type | Time (s.) |
|---|---|
| Side hung door | 10 |
| Roller security door | 30 |
| Gate | 30 |

Table 3.9: Time to Gain Entry with Keys (s.)

will occur in Chapter 4, Application of the Model.

### 3.7.3 GPSS Input

Typical GPSS input files are provided in Appendix F

## 3.8 Interior Attack Validation and Verification

As shown in Table 3.6, the Louisville study showed 6 minutes (360 seconds) for firefighters to reach the fire floor and 7 minutes 20 seconds to put water on the fire (440 seconds). The simulation was run for 1000 transactions. The results of the simulation are shown as a frequency distribution in Figure 3.23. The simulation mean time of 5.8 minutes (347 s.) with a standard deviation of 37 seconds.

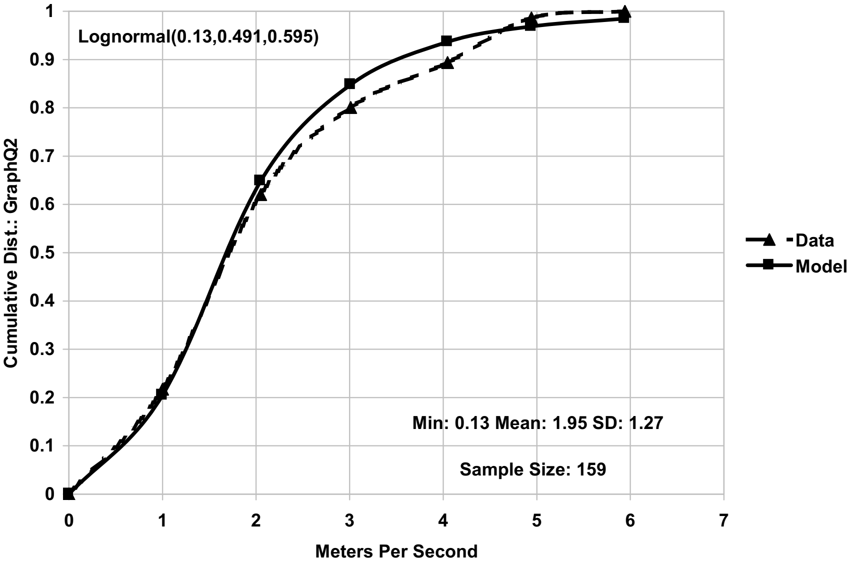

Figure 3.21: Horizontal Travel in Turnout Uniform with Equipment - Aust.

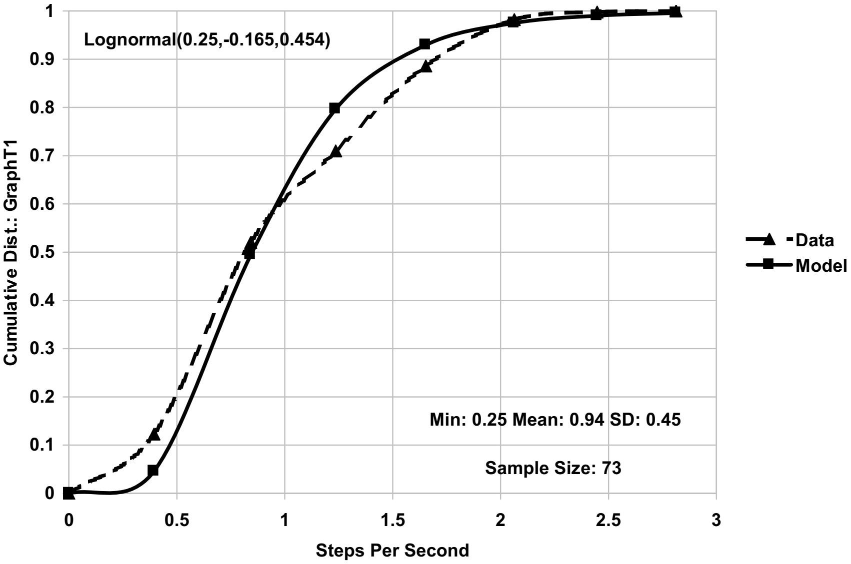

Figure 3.22: Ascend Stairs in BA w/ Equipment - Aust.

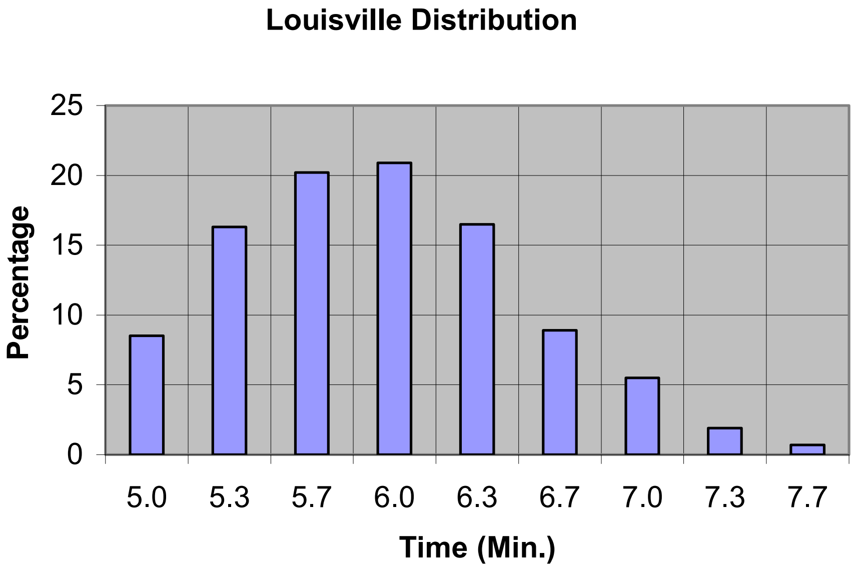

Figure 3.23: Results of Louisville Simulation

## 3.9 Conclusion

Discrete Event Simulation (DES) provides a flexible method for dealing with parallel tasks. This flexibility is required because the number of parallel tasks is directly related to the standard operating procedures and equipment of the fire department that is being modeled. It is important that the individual events are clearly defined so that test data can be properly collected. If good test data is acquired, it will be possible to estimate fire size at first water.

Several assumptions were made in defining the start and finish of events. These assumptions included the following:

1. Individual firefighter tasks correspond to lognormal distributions. The Kolmogorov-Smirnov test will be used to verify this assumption. Lognormal distributions are skewed as shown in Figure X. They are different not symmetric as normal distributions are.
2. The arrival time could be calculated based on the Rand study. Verification of the Rand study was considered outside the scope of this model.
3. Data collected concerning exterior firefighting tactics could be applied in the interior as well. For example, if a distribution was developed concerning how much time it took to connect a nozzle on the exterior of the building, it would take the same amount of time on the interior of the building. Clearly for some tasks, fire conditions and space limitations in the interior of the building will naturally be an issue. As an initial approximation, it was felt this was appropriate. The firefighters posture (crawling, etc.) due to internal conditions such as heat or smoke can be accounted for in this initial approximation.

Weather and time of day were not considered factors at this early stage of the model, but can be incorporated later. The distributions can be modified, or an entirely new set of data gathered to account for weather conditions and time of day, as this methodology develops. It should also be noted that some departments will be conditioned to work in snow or total darkness (departments above the arctic circle being an extreme example) while in other departments these conditions will be infrequent. It should also be noted that tactics in different areas may tend to be different as well, so this entire methodology may need modification when used in certain jurisdictions.

# Chapter 4

# Application of the Model

The following example was included as a proof of concept. The method described in previous chapters is used to explore the problem of a fire in an office building. The models for water supply setup and interior attack were further explored. Design fires described in the previous chapters, as summarized in Appendix B were utilized.

Changes in the design fire scenario and their influence on fire attack conceptualization are considered in this chapter to demonstrate how different design scenarios may be explored. No new data was collected for the firefighting portion of the mode, however the translation of the environmental inputs on the distributions used to model firefighter actions was considered.

As there is no test to compare this model against, verification of the output was not possible.

## 4.1 Introduction

An office park situation, shown in Figure 4.1 was used as the basis for analysis. The fourth floor layout is shown in Figure 4.2. The building is a 17,500 square foot office building (140'x125') with a central core. It was assumed that the fire department is 2 miles from the site, so the fire will had roughly 4 minutes to develop before arrival according to Figure 2.2.

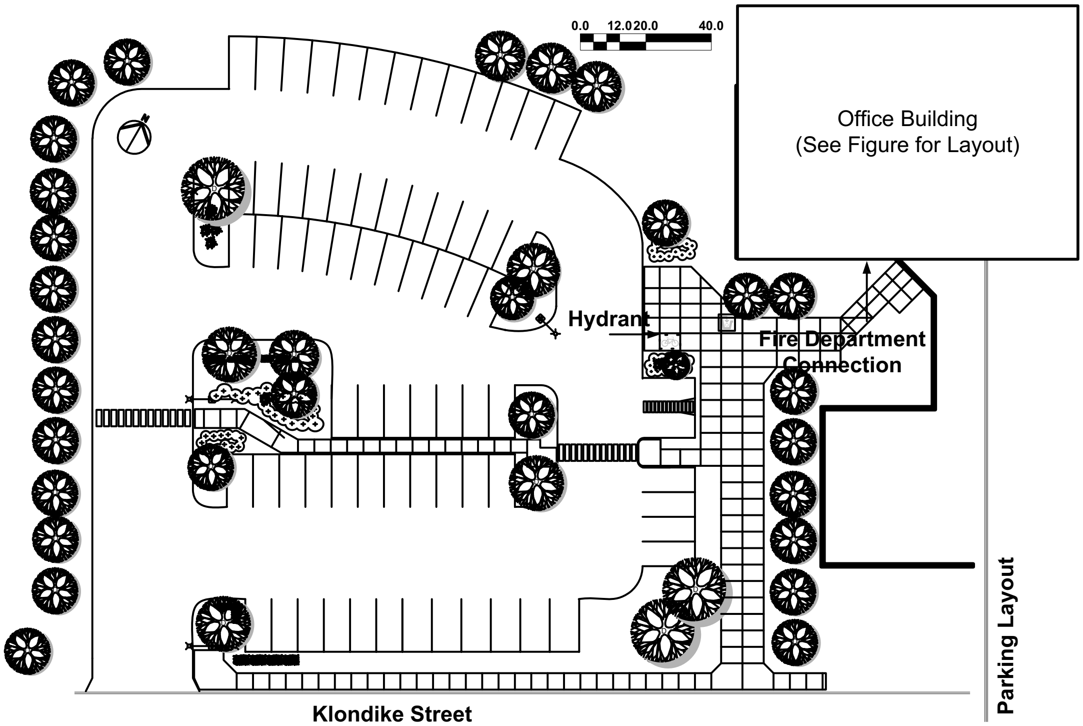

Figure 4.1: Site Plan with Building

Two interior situations are discussed. One with the office door open, and the other with the office door closed. Design fires were developed first for each of these situations, based on Appendix B, in the Data Collection section of this chapter.

## 4.2 Conceptualization

The process for setting up the water supply is the same for both fires. However, the process for attacking the fire on the fire floor is influenced by the fire, hindering the attack. This was taken into account in the DES process based on the design fire information.

The water supply setup is described in the previous chapter, and is not be repeated here. It is assumed that when the firefighters called for water it was available.

The interior attack will be as shown in Figure 4.3 . The sequence of events will be similar in

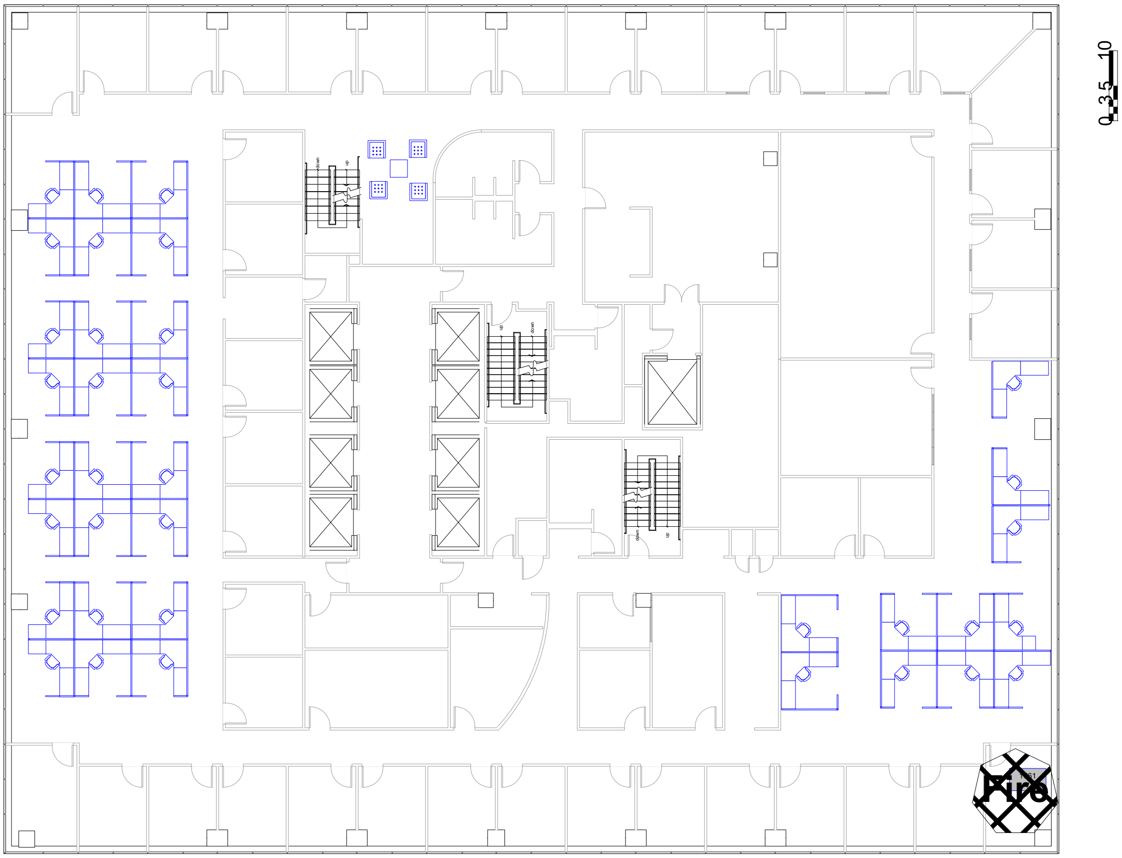

Figure 4.2: Fourth Floor Layout

both cases, but in the case with the door open, firefighters will be slowed down by the heat and smoke in the environment.

In a fire attack on the office in the lower right hand corner of Figure 4.2, the tasks shown in Table 4.3 must be performed. The table shows estimated times and variances based on collected data using triangular distributions. The tasks are broken down by numbered assembly as shown in Figure 4.4.

## 4.3 Data Collection

No new data was collected for the firefighting portion of the mode, however in the translation of the model fire conditions was considered based on the design fires developed in Appendix B.

Using the medium sized office described in Table C.1, with a medium speed fire flashover in the office will occur in about 4.5 minutes, according to the design fires developed in Appendix C. If the door is closed, it is assumed that the door will burn through in roughly 10 minutes. Assuming the office door is open, and using the data developed in Table C.2, roughly 4 workstations in an 18'x8' area outside the office will be involved in another 460s.

In Figure 4.5 information about ceiling layer development is shown for the open office area after the door is breached.

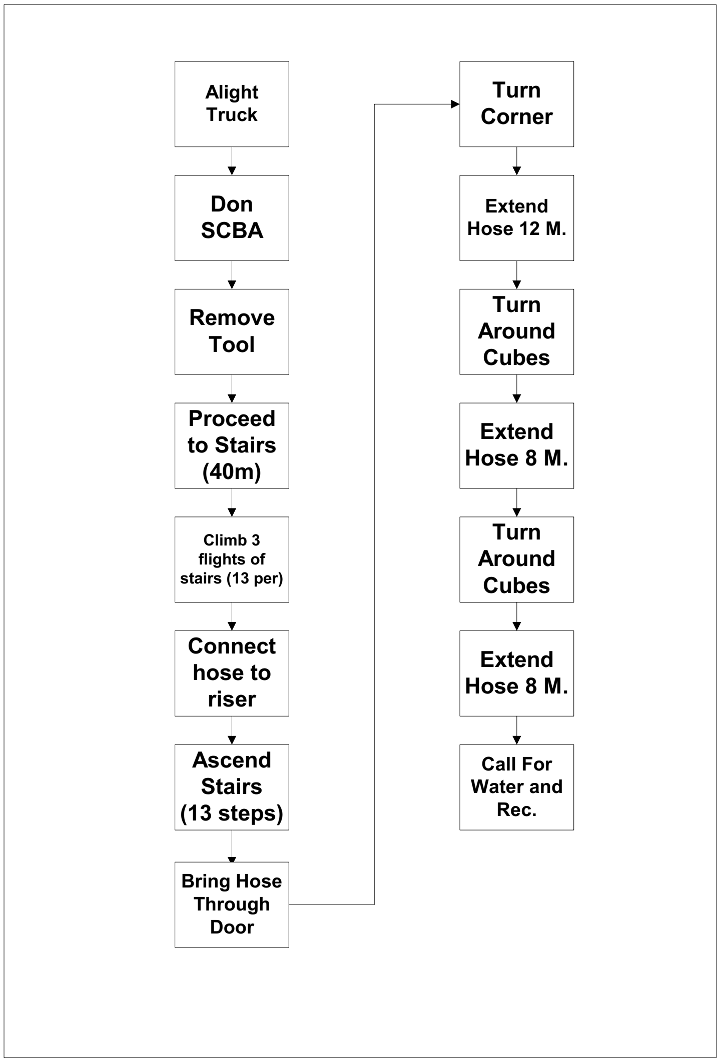

Figure 4.3: Office Building Fire Attack Conceptualization

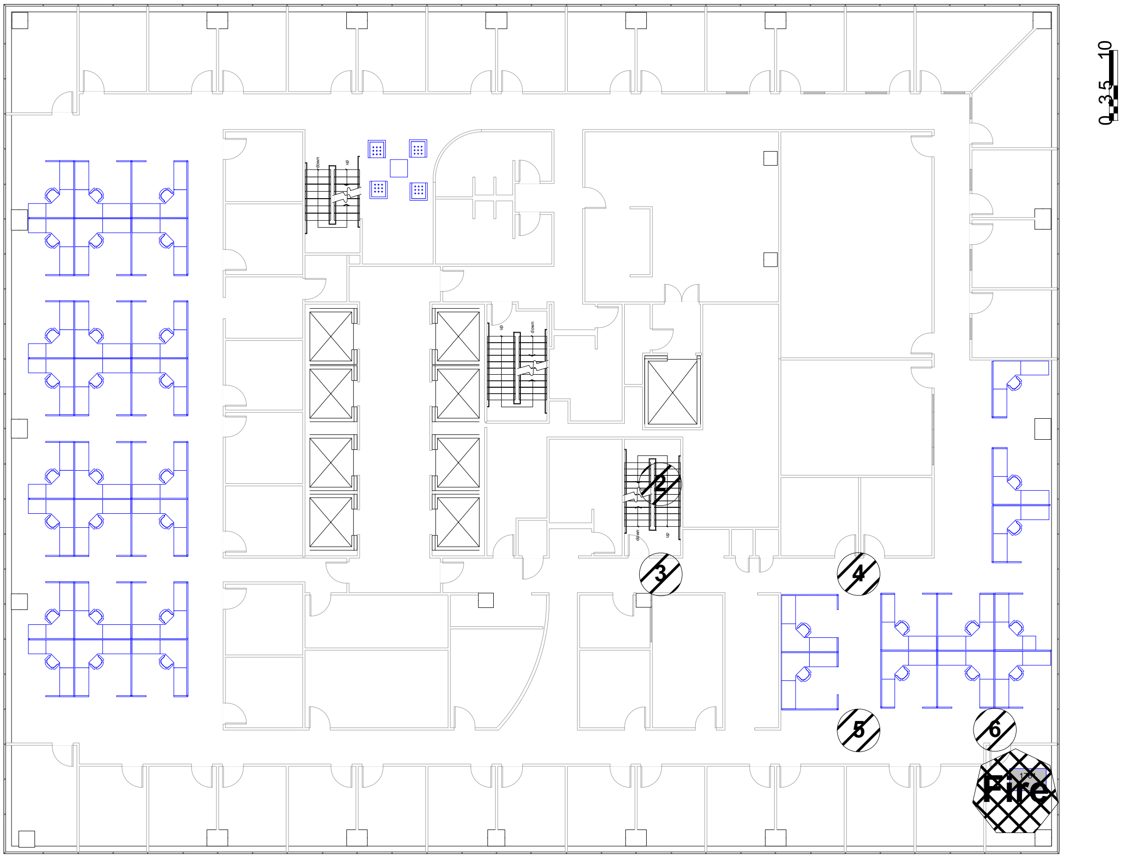

Figure 4.4: Floor Plan - Door Closed

| Task | Assembly |
|---|---|
| Alight Truck | O |
| Don SCBA | O |
| Remove Tool | O |
| Proceed to Stairs (40m) | O-1 |
| Climb 3 flights of stairs (13 per) | 1-2A |
| Connect hose to riser | 1-2B |
| Ascend Stairs (13) | 1-2C |
| Bring Hose Through Door | 2-3A |
| Turn Corner | 2-3B |
| Extend Hose 12 M. | 3-4A |
| Turn Around Cubes | 4 |
| Extend Hose 8 M. | 4-5A |
| Turn Around Cubes | 5 |
| Extend Hose 8 M. | 5-6A |
| Call For Water and Rec. | 6 |

Table 4.1: Fire Attack Concept

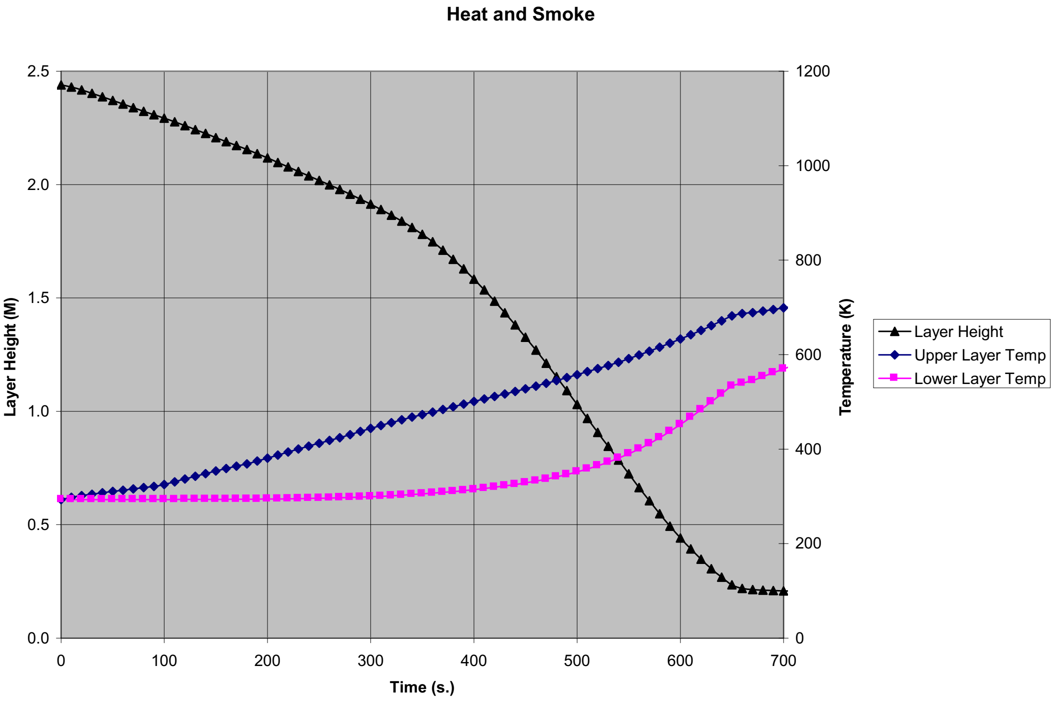

Figure 4.5: Influence of Heat and Smoke on Open Area

| Location | Cumulative Area | Cumulative Time (Min.) | | |
|---|---|---|---|---|
| | | Slow | Med | Fast |
| Room Of Origin | 192 | 0 | 5 | 3 |
| Door | 192 | 5 | 5 | 3 |
| Open Office | 516 | 15 | 12.5 | 8 |
| Open Office | 1164 | 25 | 20 | 13 |
| Office | 1308 | 35 | 20 | 13 |
| 2 Office | 1596 | 39 | 24 | 15 |

Table 4.2: Design Fire Spread

## 4.4 Model Translation

Two distribution types will be used in the model translation. In this system the most optimistic, pessimistic and most likely times are assumed to be the corners of a triangle. The centroid of the triangle can be used to determine the mean time for the operation. Then the triangles can be summed and variances determined by summing the mean values and the variances. This method has a number of advantages, as described in Moder. [20] One is that it doesn't require a computer. Another is that it provides a method for expert estimates of task times to be readily integrated. One disadvantage is that all tasks must be independent of one another. This assumption is sometimes difficult to make. It was easy here because of the serial nature of this particular problem.

Later, a lognormal distribution will be used. As discussed previously, the lognormal distributions describe the processes better than the triangular distributions. However, the use of a computer is required to sum them.

### 4.4.1 Triangular Distributions - Door Closed

The use of the triangular distributions for setting up the attack line is summarized in Table 4.3 and its output distribution is summarized in Figure 4.7. It should be noted that the triangular distribution generally overemphasizes the tails of the distribution and underemphasizes the shoulders in comparison with other, more natural, distributions[44]. Using triangular distributions, the mean value was calculated to be 237.

### 4.4.2 Triangular Distributions - Door Open

In the case of an open door, it is expected that the fire would easily spread to the "cube farm" located immediately outside. Note that in this case, it will actually take less time to attack the fire, because the fire has moved to the firefighters. The table shows the estimated times. Note that the firefighters are crawling. In the First Interstate Bank Fire the ceiling layer descended to two feet

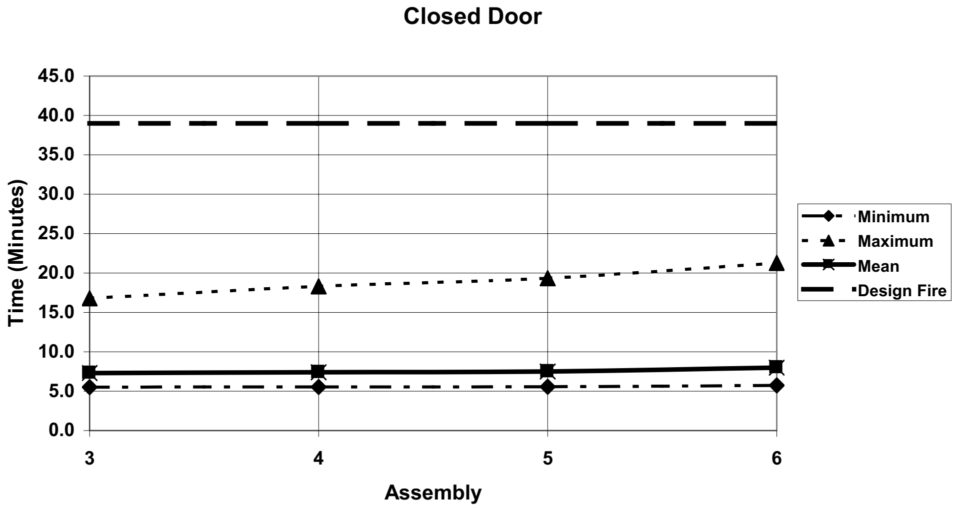

Figure 4.6: Closed Door Times - Triangular Dist. - Includes Arrival

above the floor in 7 minutes. The First Interstate bank fire is similar to the design fire shown in Figure 4.5 The firefighters arrive at the top of the staircase at about 7 minutes, so crawling seems likely. Six 12 M. hose streteches are used, instead of the original 3 hose stretches to account for the fact the firefighters are crawling because of the smoke. The steps in this case are shown in Table 4.4

It can be seen that the average time to first water has increased to about 260 seconds.

### 4.4.3 Lognormal Distributions - Door Closed

The use of the triangular distributions for setting up the attack line is summarized in Table 4.5. The lognormal distributions used are also summarized in this table. The output distribution is summarized in Figure 4.8 the results are shown for a GPSS simulation for the closed door scenario. With the door to the room of origin closed the firefighters have more than enough time to get a hose to the room of origin and put the fire out in this demonstration. They do not have to creep or crawl to move the hose to the fire, as the ceiling layer has not descended in the open area. Even if they move at the slowest speed through the building, the door provides enough of a fire stop so

| Task | Assembly | Min. | Mean. | Max. |
|---|---|---|---|---|
| Alight Truck | O | 3 | 11.1 | 25 |
| Don SCBA | O | 38 | 67 | 136 |
| Remove Tool | O | 7 | 21.5 | 43 |
| Proceed to Stairs (40m) | O-1 | 6.6667 | 20.513 | 307.6923 |
| Climb 3 flights of stairs (13 per) | 1-2A | 17.143 | 38.298 | 144 |
| Connect hose to riser | 1-2B | 13 | 26.4 | 59 |
| Ascend Stairs (13) | 1-2C | 6.1905 | 13.83 | 52 |
| Bring Hose Through Door | 2-3A | 0 | 0 | 0 |
| Turn Corner | 2-3B | 0 | 0 | 0 |
| Extend Hose 12 M. | 3-4A | 2 | 6.1538 | 92.30769 |
| Turn Around Cubes | 4 | 0 | 0 | 0 |
| Extend Hose 8 M. | 4-5A | 1.3333 | 4.1026 | 61.53846 |
| Turn Around Cubes | 5 | 0 | 0 | 0 |
| Extend Hose 8 M. | 5-6A | 1.3333 | 4.1026 | 61.53846 |
| Call For Water and Rec. | 6 | 8 | 24.3 | 55 |
| Totals | | 103.67 | 237.3 | 1037.077 |

Table 4.3: Fire Attack Time Estimates - Triagular Distribution - Door Closed

| Task | Assembly | Min. | Mean. | Max. |
|---|---|---|---|---|
| Alight Truck | O | 3.0 | 11.1 | 25.0 |
| Don SCBA | O | 38.0 | 67.0 | 136.0 |
| Remove Tool | O | 7.0 | 21.5 | 43.0 |
| Proceed to Stairs (40m) | O-1 | 6.7 | 20.5 | 307.7 |
| Climb 3 flights of stairs (13 per) | 1-2A | 17.1 | 38.3 | 144.0 |
| Connect hose to riser | 1-2B | 13.0 | 26.4 | 59.0 |
| Ascend Stairs (13) | 1-2C | 6.2 | 13.8 | 52.0 |
| Bring Hose Through Door | 2-3A | 0.0 | 0.0 | 0.0 |
| Turn Corner | 2-3B | 0.0 | 0.0 | 0.0 |
| Call For Water and Rec. | 6 | 8.0 | 24.3 | 55.0 |
| Extend Hose 12 M. | 3-4A | 2.0 | 6.2 | 92.3 |
| Extend Hose 12 M. | 3-4A | 2.0 | 6.2 | 92.3 |
| Extend Hose 12 M. | 3-4A | 2.0 | 6.2 | 92.3 |
| Extend Hose 12 M. | 3-4A | 2.0 | 6.2 | 92.3 |
| Extend Hose 12 M. | 3-4A | 2.0 | 6.2 | 92.3 |
| Extend Hose 12 M. | 3-4A | 2.0 | 6.2 | 92.3 |
| Totals | | 111.0 | 259.9 | 1375.5 |

Table 4.4: Fire Attack Time Estimates - Triangular Distributions - Door Open

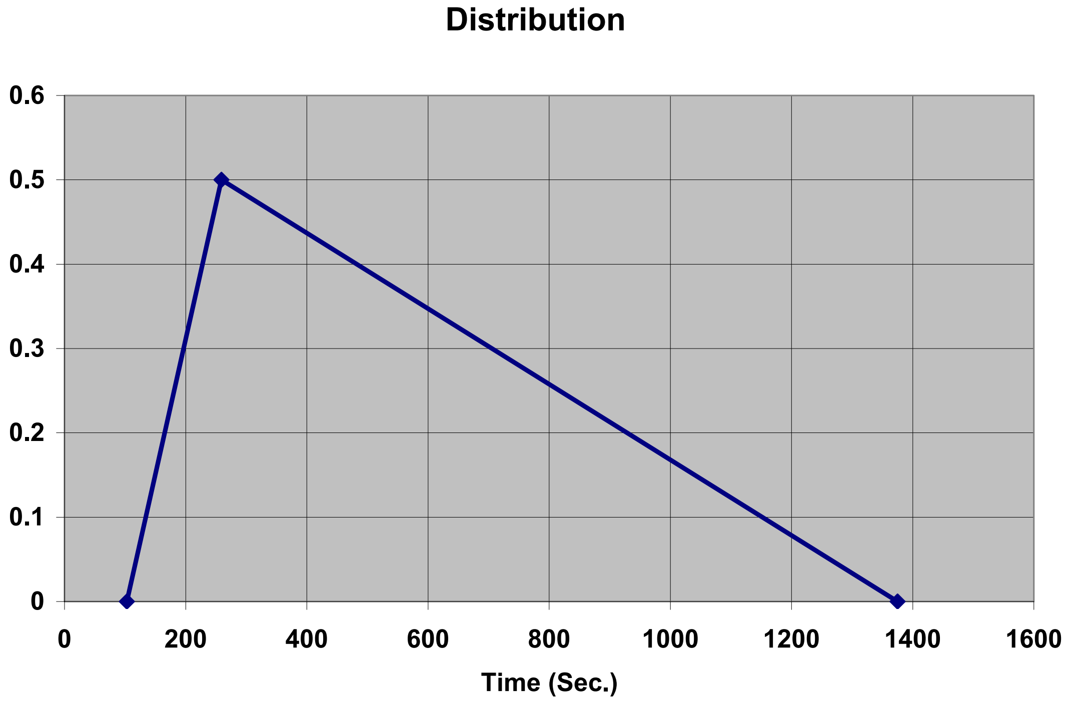

Figure 4.7: Door Closed Vs. Door Open - Triangular Output Dist. - Without Arrival Time

that the fire cannot grow in size to anywhere near 1400 sq. feet.

The mean in this case is roughly 250 seconds. The GPSS source code is below.

| Task | Assembly | Distribution Used |
|---|---|---|
| Alight Truck | O | Figure D.2 |
| Don SCBA | O | Figure D.27 |
| Remove Tool | O | Figure D.35 |
| Proceed to Stairs (40m) | O-1 | Figure E.9 |
| Climb 3 flights of stairs (13 per) | 1-2A | Figure E.13 |
| Connect hose to riser | 1-2B | Figure D.12 |
| Ascend Stairs (13) | 1-2C | Figure E.13 |
| Bring Hose Through Door | 2-3A | 0 |
| Turn Corner | 2-3B | 0 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |
| Turn Around Cubes | 4 | 0 |
| Extend Hose 8 M. | 4-5A | Figure E.10 |
| Turn Around Cubes | 5 | 0 |
| Extend Hose 8 M. | 5-6A | Figure E.10 |
| Call For Water and Rec. | 6 | 8 |

Table 4.5: Fire Attack Time Estimates with Door Closed

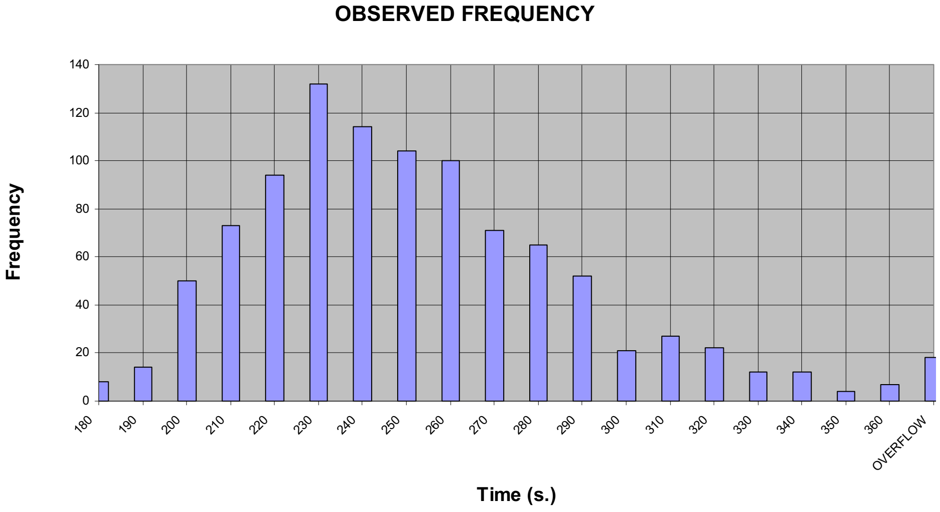

Figure 4.8: GPSS Output Histogram - Door Closed - Does Not Include Arrival

```
SIMULATE                          *base time unit: 1 second
* WATER SUPPLY
*///////////////////////////////////////////////////////////////////////
* SIMULATION OF OFFICE BUILDING
* WITH DOOR CLOSED
*12/13/2000 4:19PM
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
RTIME    TABLE      M1,180,10,20
*
GENERATE                          *PROVIDE A TRANSACTION WHENEVER NEEDED
GATE LR    NEXT1                  *WAIT UNTIL PRECEDING ITERATION IS FINISHED
LOGIC S    NEXT1                  *SHUT GATE ON FOLLOWING TRANSACTION
QUEUE      FB1                    *BACKUP PERFORMS OPERATIONS AT APP.*B*
SEIZE      FBA
*Alight Truck Alight  6 3+RVLNOR(1,8.33,24.8)
ADVANCE    3+RVLNOR(1,8.33,24.8)  *Alight Truck
*Don SCBA donscba 5 38+RVLNOR(1,30.6,525)
ADVANCE    38+RVLNOR(1,30.6,525)  *Don Scba
*Remove Tool from App. rmtool 6 7+RVLNOR(1,16.3,249)
ADVANCE    7+RVLNOR(1,16.3,249)
*Proceed to Stairs (40m) - Horiz. Travel in Turnout w/ Equip m/s
ADVANCE    (40/(0.13+RVLNOR(1,1.95,1.6)))
*Climb 3 flights of stairs (13 Steps per flight)
ADVANCE    (36/(0.25+RVLNOR(1,0.94,0.2025)))
*Connect hose to riser
*Connect Hose to Hydrant conhohyd           4 13+RVLNOR(1,13.9,80.8)
ADVANCE    13+RVLNOR(1,13.9,80.8)
*Ascend Stairs
ADVANCE    (13/(0.25+RVLNOR(1,0.94,0.2025)))
*Bring Hose Through Door
*Extend Hose 12M.
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
*Turn Around Cubes
*Extend Hose
*Turn Around Cubes
*Extend Hose 8 m
ADVANCE    (8/(0.13+RVLNOR(1,1.95,1.6)))
*Open Valve at Riser
*Pressurize Hose
*Call and Receive Water Calrecwa           3
ADVANCE    8+RVLNOR(1,18.1,267)
*Open Door
*Apply Water
DEPART     FB1
RELEASE    FBA
LOGIC R    NEXT1                  *OPEN GATE FOR THE NEXT ITERATION
TABULATE   RTIME
TERMINATE  1                      *CURRENT ITERATION IS FINISHED
START      1000                   *SIMULATE FOR A MANPOWER LEVEL OF 3
END
```

### 4.4.4 Lognormal Distribution - Door Open

Assuming two firefighters using a high rise pack, a pressurized standpipe, an arrival time of 4 minutes to arrive on scene. For the open door scenario it is assumed that the firefighters will have to crawl to a position near the corner office. The problem of when firefighters will be walking, duckwalking or crawling becomes particularly evident here. It was assumed that they were crawling. Actually when they arrived at the top of the stairs before flaking out the hose, the ceiling layer is below 2 meters. This would them in a position to choose to duckwalk or crawl with an uncharged hose. The same method for extending the travel time in the triangular distribution analysis was used here.

| Task | Assembly | Lognormal Distribution Used |
|---|---|---|
| Alight Truck | O | Figure D.2 |
| Don SCBA | O | Figure D.27 |
| Remove Tool | O | Figure D.35 |
| Proceed to Stairs (40m) | O-1 | Figure E.9 |
| Climb 3 flights of stairs (13 per) | 1-2A | Figure E.13 |
| Connect hose to riser | 1-2B | Figure D.12 |
| Ascend Stairs (13) | 1-2C | Figure E.13 |
| Bring Hose Through Door | 2-3A | 0 |
| Turn Corner | 2-3B | 0 |
| Call For Water and Rec. | 6 | Figure D.4 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |
| Extend Hose 12 M. | 3-4A | Figure E.10 |

Table 4.6: Fire Attack Time Estimates with Door Open

```
SIMULATE                          *base time unit: 1 second
* WATER SUPPLY
*/////////////////////////////////////////////////////////////////////
* SIMULATION OF OFFICE BUILDING
* WITH DOOR OPEN
*12/13/2000 4:19PM
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
RTIME    TABLE      M1,200,10,20
*
GENERATE                          *PROVIDE A TRANSACTION WHENEVER NEEDED
GATE LR    NEXT1                  *WAIT UNTIL PRECEDING ITERATION IS FINISHED
LOGIC S    NEXT1                  *SHUT GATE ON FOLLOWING TRANSACTION
*////////////////////////////////////////////////////////////////////////////////////////
*
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
QUEUE      FB1                    *BACKUP PERFORMS OPERATIONS AT APP.*B*
SEIZE      FBA
*Alight Truck Alight  6 3+RVLNOR(1,8.33,24.8)
ADVANCE    3+RVLNOR(1,8.33,24.8)  *Alight Truck
*Don SCBA donscba 5 38+RVLNOR(1,30.6,525)
ADVANCE    38+RVLNOR(1,30.6,525)  *Don Scba
*Remove Tool from App. rmtool 6 7+RVLNOR(1,16.3,249)
ADVANCE    7+RVLNOR(1,16.3,249)
*Proceed to Stairs (40m) - Horiz. Travel in Turnout w/ Equip m/s
ADVANCE    (40/(0.13+RVLNOR(1,1.95,1.6)))
*Climb 3 flights of stairs (13 Steps per flight)
ADVANCE    (36/(0.25+RVLNOR(1,0.94,0.2025)))
*Connect hose to riser
*Connect Hose to Hydrant conhohyd           4 13+RVLNOR(1,13.9,80.8)
ADVANCE    13+RVLNOR(1,13.9,80.8)
*Ascend Stairs
ADVANCE    (13/(0.25+RVLNOR(1,0.94,0.2025)))
*Charge Hose
*Call and Receive Water Calrecwa           3
ADVANCE    8+RVLNOR(1,18.1,267)
*Conveyor Method
*Get 12 M thru the door
*Then move it 12 M
*Extend Hose 12 m
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
*Extend Hose 12 m
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
*Extend Hose 12 m
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
*Extend Hose 12 m
*Double the above because they are crawling.
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
*Extend Hose 12 m
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
*Extend Hose 12 m
ADVANCE    (12/(0.13+RVLNOR(1,1.95,1.6)))
```

```
*Pressurize Hose
*Open Door
*Apply Water
DEPART     FB1
RELEASE    FBA
LOGIC R    NEXT1                 *OPEN GATE FOR THE NEXT ITERATION
TABULATE   RTIME
TERMINATE  1                     *CURRENT ITERATION IS FINISHED
START      1000                  *SIMULATE FOR A MANPOWER LEVEL OF 1
END
```

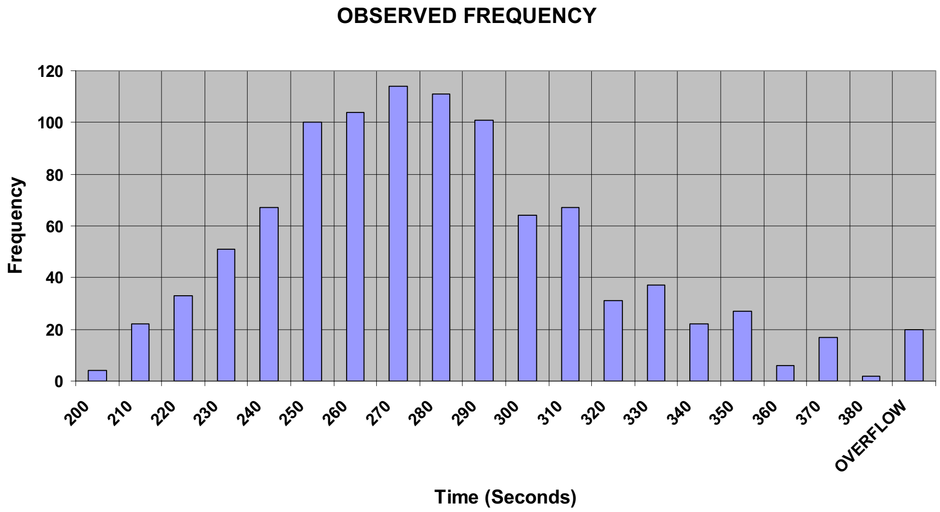

Figure 4.9: Open Door - Observed Frequency

# Chapter 5

# Conclusions

Discrete event simulation is a very powerful tool that can be used to model firefighter operations with some degree of accuracy. It is possible through the use of statistical distributions to model the variability of events as well as any "waiting" for other tasks that need to be done concurrently by other firefighters. In more advanced modeling it is possible that logical switches and other means can also be used in more advanced modeling to account for fire conditions within the structure. More data on individual events and accurate descriptions of these events will be necessary to expand this research. The use of video tape and digital video will simplify the gathering of this information in the future. It will also provide the assurance that data provided from different groups is being collected about similar evolutions.

## 5.1 Contributions

### 5.1.1 Discrete Event Simulation

The overall model appears to be valid provided that the individual events are properly accounted for. This was shown in the comparison with the Louisville study. The water supply setup model provided data consistent with those recommended in NFPA 1410. More data will need to be acquired to validate this model further.

### 5.1.2 Integration of the Design Fire

The use of simplified design fires was used to demonstrate the validity of discrete event simulation. More complex design fires may provide more realistic results.

### 5.1.3 Lognormal Distribution

The lognormal distribution was found to be better than the normal distribution in describing individual event data used as input for the model. The use of normal distributions will generally increase the time for individual events and resulting in longer overall simulation times.

### 5.1.4 Video Tape

The use of video tape in the acquisition of data allowed for the review of individual events and resulted in consistent method for gathering data. In addition the review and discussion of this data will allow other researchers to understand the tactics being modeled.

## 5.2 Limitations

The model will need further validation before it can be used by engineers. Tactical variations will need to be incorporated and the influence of the environment on the firefighter will need to be studied further in order for this model to evolve into a more practical tool. The fire model integration into the simulation will also need to be improved. This would allow for improvement in the logic as to whether a firefighter is walking or crawling in a given assembly in the building interior.

## 5.3 Future Work

Future work can be performed using more advanced DES models. In particular models incorporating graphical user interfaces should provide results more easily. In addition, it may be possible to provide distributions for fire characteristics such as ceiling layer height and temperature that would allow the fires to modeled as discrete events as well. Continuous models could be utilized using appropriate distributions for ventilation characteristic and fire loading. The influence of the evacuation of occupants on firefighter response could further be integrated into the model.

In addition more data concerning the movement of charged hose, particularly when firefighters are crawling and moving around corners would be very helpful to the development of this method. The correlation of statistical distributions to data is an area that could be expanded an improved.

Other areas that need incorporation are:

- Independence of distributions must be explored further
- Fatigue should be incorporated
- Locating of room of origin
- Possible use of Latin hypercube or other methods to handle "tails" in lognormal distributions.
- The firefighter/evacuee interface
- Level of training and esprit de corps

Finally it should be noted that much more data should be made publicly available so that further research can be performed.

# Appendix A

# Water Supply Setup

## A.1 Water Supply

The fire hydrant is the most common urban water supply. Hydrants are supplied by a very large elevated tank or tanks, from a pressurized municipal water system, of from a pumping station. Hydrants are the most common and reliable supplies of water.

Large capacity tanker trucks are the next most common type of water supply used in firefighting. These tankers may be equipped with a pump so that they are self contained. They will therefore only need supply hose lines to deliver water to the engine on the fire scene. Other tankers are not equipped with a pump, and will need an engine to supply water to the scene. Water tankers are more common in rural areas, where a municipal water supply is very expensive to install. Even small communities with a hydrant system may need to make use of alternate water supplies due to lack of redundant water mains.

The last common type of water supply is the use of natural static sources such as ponds, rivers, and lakes. Hard suction is used to force water up from the static source. Hard suction refers to a rigid hose in which a vacuum must be produced to draw water. This process is referred to as drafting. The laying of this rigid hose is usually done by hand when the engine arrives at the source of water. This type of hose is more difficult to handle than regular hose because of the hose rigidity. The number of lengths needed also influences the difficulty because of added weight. Drafting hose sections are commonly between 10 and 12 feet (3 and 3.66 meters) long. Lack of staffing can make drafting a very time consuming activity.[31]

## A.2 Supply Line Hose Lays

Once a reliable source of water is secured that water must be conducted to the scene of the fire. Hose provides firefighters with the ability to put water on the fire. It is therefore one of the most important elements to set up when preparing to extinguish a fire. Two basic types of hose lines are used. One is the large diameter hose lines that are used to set up supplies. These lines are used to transport water from a supply point to the fire attack engine. The other type of hose is the small diameter hose that is run from the engine to the point of the fire. These are called attack lines.

The supply line is the hose line used to transport water from the supply source to the fire scene. These supply lines are almost always laid out using a fire engine. One end of the supply line is secured and the engine drives in the opposite direction while the hose is pulled out of the hose bed onto the ground. The firefighters can also physically pull the hose from the hose bed and drag it to the water supply. This is referred to as "hand laying" the supply line. This type of lay is generally only used when the distance between the engine and the water source is small.

The three most common sizes of supply line are three inch, four inch and five inch diameter hose. The size line used by a given department depends on the fire conditions expected, the length of line needed, and the type of hose on hand. In cities where hydrants are spaced every three hundred feet (100 meters), a smaller supply line can be used, as the head loss will be less important in this situation.

A larger diameter supply line is generally required in rural areas where there is no hydrant system, and longer hose lays are required.

Naturally, expected fire conditions influence the choice of hose used as well. The larger the fire size, the greater the water flow necessary to extinguish the fire. Water flow is very important, because if a minimum flow is not applied to the fire it will continue to grow. Firefighters in smaller communities would need larger diameter hose provide the necessary flow, as they are generally limited to one or two engines. Having larger hose lines is generally less important in cities, where there are multiple engine companies that can lay as many hose lines as needed. There are three major types of supply line hose lays. They are forward lay, reverse lay, and dead end.

### A.2.1 Forward Lay

A forward lay is generally the method of hose laying described above. This is generally used when the first arriving engine begins a supply line before it reaches the fire building. The engine

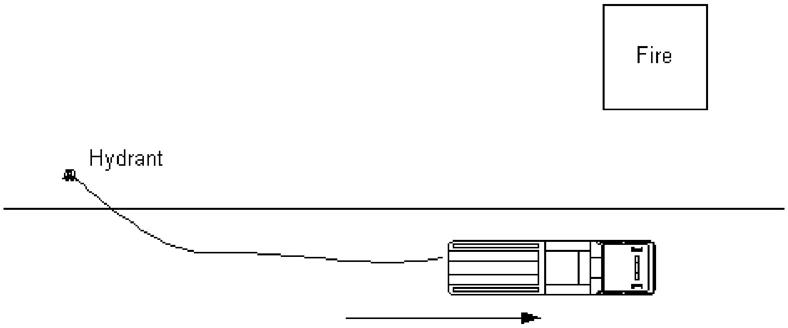

Figure A.1: Forward Lay

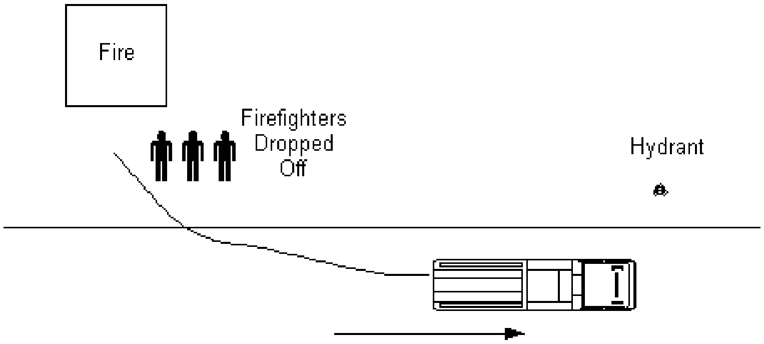

Figure A.2: Reverse Lay

arrives at a hydrant and drops one end of the supply line, leaving a firefighter to connect it to the hydrant. The engine then continues on to the fire, laying supply line as it goes. This gives the engine a large supply of water quickly and easily.

### A.2.2 Reverse Lay

This type of hose lay is used when an engine is already at the scene of a fire, and it is determined that a continuous water supply is necessary, such as in the case that an engine arrives to investigate a possible fire and one is found. Generally, the company fire officer will send his engine to the nearest hydrant, but retain the majority of his staff at the scene.

Figure A.3: Dead End

**Dead End** A dead end is when an engine starts a supply line lay from a point other than a water supply and precedes to the fire, effectively executing a forward lay, but not starting at the water supply. A second engine will then execute a reverse lay at the point where the first engine left the hose. This type of hose lay is often used in rural communities that are dependent on static water supplies. [31]

## A.3 Forcible Entry

Forcible entry allows fire fighters to gain access to secured areas for he purpose of fire extinguishment and search and rescue efforts. In larger departments with adequate staffing, this is done by the ladder crew. However, in call and volunteer departments, or career departments with low staffing levels, this job is done by whatever staff are available.

Several specialized tools are used in forcible entry. They can range from a pry bar to hydraulically powered tools. Naturally, different tools are used on different doors, depending on the how difficult a particular door is to open. Difficulty generally depends on the locking mechanism, the doors materials and the door frame. These items taken singularly rarely cause problems, but in combination they can make forcible entry difficult. For example, a difficult door and door frame combined with an average deadbolt lock would be relatively easy to open. However, if the same door and frame were combined with a heavier lock, it will take much longer to open the door. If a glass door was used, it is much less expensive to replace the glass than to replace the door frame. Sometimes, it is easier to breach an adjacent wall than to try to open a door. [31]

Tools used to open doors can be divided into three groups

1. Axes and portable hand tools
2. Mechanical hand tools
3. Portable power tools

The first group consists of two types of axes (flat headed and pick headed), Halligan tool, pry bar, Kelly Tool, claw tool and sledge hammer. The Halligan and Kelly tools combine the benefits of many tools into one unit (pry bar, claw, hooks, punch and lock breaker). The firefighter can be more efficient using these tools, without adding weight that will slow him down.

The mechanical hand tools include bolt cutters, rabbet tools, and the Detroit door opener. Bolt cutters are used on padlocks. The rabbit tool is a small hand powered hydraulic tool used to spread the door jam away from the door and its locking mechanism.

Portable power tools include gas powered hydraulic tools, gas powered saws, and oxy-acetylene torches. Although it is very heavy and has poor mobility, gas powered hydraulic tools can be useful when a difficult door is encountered. Gas powered saws can be used to cut out a locking mechanism on a door or to breach an adjacent wall. The blades of circular saws can be changed to accommodate many materials such as metal, masonry or wood. Finally, when thick steel is encountered, an oxy-acetylene torch can be very helpful, as it may be quicker to cut a locking mechanism out of a door than to pry it open. An engineer must recognize all of these tools when modeling the time to perform a forcible entry.

# Appendix B

# Sample Room Layouts

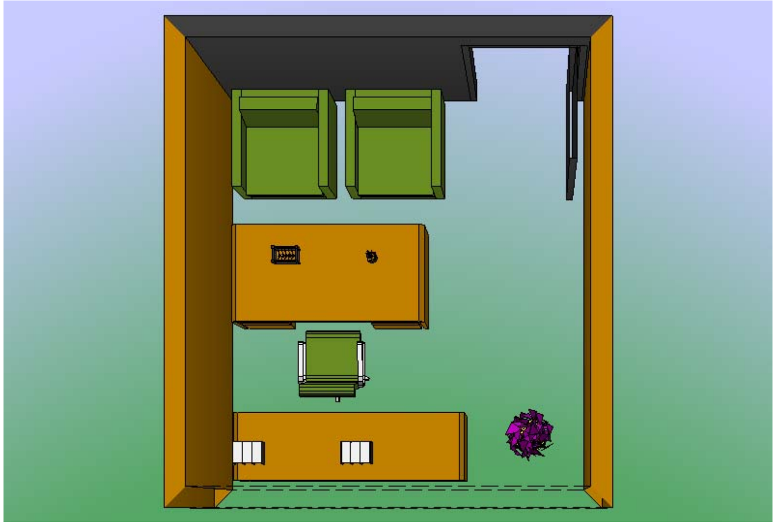

Figure B.1: Small Middle Managers Office

| Quantity | Typical Contents |
|---|---|
| 1 | Credenza |
| 2 | Chair |
| 1 | Executive Chair |
| 1 | Office Workdesk |

Table B.1: Typical Small Office Contents

| | Two A13 Chairs - 60s Apart |
|---|---|
| Medium Fire | 229s. |
| Fast Fire | 126s. |

Table B.2: Time to Flashover

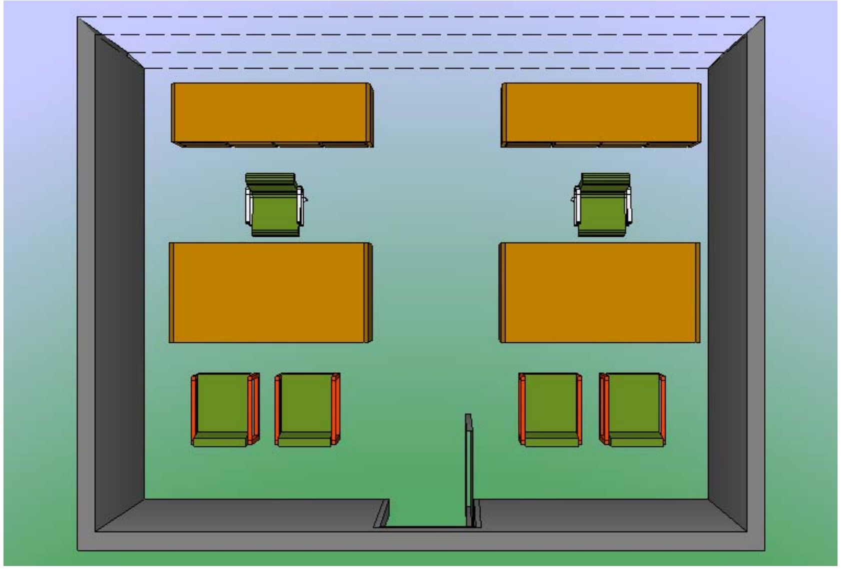

Figure B.2: Model Medium Office

| Quantity | Typical Contents |
|---|---|
| 2 | Credenza |
| 4 | Sled Base Chair |
| 2 | Executive Chair |
| 2 | Office Workdesk |

Table B.3: Model Medium Office Contents

| | Four A13 Chairs - 60s Apart |
|---|---|
| Medium Fire | 283s. |
| Fast Fire | 159s. |

Table B.4: Time to Flashover

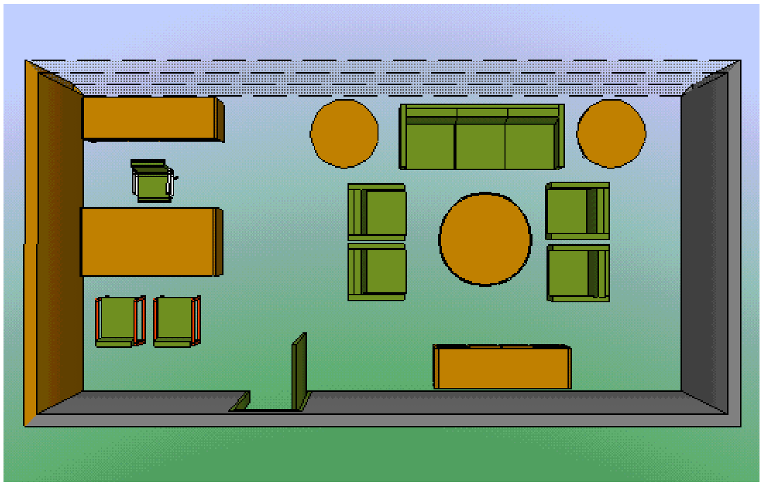

Figure B.3: Model Large Office

| Quantity | Typical Contents |
|---|---|
| 2 | Credenza |
| 4 | Chair |
| 1 | Sofa |
| 2 | Round Pedestal Table |
| 1 | Round Table |
| 2 | Sled Base Chair |
| 1 | Executive Chair |
| 2 | Office Workdesk |

Table B.5: Model Large Office Contents

|  | Four A13 Chairs - 60s Apart |
|---|---|
| Medium Fire | 230s. |
| Fast Fire | 149s. |

Table B.6: Time to Flashover

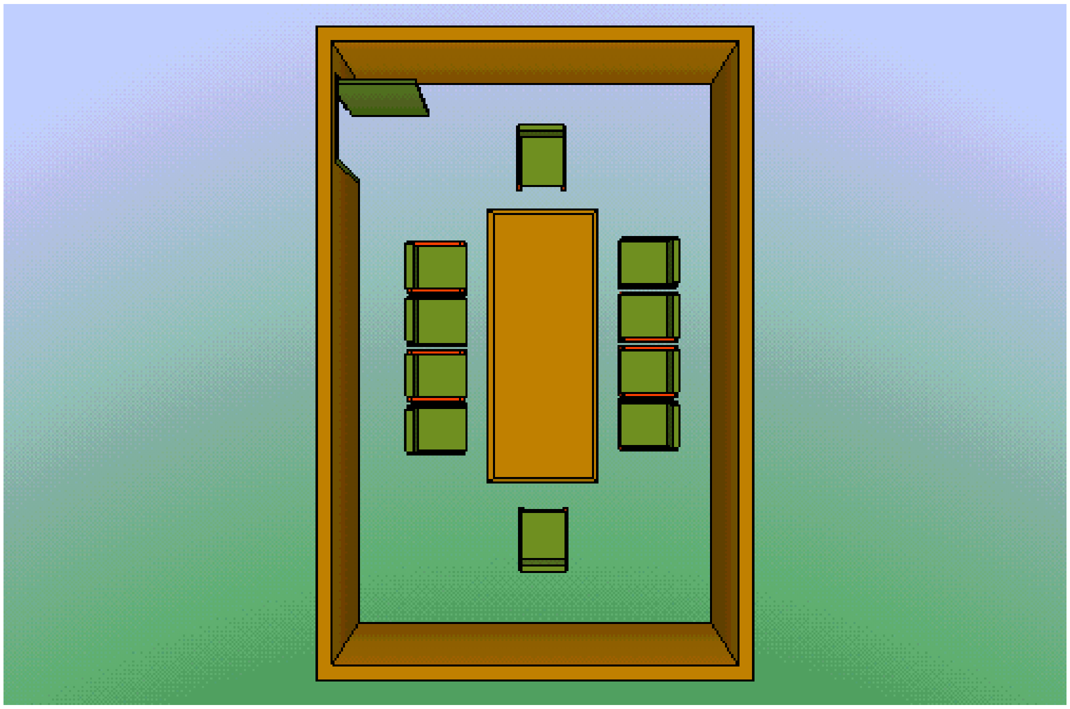

Figure B.4: Model Conference (Board) Room

| Quantity | Typical Contents |
|---|---|
| 10 | Chair |
| 1 | Table |

Table B.7: Model Conference Room Contents

| | Four A13 Chairs - 60s Apart |
|---|---|
| Medium Fire | 256s. |
| Fast Fire | 218s. |

Table B.8: Time to Flashover

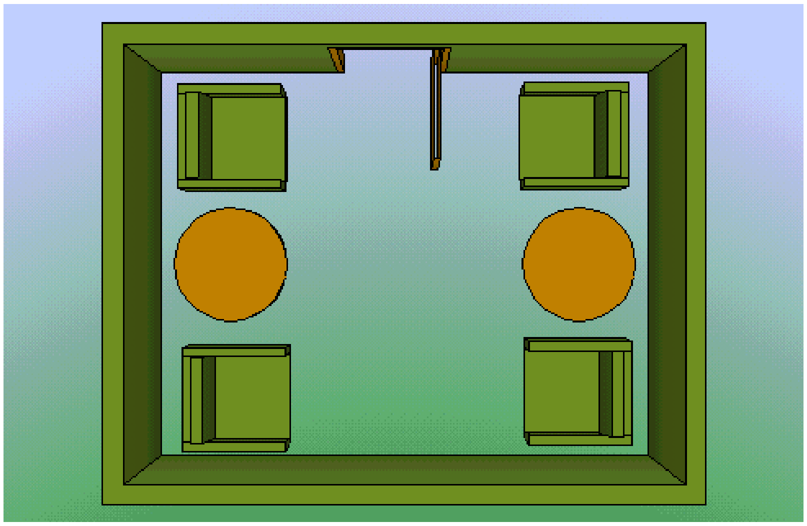

Figure B.5: Model Lobby Layout

| Quantity | Typical Contents |
|---|---|
| 4 | Chair |
| 2 | Table |

Table B.9: Model Lobby Contents

| | Four A13 Chairs - 60s Apart |
|---|---|
| Medium Fire | 190s. |
| Fast Fire | 134s. |

Table B.10: Time to Flashover

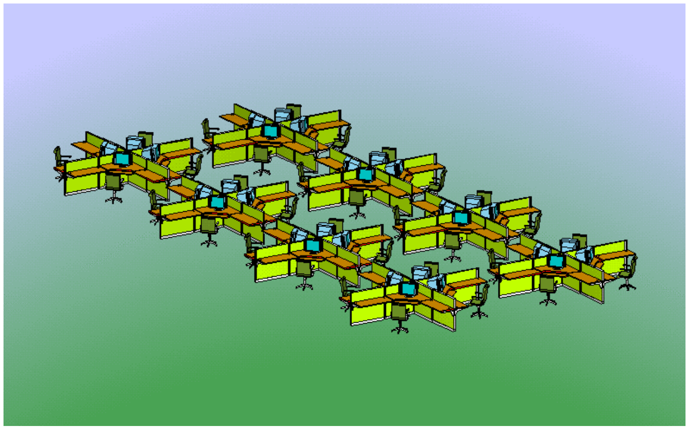

Figure B.6: Model Open Office

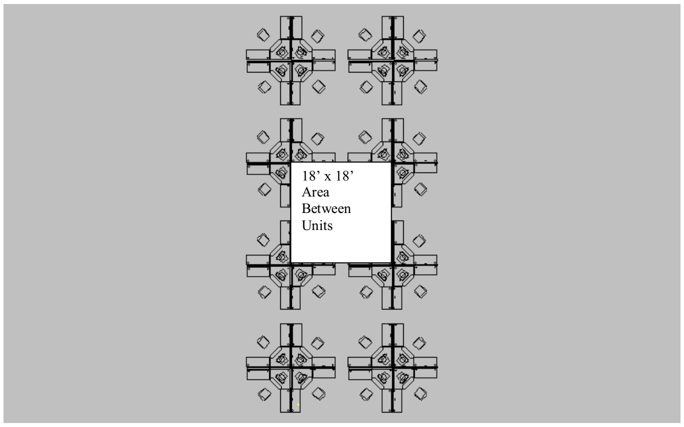

Figure B.7: Open Office Layout

File and library areas are areas where bulk materials are stored. Most of the material consists of paper. Configuration is not deemed as important as the other areas, and only statistical data will be used to perform analysis in these areas. Based on the data presented in the paper by Culver and Milke[9][6], an area of 100 Sq. Ft. was chosen for the file storage area, and 300 Sq. Ft. for the library.

# Appendix C

# Example Design Fires

## C.1 Design Fire

Fires must be developed for the associated office building compartments for the type of building layout that is being studied. An associated model for the spread of fire to other compartments must also be developed.

It is important that information about smoke and heat in the burning compartments and their neighbors is available so the influence of these factors on firefighter movement can be established. For some occupancies such as office buildings, there is a large amount of generalized information available about ventilation and fire loading. Information about the building is vital to the development and integration of the overall model.

Fire models such as the zone model CFAST can be used to develop generalized design fires for individual compartment types. The output from these programs includes information on time to compartment flashover and smoke movement information outside the room of origin.

### C.1.1 Fast Design Fire

Due to the large number of potential disadvantages of choosing an absolutely worst case fire, the method of pessimization will be utilized to develop the "fast" fire instead. This method is described by Babrauskas [2] as follows:

> Pessimization is analogous, but inverse to, optimization. In optimization the designer the loading given and varies the structure. In pessimization he takes the structure as given and varies the loading(i.e., fire). Pessimization is not the same as a worst case approach. In a worst case approach all the controlling problem variables are adjusted for the worst value. On the other hand, in pessimization, only certain problem variables are adjusted. Limits are placed on the range of the pessimized variables to correspond to the expected design limits. The design range for any variable is usually smaller than the total physically possible range.

Babrauskas' was concerned with fire endurance in buildings. This he defined as the property of a building element (barrier) that enables it to stop or delay the spread of fire in a building after the room of origin becomes fully involved. The design fire he used contained with three elements:

1. Walls
2. Fire Loading
3. Ventilation

He argued that a worst case fire is not the best approach. In the worst case approach all three elements would be pessimized and the resulting room design would flash over immediately and burn at adiabatic flame temperature for an infinite time. He stated that the most useful way to utilize this approach in the post flashover regime is to specify over two variables and pessimize over the remaining one. One of the variables he deemed desirable to specify is the wall properties. This was for two reasons: (a) there is normally less variation in wall losses than in fuel and window sizes so therefore one curve should provide sufficient generality and (b) if you don't specify wall losses the temperatures can theoretically near the stoichiometric conditions, which are clearly inappropriate.

He suggested that pessimizing over ventilation is more useful than pessimizing over fuel load. In the post flashover regime, pessimizing over fuel load tends to be a monotonic exercise. The more fuel, the longer the fire burns, and generally the hotter it burns. There is a point where having too much fuel will lower the temperature, but data for this condition is difficult to obtain, and not especially significant. In contrast, too much ventilation cools the fire, too little chokes it, which also leads to cooling. Varying the ventilation results in an intermediate value giving the most pessimistic result. Ventilation was the variable that Babrauskas chose to pessimize.

It should be noted that Babrauskas was concerned with the post flashover regime. For the purpose of this study examining the pre-flashover regime is more significant. Once the room of origin has flashed over a reasonable model can be created to deal with how it will influence adjacent rooms.

## C.2 Compartmentation - Time to Flashover

To calculate flashover times for office buildings different room types will be defined, and characteristics will be attached to these types. These characteristics will be wall type, dimensions, initial burning fuel package, and ventilation. As in Babrauskas' case, the subject of which variable to specify and which to pessimize arises.

### Influence of Wall Type

In the pre-flashover regime, walls are appropriate to specify for the same reasons as in post-flashover. There is normally less variation in wall losses for different building designs than there will be in fuel packages and ventilation, so this variable will have less influence than the others. The room dimensions for the chosen design fires will also roughly correspond to any room of that particular type. The influence of this variable should be small as well.

### Influence of Fuel Package

The initial fuel package is extremely important, and should be pessimized. One piece of furniture could result in no flashover at all, while another could result in flashover in a very short period of time. From a firefighting case, we are more considered with the latter than the former. The vast majority of fire departments can put of a fire that is confined to the room of origin and provides no threat of flashover. The fire will probably burn itself out. In pessimizing the fire, it is clear that the faster an item reaches a particular heat release rate, the quicker the room will flash over. The problem then becomes choosing a reasonable fuel package. The CFAST program provides for a number of fuel packages that can be used in this capacity.

### Influence of Ventilation

In the pre-flashover regime, the more ventilation that is provided the longer flashover will take for a room to flash over. Ventilation in the pre-flashover regime provides more air that needs to

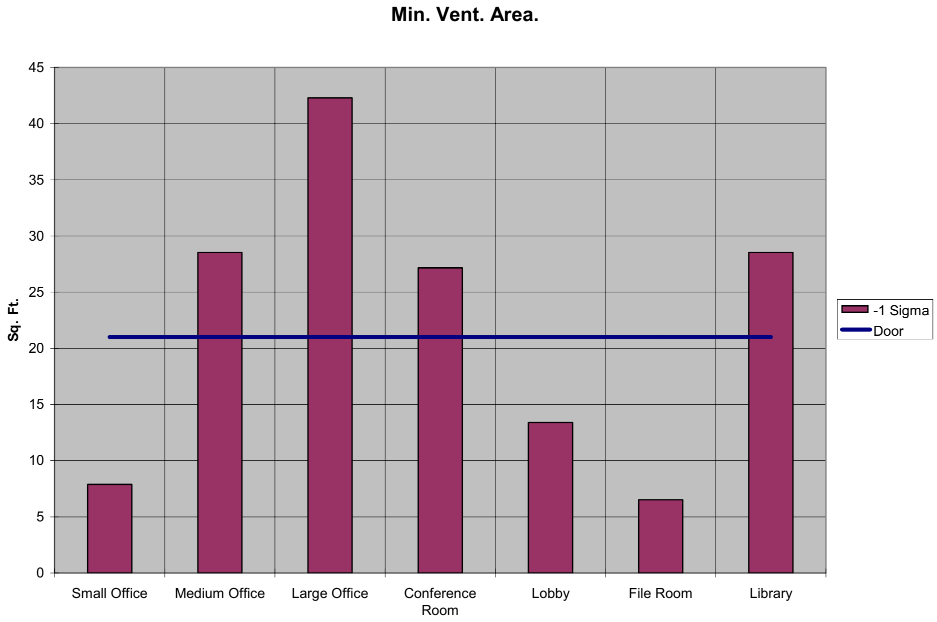

Figure C.1: Minimum Ventilation Area

be heated. In the pre-flashover regime, ventilation may be inadequate for flashover to occur, even with sufficient fuel load. The fire will smother. If a large amount of ventilation is provided, a large volume of air will need to be heated for flashover to occur, and therefore it will take a relatively long time. It is assumed that in a lot of cases (the small office shown in Appendix B being a good example) an open door is the most pessimized ventilation, as it provides adequate ventilation for flashover to occur, but not so much that the fire will be over ventilated, or so little that it will be smothered. A comparison of an open door with Culver's -1 Sigma areas is shown in Figure C.1. It should be noted that in most cases, Culver's -2 Sigma limits were less than zero so it is believed these are good numbers for comparison.

To compare this assumption with real office information, data taken from Culvers' paper is shown . Culver's distribution data points are not provided, but it is clear that his data results in negative ventilation areas in the negative 2 sigma area. Therefore the "no window condition, in which all the results in the table would be zero is a reasonable pessimistic assumption In this case minimum

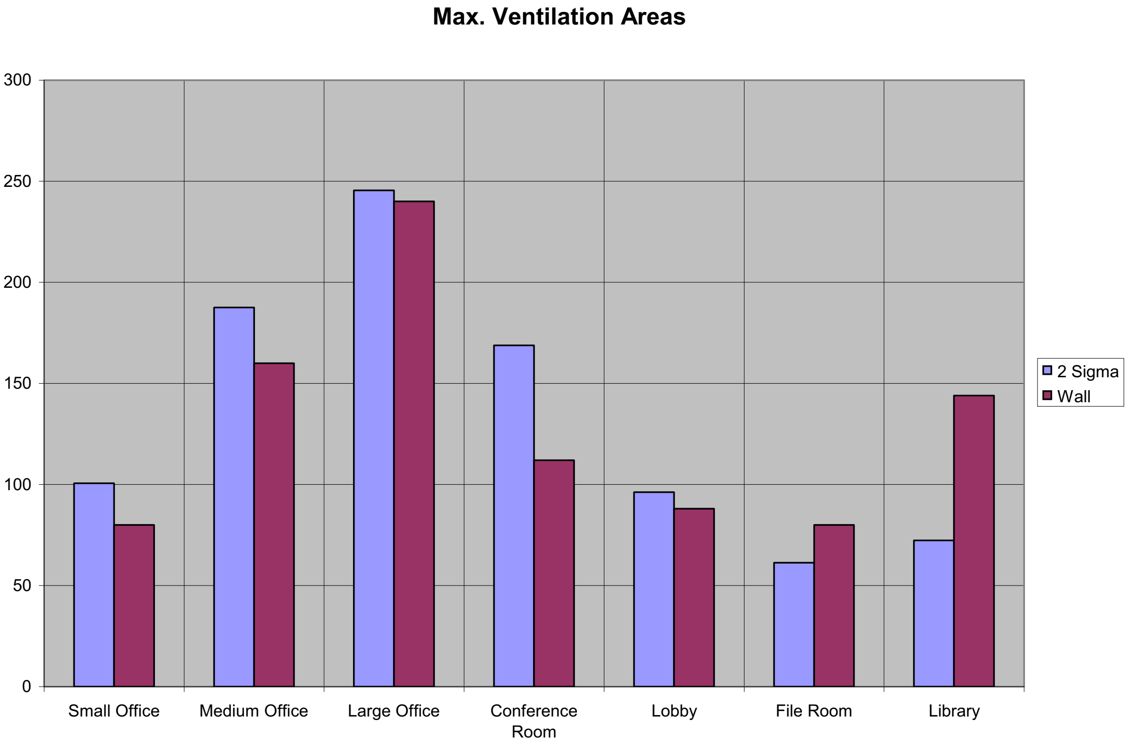

Figure C.2: Maximum Ventilation Area

ventilation would be provided by an open door only.

Piloted ignition in rooms adjacent to the door of the room is assumed to occur when the room of origin flashes over for the fast building fire model. Other adjacent rooms are also ignited if they have an open area in common with the room of origin. This relatively simple method allows for a pessimistic fire that defines one side of the firefighter fire problem.

### C.2.1 Medium Design Fire

To develop a medium fire, the fuel packages from the room of origin will kept the same, but the ventilation will be increased to slow the fire down. Babrauskas argues that the maximum ventilation encountered will consist roughly of having one wall open as ventilation[2]. This correlates well with information drawn from Culver[9] as shown in Figure C.2

| Type | Fuel Package | Medium Fire | Fast Fire |
|---|---|---|---|
| Small Office | Two A13 Chairs - 60s. apart | 229 | 126 |
| Medium Office | Four A13 Chairs - 60s. apart | 283 | 159 |
| Large Office | Sofa - Small Office 60s later | 230 | 149 |
| Conference Room | Four A13 Chairs - 60s. apart | 256 | 218 |
| Lobby | Four A13 Chairs - 60s. apart | 190 | 134 |
| File Room | Stacked Paper in Cartons | 142 | 100 |
| Library | Stacked Paper in Cartons | 186 | 128 |

Table C.1: Compartment Time to Flashover

### C.2.2 Slow Design Fire

In slow fires are taken to be the same as medium fires for each of the rooms, but all doors are assumed to be closed, and ignition of spaces adjacent to doors is limited to door burn through.

### C.2.3 Special Cases

Note that there are a number of special cases that require simulation that is beyond the scope of this general model. Smoldering fires are difficult to model using zone fire models, due to the indistinct formation of layers that are assumed using zone models. Smouldering fires are potentially very dangerous as they are difficult to find and can quickly erupt into much larger fires once they are located and ventilated. Fires that occur as a result of arson are also difficult to model. These fires can occur with much larger heat release rates due to the use of accelerants. Due to accelerants, ignition can begin over a large area consisting of many rooms, rather than starting at a point, as occurs in most ”normal” fires.

## C.3 Design Fire for Offices - Open Office Plans

In open offices, sizes of the components become an issue. The sizes of the open office stations for secretarial, clerical and executive shown above are all roughly 10’ x 10’, but they house 4, 4 and 1 person respectively, each in a different configuration. Very large spaces may not flash over in the traditional sense, so they will need special treatment. A localized flashover condition may be more appropriate. We may consider that flashover conditions will occur over a certain area of the space. For example, if the flashover conditions occur in an area of say 100 $m^2$, it may be considered a much more significant hazard than if it was smaller, and firefighting tactics may be changed as a result.

A number of important conclusions were drawn about fires in open office spaces in Harold Nelson's review of the First Interstate Bank Fire of 1988. [22] These conclusions include:

1. The recognition that open arrangements in office settings can develop to flashover. There is a demonstrable fire potential associated with open office arrangements that contain concentrated grouping of combustible work areas. Where such concentrations occur in spaces involving large floor areas and relatively low ceilings, there is usually sufficient combustion air within the space to allow a developing fire to reach flashover conditions. *This even if no additional air is introduced into the space. The traditional light hazard expectations associated often associated with offices do not apply in these cases.*
2. High space utilization office landscape have the potential, even without the assistance of flashover, of spreading fire over large areas producing fires of major portions.
3. There is an important relationship between the release of fuel from a burning array as the result of heat impinging on it and the availability of oxygen (air.) These relate to efficiency of combustion. Efficiency of combustion is in turn a major determinant of the ability to burn, room layer temperature, carbon monoxide production, oxygen content, fuel transport and flame length.
4. It must be expected that fire products will be spread by natural forces to remote portions of the building given sufficient time. The degree of problem ensuing will be a function of the efficiency of combustion of the fire, the tightness of the shafts and other communicating passages, the presence or absence of smoke control systems, the height of the building, and the weather conditions at the time. Analysis of the potential involved is important if persons may have to take refuge in the building during the fire.
5. Floor to floor propagation is a potentially serious problem in window wall buildings. The

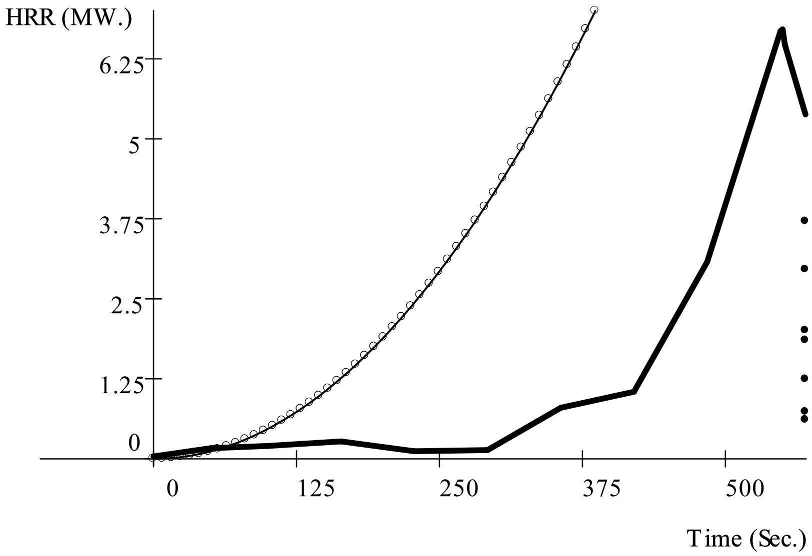

Figure C.3: 3 Panel Workstation HRR Compared to Fast Fire

knowledge of flame extension from windows, particularly where petroleum base polymers are involved is insufficient. A better understanding of the relationships between burning rates and flame lengths is needed.

6. In this fire the duration of burning on a floor and the rate of fire propagation from floor to floor were close to each other. A longer duration fire or a faster floor to floor spread could result in an unstoppable fire. Longer duration condition would be expected where a higher total fuel load existed such as commonly occur with merchandising displays or extensive use of combustible interior finishes.

Workstation configurations are commonly used in open office plans. It can be seen from Figure C.3 that the slope of the burning rate rapidly approaches that of a fast fire. This is the type of fire Nelson used to describe burning workstations.[22]

Data is also available on workstation heat release rates from a paper by Madrzykowski[**?**]. Using data he developed design fires were constructed for workstations with 2,3 and 4 panels respectively. These resulted in the estimated flashover times for 18' x 18' cube areas shown in Table C.2. Four workstations were assumed to be involved. Ignition of adjacent workstations was assumed when

| Type | Ceiling Height | Fire | Time to Flashover |
|---|---|---|---|
| Slow Fire | 9’ | 2 Panel | 568s |
| Medium Fire | 8’ | 3 Panel | 457s |
| Fast Fire | 8’ | 4 Panel | 292s |

Table C.2: Open Office Flashover Time

the first workstation reached a heat release rate of 1 MW.

# Appendix D

# Collected Task Data

Design charts are not included for some static operations. In static operations firefighters do not move from a particular location, so design charts do not provide useful information. The graphs appearing in this Appendix are formatted differently than the rest of the graphs used in this paper. They are the result of using specialized distribution fitting software.

| Operation | Points | KS-Stat | Calc. KS Stat | P-value | Result |
|---|---|---|---|---|---|
| Alight Truck | 102 | 0.101 | 0.133 | 0.239 | DNR |
| Bring 2.5 in. Hose to Side of Truck | 24 | 0.234 | 0.269 | 0.124 | DNR |
| Call and Receive Water | 12 | 0.16 | 0.375 | 0.871 | DNR |
| Chock Wheels | 31 | 0.188 | 0.238 | 0.198 | DNR |
| Clamp Supply Hose | 12 | 0.213 | 0.375 | 0.577 | DNR |
| Connect Hose to Hydrant | 19 | 0.161 | 0.301 | 0.649 | DNR |
| Connect Hose From Bed | 25 | 0.152 | 0.264 | 0.555 | DNR |
| Connect LD hose to suction port | 19 | 0.272 | 0.301 | 0.0997 | DNR |
| Connect Nozzle | 10 | 0.19 | 0.409 | 0.799 | DNR |
| Disconnect Hose From Bed | 29 | 0.134 | 0.246 | 0.623 | DNR |
| Don SCBA | 34 | 0.121 | 0.227 | 0.661 | DNR |
| Drop Supply Line (50') | 30 | 0.113 | 0.242 | 0.795 | DNR |
| Extend 50' Attack | 12 | 0.198 | 0.375 | 0.668 | DNR |
| Extend 150' Attack | 12 | 0.175 | 0.375 | 0.798 | DNR |
| Extend 50' 2.5 in. Line - FF | 12 | 0.198 | 0.375 | 0.668 | DNR |
| Extend LD hose | 18 | 0.175 | 0.309 | 0.58 | DNR |
| Get Hose From Mattydale | 12 | 0.199 | 0.375 | 0.659 | DNR |
| Pull Hose off Bed (100') | 16 | 0.165 | 0.327 | 0.717 | DNR |
| Mount Truck | 19 | 0.165 | 0.301 | 0.618 | DNR |
| Open Hydrant | 18 | 0.149 | 0.309 | 0.763 | DNR |

| Operation | Points | KS-Stat | Calc. KS Stat | P-value | Result |
|---|---|---|---|---|---|
| Pump Runs Away | 16 | 0.195 | 0.327 | 0.513 | DNR |
| Remove Ladder | 36 | 0.0679 | 0.221 | 0.992 | DNR |
| Remove LD hose | 16 | 0.226 | 0.327 | 0.335 | DNR |
| Remove Tool | 67 | 0.12 | 0.163 | 0.264 | DNR |
| Straighten Hose | 15 | 0.164 | 0.338 | 0.759 | DNR |
| Unchock Wheels | 19 | 0.236 | 0.301 | 0.205 | DNR |
| Wrap Hydrant | 12 | 0.235 | 0.375 | 0.453 | DNR |

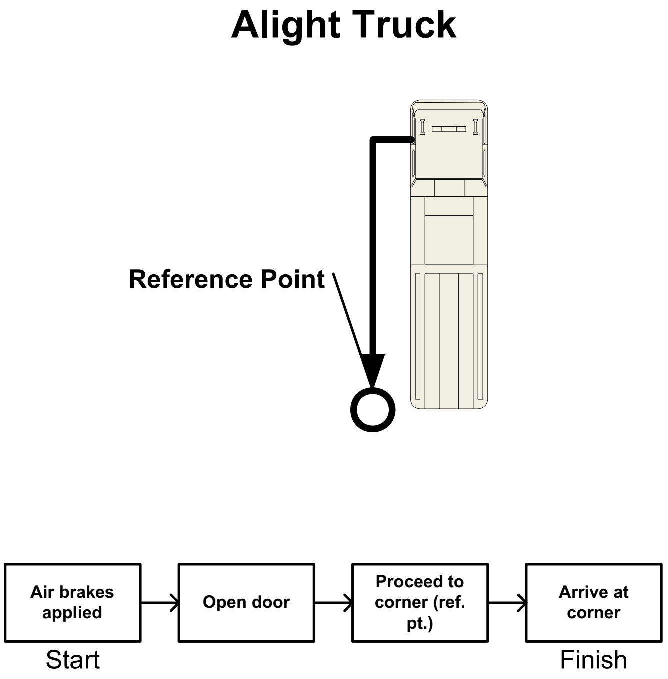

Figure D.1: Alight Truck

*You are using the minimum numbers - they are in the tables - make sure this is reflected in the text*

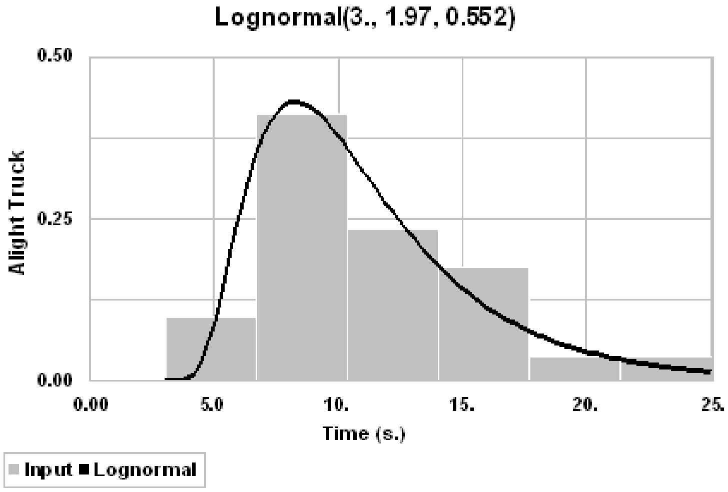

Figure D.2: Fitted Density - Alight Truck

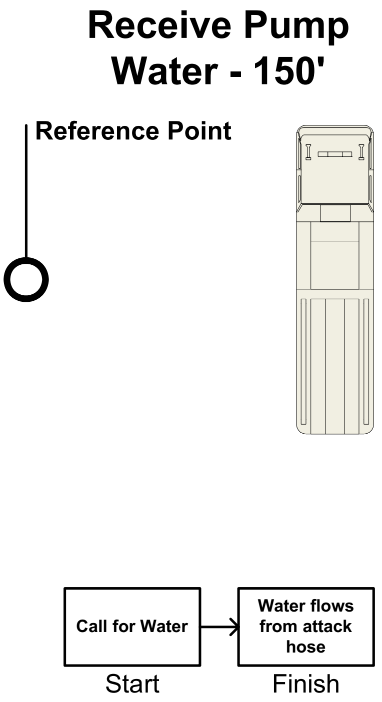

Figure D.3: Call and Receive Water - 150’ Attack Hose

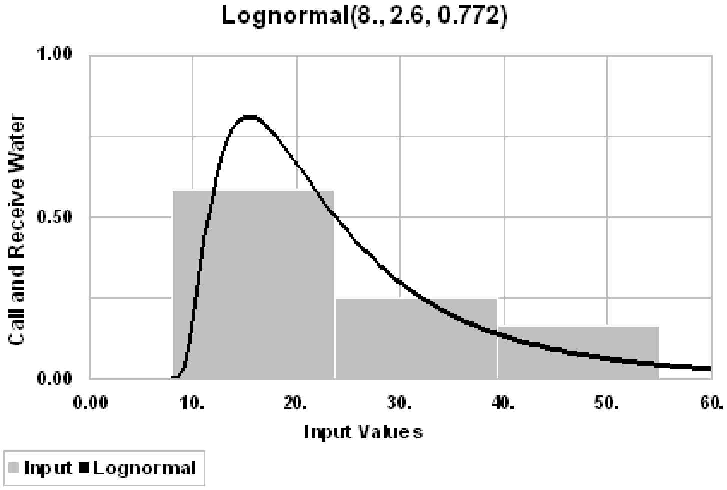

Figure D.4: Fitted Density - Call for and Receive Water

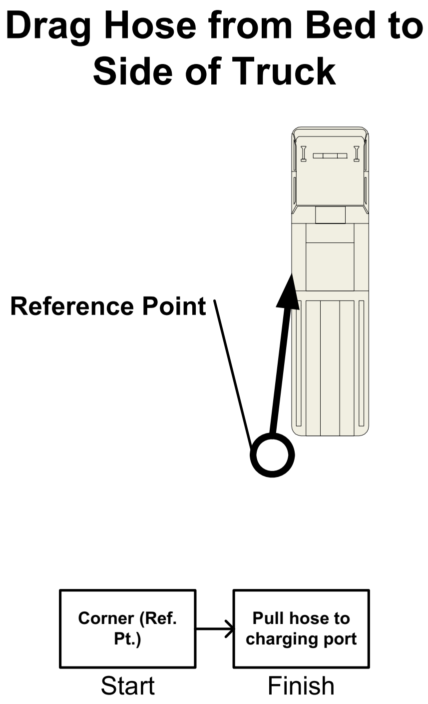

Figure D.5: Move Hose - Bed to Pump

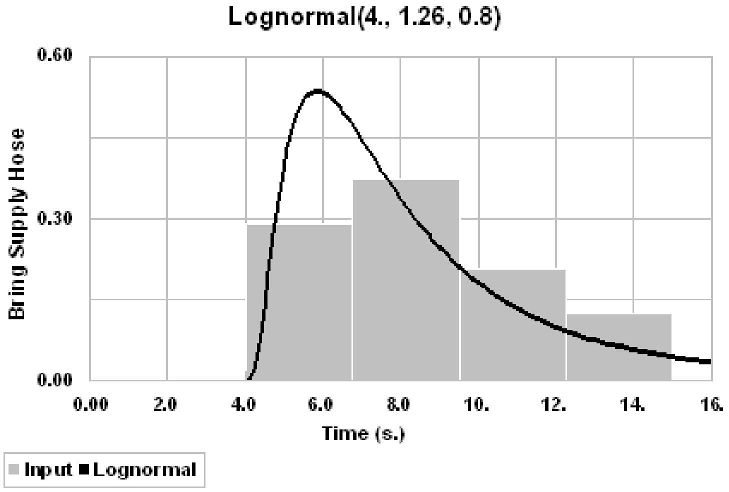

Figure D.6: Fitted Density - Bring Supply Hose From Bed to Side of Appliance

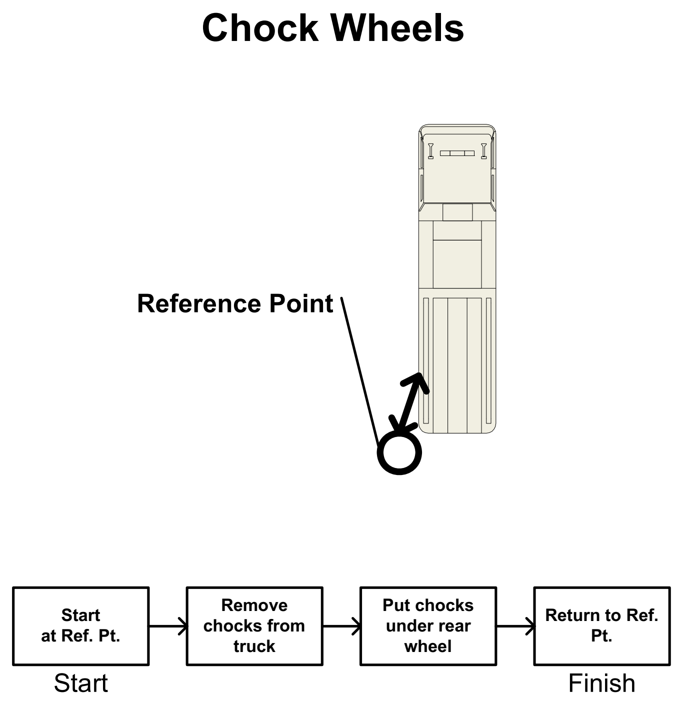

Figure D.7: Chock Wheels

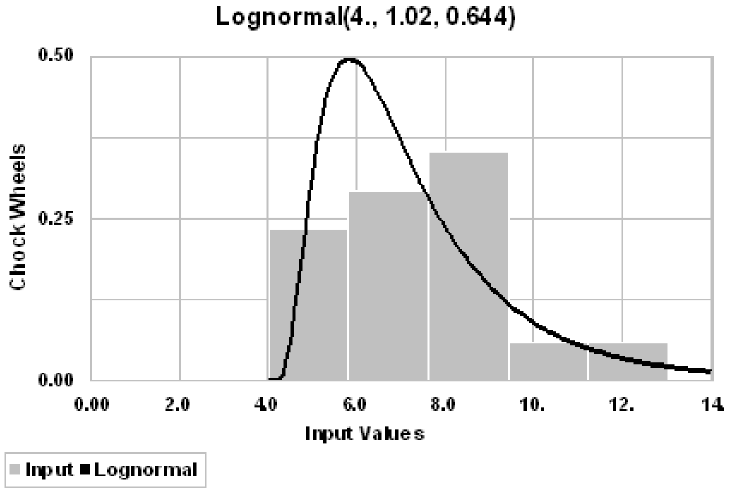

Figure D.8: Fitted Density - Chock Wheels

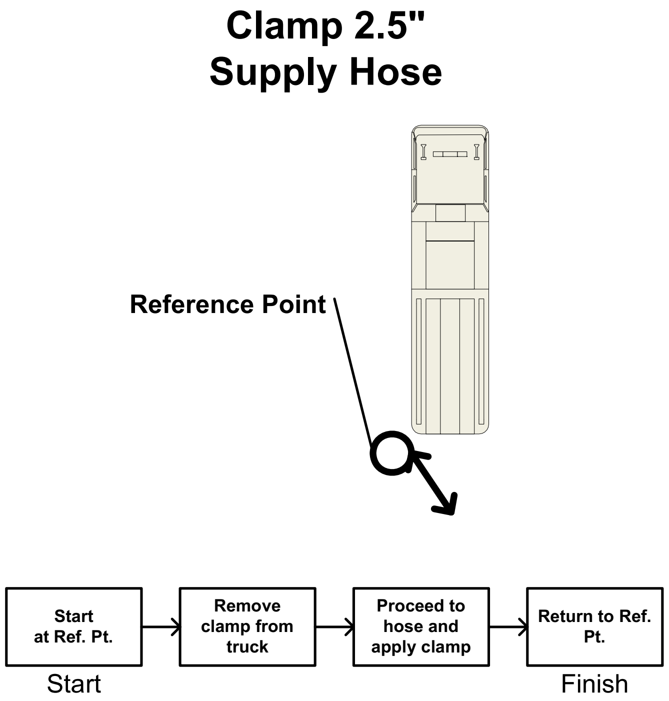

Figure D.9: Clamp Supply Hose

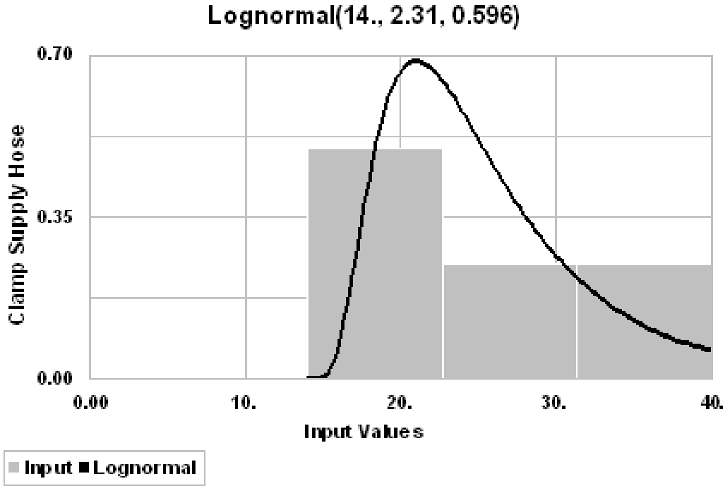

Figure D.10: Fitted Density - Clamp Supply Hose

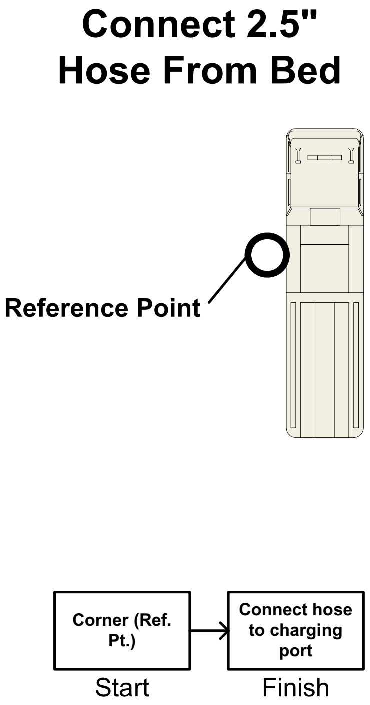

Figure D.11: Connect 2.5” Supply Line From Hose Bed

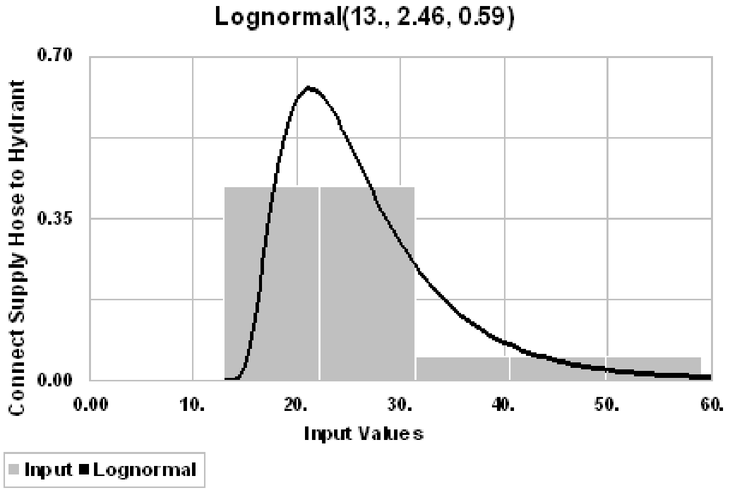

Figure D.12: Fitted Density - Connect Supply Hose to Hydrant

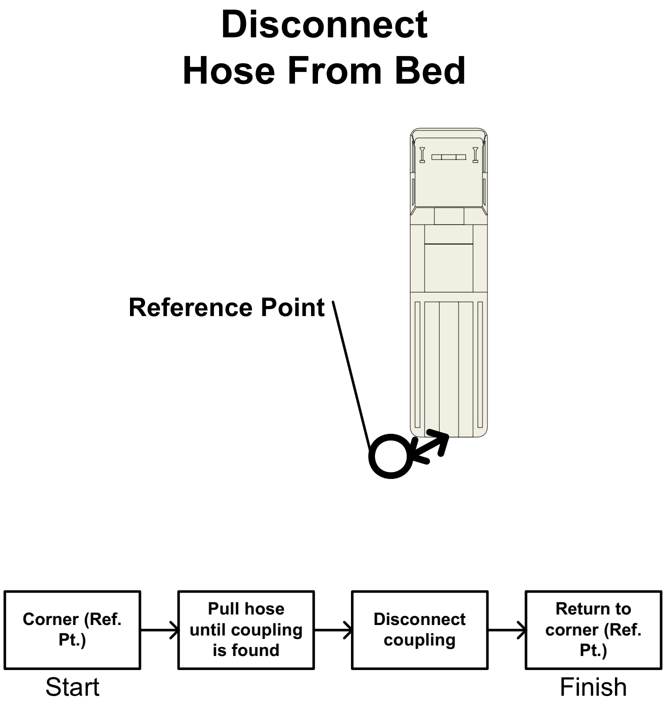

Figure D.13: Disconnect Hose From Bed

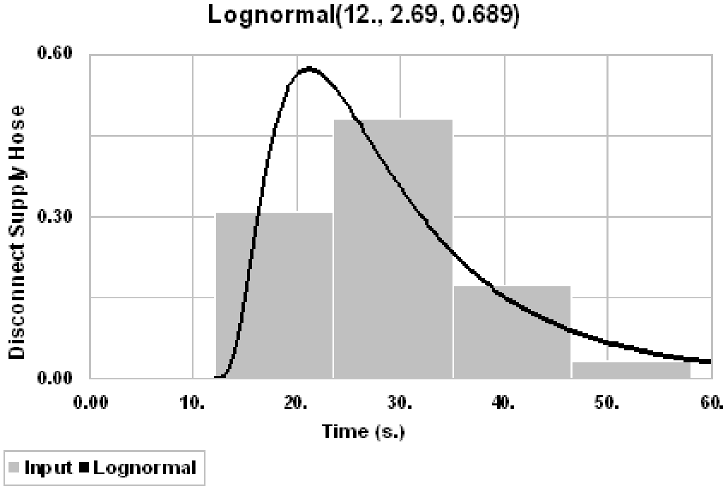

Figure D.14: Fitted Density - Disconnect 2.5” Supply Hose from Hose Bed

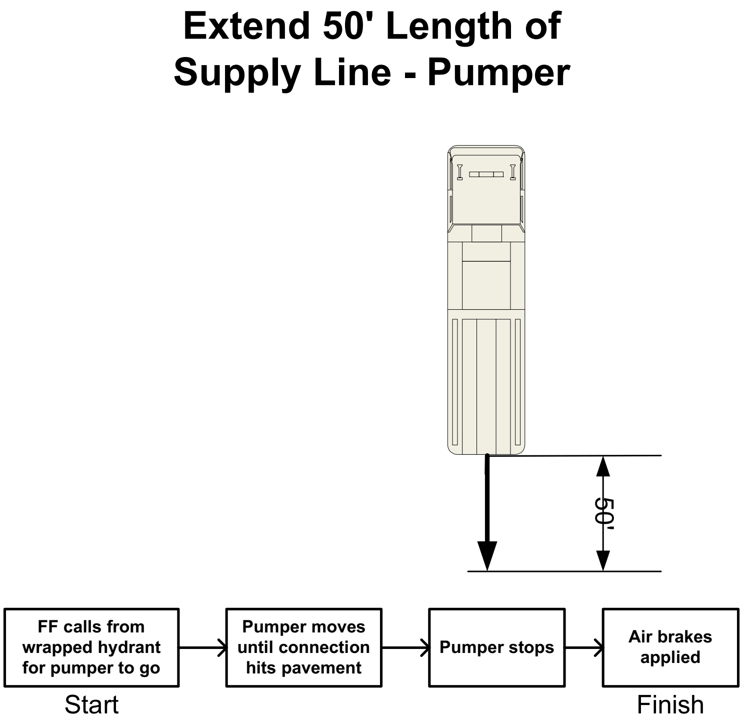

Figure D.15: Extend 50’ of 2.5” Line - Appliance

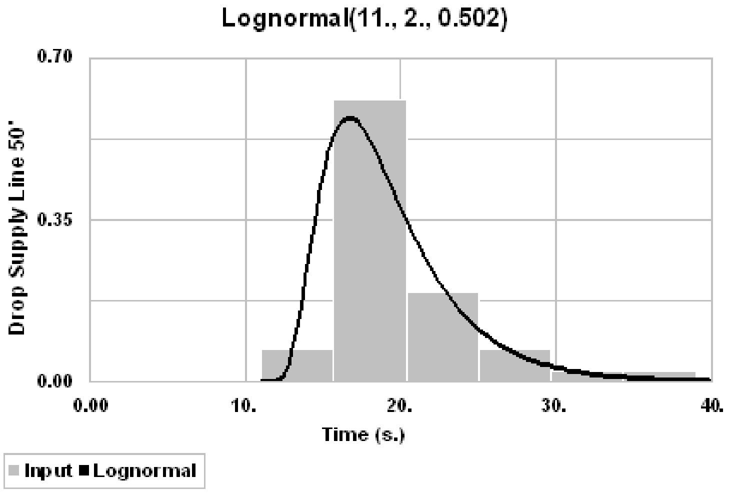

Figure D.16: Fitted Density - Drop Supply Line 50’ (Appliance)

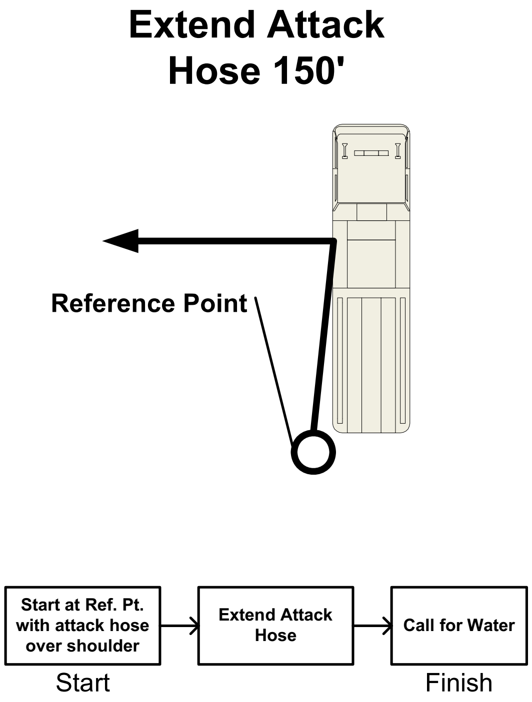

Figure D.17: Extend 1.75” Hose 150’

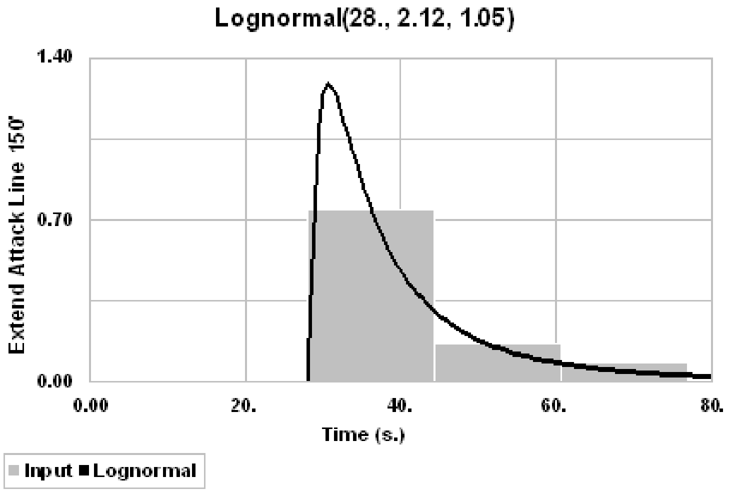

Figure D.18: Fitted Density - Extend Attack Line 150’ (Firefighter)

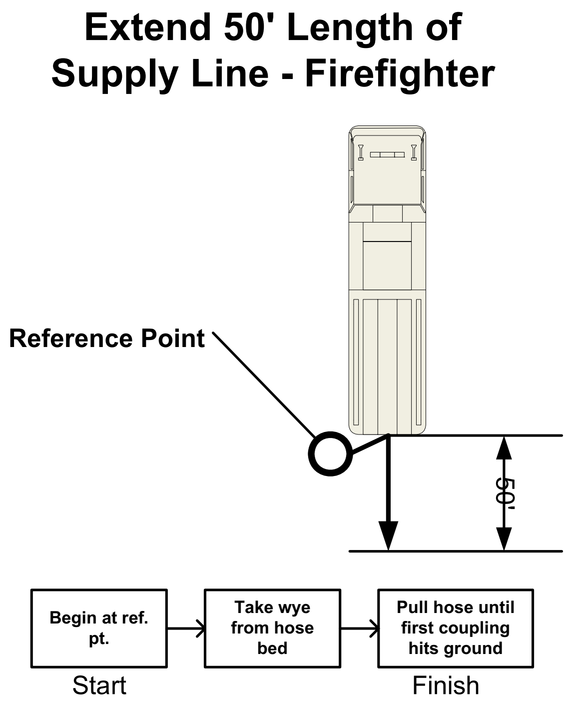

Figure D.19: Extend 50’of 2.5” Line - Firefighter

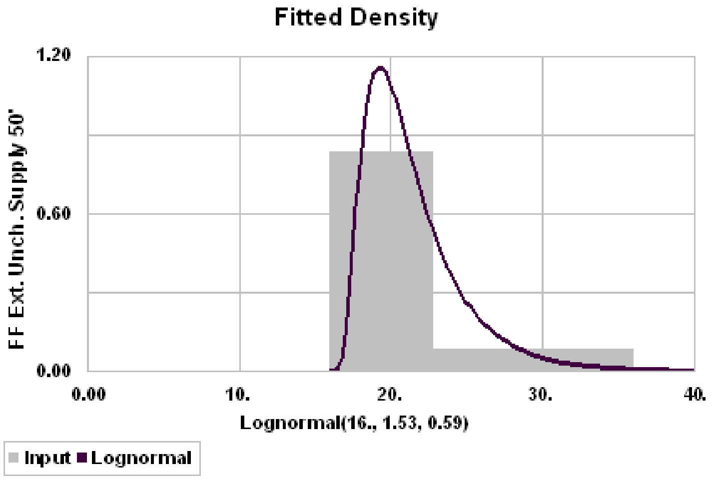

Figure D.20: Fitted Density - Extend Uncharged 2.5” Supply Line 50’

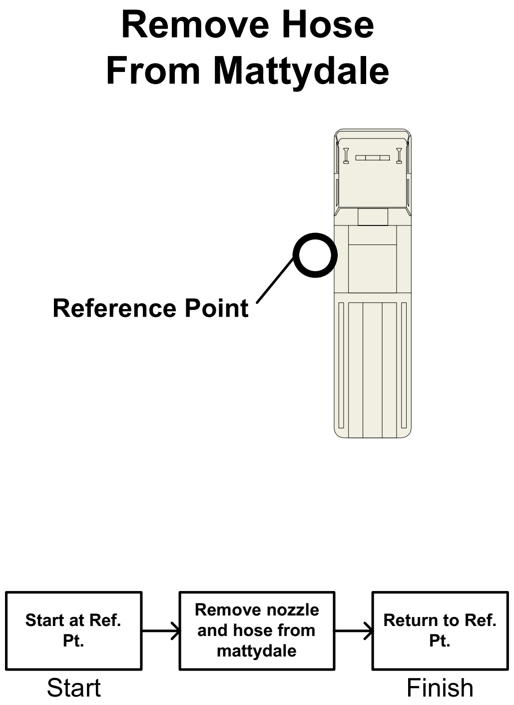

Figure D.21: Remove Hose From Mattydale

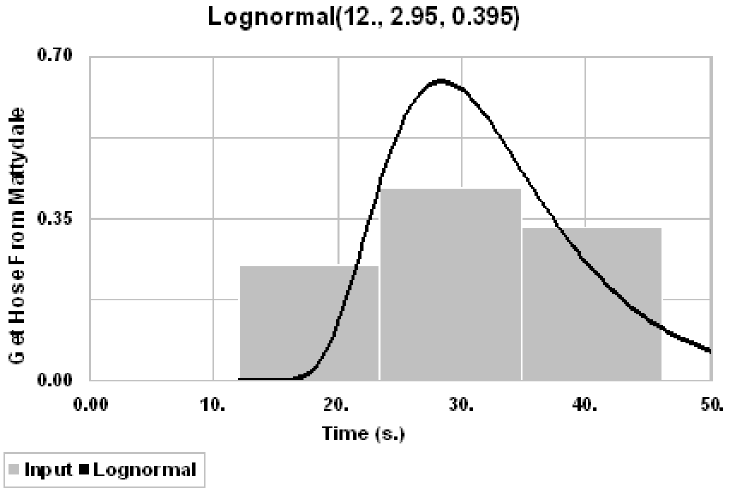

Figure D.22: Fitted Density - Remove Hose from Mattydale

# Wrap Hydrant

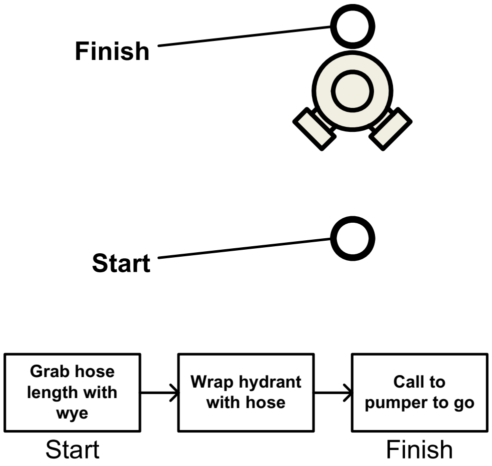

Figure D.23: Wrap Hydrant

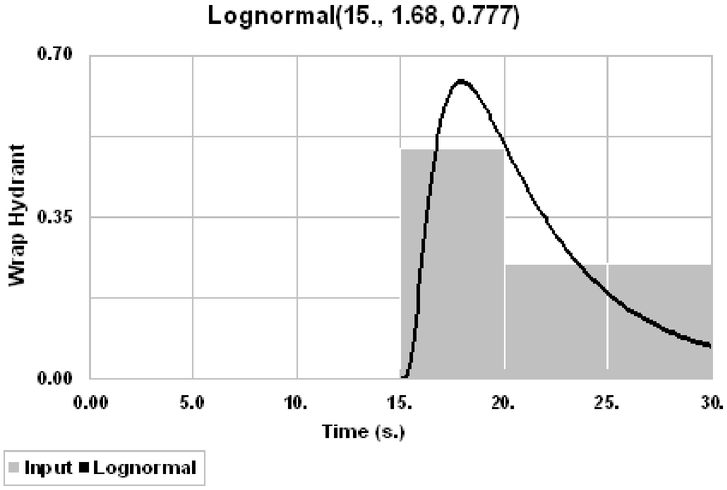

Figure D.24: Fitted Density - Wrap Hydrant

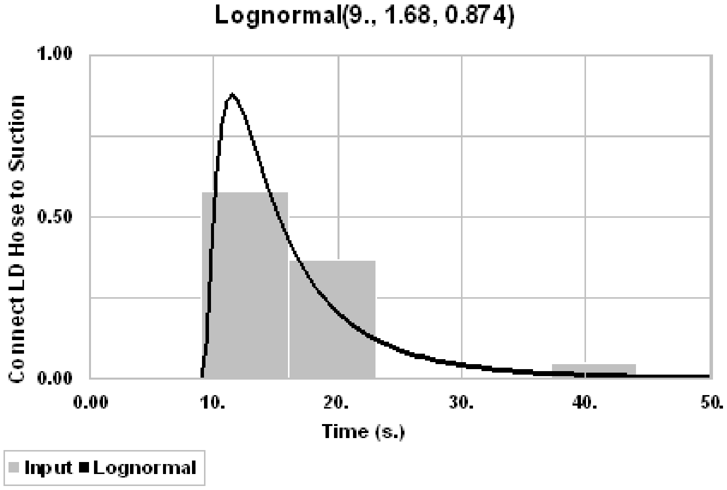

Figure D.25: Fitted Density - Connect LD Hose to Suction

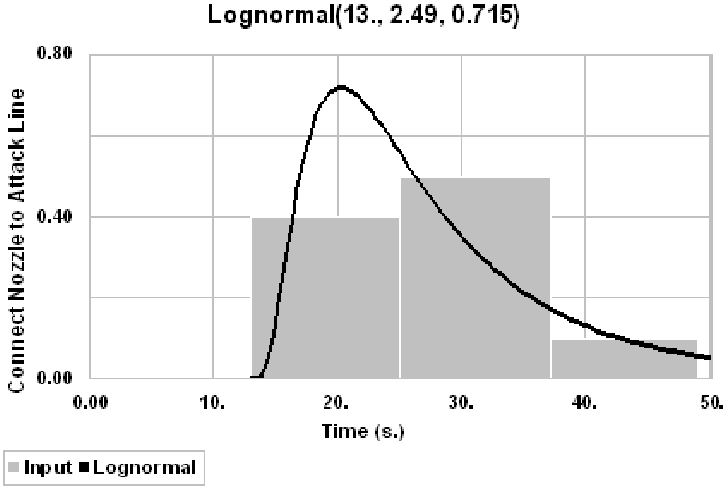

Figure D.26: Fitted Density - Connect Nozzle to Attack Line

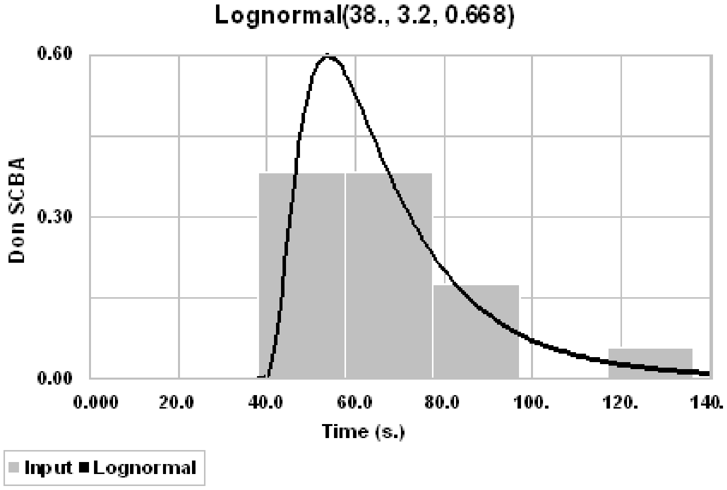

Figure D.27: Fitted Density - Don SCBA

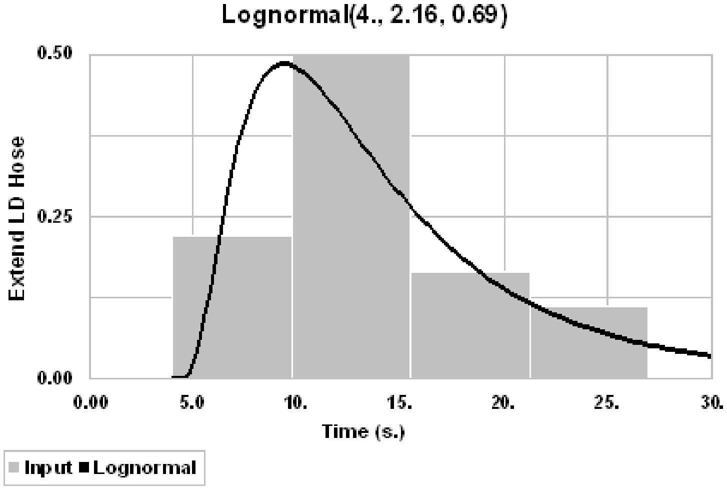

Figure D.28: Fitted Density - Extend LD Hose

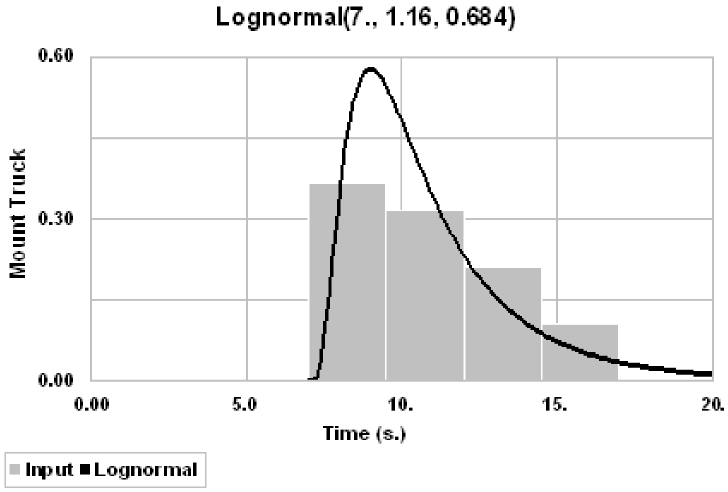

Figure D.29: Fitted Density - Mount Truck

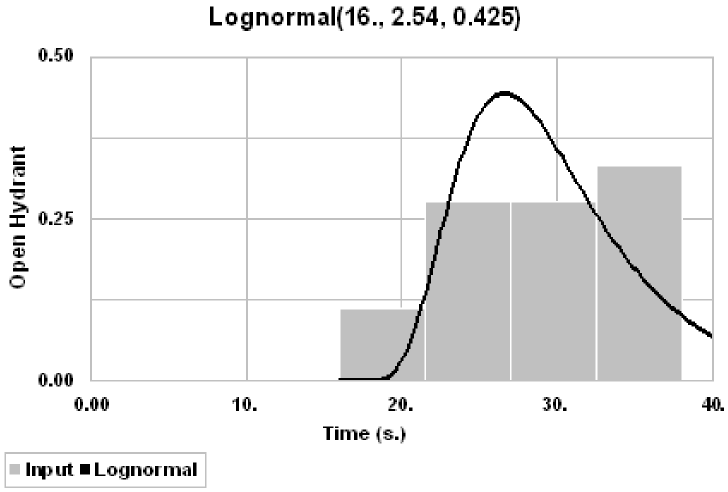

Figure D.30: Fitted Density - Open Hydrant

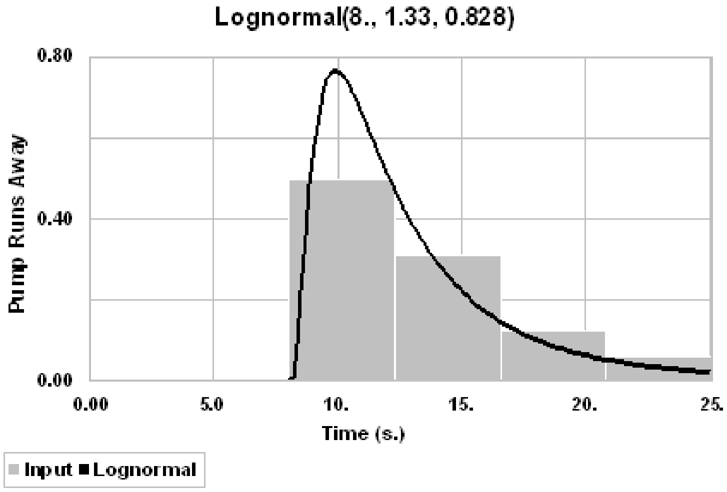

Figure D.31: Fitted Density - Pump Runs Away

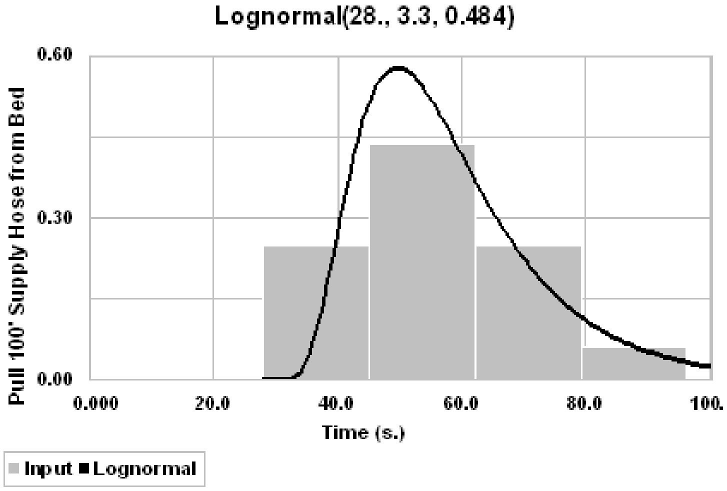

Figure D.32: Fitted Density - Pull 100' Supply Hose From Bed

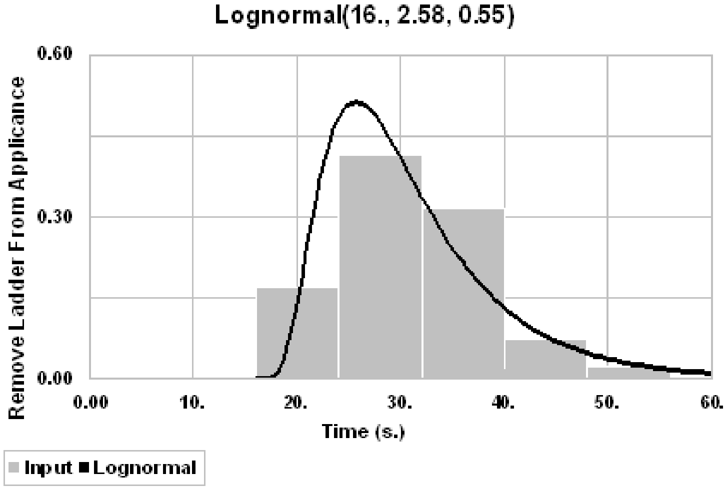

Figure D.33: Fitted Density - Remove Ladder from Appliance

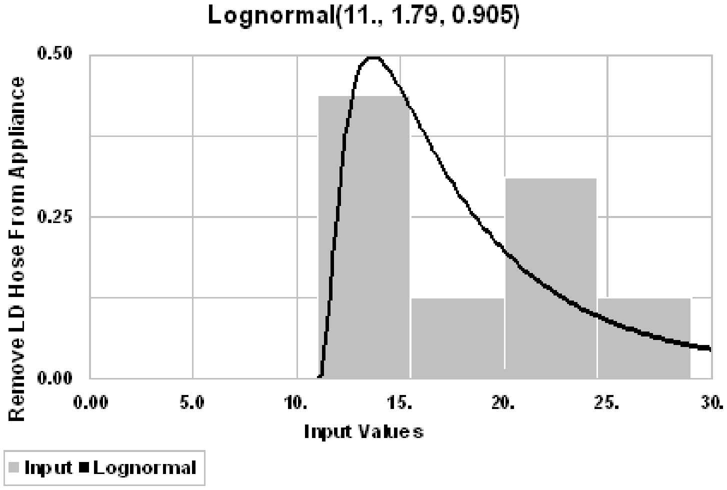

Figure D.34: Fitted Density - Remove LD Hose From Applicance

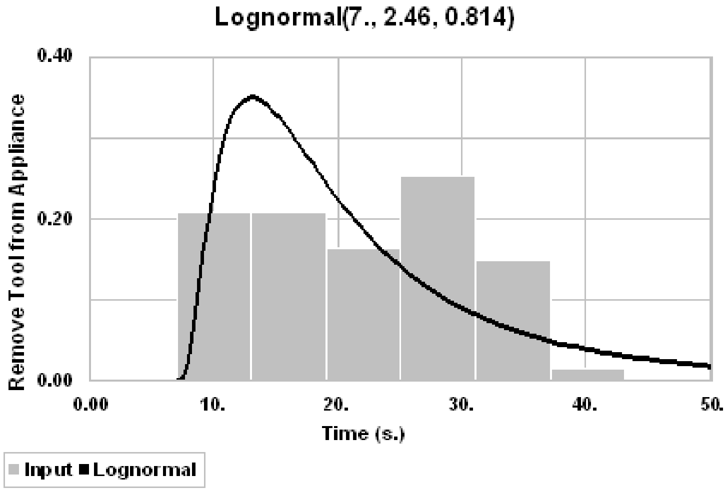

Figure D.35: Fitted Density - Remove Tool from Appliance

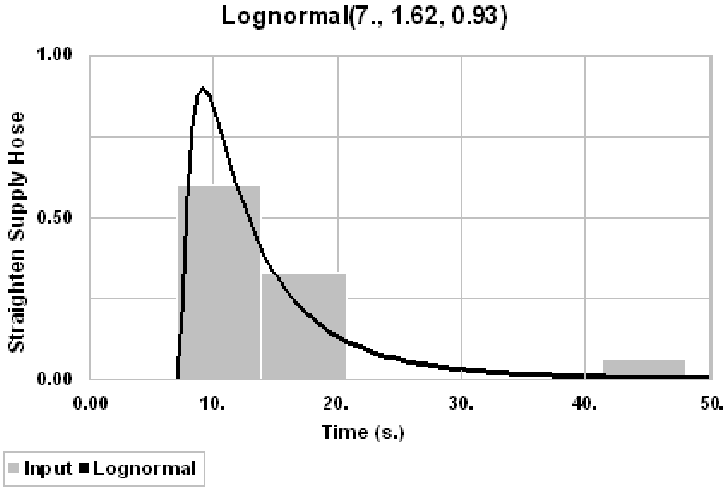

Figure D.36: Fitted Distribution - Straighten Supply Hose

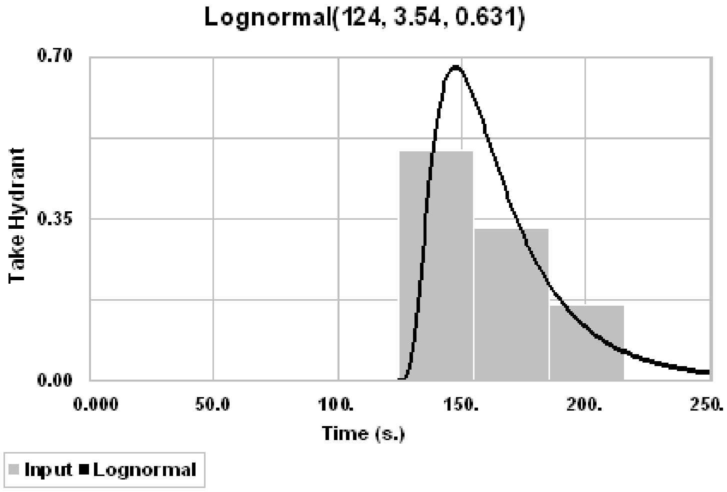

Figure D.37: Fitted Density - Take Hydrant

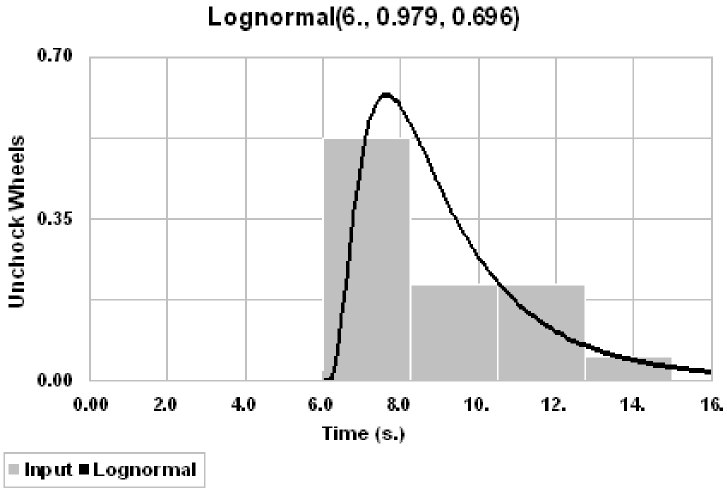

Figure D.38: Fitted Density - Unchock Wheels

# Appendix E

# Australian Task Data

| Graph | Task | Sample: | Min. | Mean | SD | Max. |
|---|---|---|---|---|---|---|
| M | Dismount Appliance & don BA | 259 | 10 | 88.1 | 34.9 | 187 |
| N | Don BA & Hazardous Incident Suit | 40 | 200 | 584.5 | 298 | 1155 |
| O1 | Flush Hydrant | 124 | 4 | 32.8 | 20.64 | 100 |
| O2 | Obtain Hazardous Material Info. | 49 | 153 | 701 | 409.5 | 1400 |
| O3 | Decontamination Unit Set Up | 7 | 624 | 764.9 | 186.1 | 1170 |
| O4 | Assemble Misc. Safety Equip. | 7 | 97 | 290.6 | 132.1 | 465 |
| P1 | Remove Hydrant Equip. | 125 | 7 | 32.5 | 18.1 | 90 |
| P2 | Remove High Rise Pack or Similar | 39 | 5 | 13.5 | 6 | 30 |
| Q1 | Horiz. Travel in Turnout Gear | 244 | 0.32 | 2.33 | 1.44 | 6.25 |
| Q2 | Horiz. Travel in Turnout w/ Equip | 159 | 0.13 | 1.95 | 1.27 | 6.00 |
| Q3 | Horiz. Travel in Turnout w/w/o Equip. | 113 | 0.28 | 1.39 | 0.57 | 3.33 |
| Q4 | Horiz. Travel in Full Hazard Suit/BA | 48 | 0.13 | 0.83 | 0.54 | 2.50 |
| T1 | Ascend Stairs in BA w/ Equip. | 73 | 0.25 | 0.94 | 0.45 | 2.10 |
| T2 | Ascend Stairs with High Pressure Hose | 33 | 0.09 | 0.48 | 0.28 | 1.21 |
| T3 | Ascend Stairs w/ 65mm. Dia. Hose | 34 | 0.15 | 0.71 | 0.31 | 1.4 |
| T4 | Ascend Stairs w/ 38mm. Dia. Hose | 33 | 0.4 | 0.77 | 0.27 | 1.4 |
| T5 | Descend Stairs in BA | 68 | 0.2 | 0.97 | 0.45 |  |
| T6 | Rest Breaks | 11 | 0.5 | 1.86 | 0.82 |  |
| V11 | Rem., Conn & Charge 90mm Hyd to App. | 3 |  |  |  |  |
| V21 | Remove & Connect 65mm. (App to Hose) | 82 | 6 | 39.4 | 17.1 | 80 |
| V22 | Remove & Connect 38mm. (App to Branch) | 36 | 2 | 33.3 | 15.4 | 70.7 |
| V3 | Remove & Connect 65mm. (App to Boost) | 39 | 17.5 | 45.3 | 17.1 | 80 |

| Graph | Task | Sample: | Min. | Mean | S.D. | Max. |
|---|---|---|---|---|---|---|
| V41 | Charge 65mm. from Appliance | 119 | 2.5 | 20.3 | 13.2 | 80 |
| V42 | Charge 38mm. from Appliance | 37 | 6 | 18.42 | 10.19 | 45 |
| V51 | Connect 65mm. to Boosted Hyd & Charge | 52 | 15 | 59.59 | 37.89 | 163 |
| V52 | Connect 38mm. to Boosted Hyd & Charge | 28 | 14 | 40.9 | 17.8 | 90 |
| X1 | Position Appliance | 84 | 0.16 | 1.09 | 0.48 | 2.42 |
| X2 | Rem. Suction & Connect to Tank | 85 | 3 | 18.6 | 7.5 | 37.5 |
| X3 | Prime Suction Hose from Tank | 39 | 7 | 23.5 | 15.3 | 70 |
| X4 | Secure for Open Water Drop | 49 | 23 | 97.7 | 54.4 | 265 |
| X5 | Lower Suct. Hose to Open Water & Prime | 48 | 10 | 60.7 | 37.9 | 180 |
| Y1 | Complete Secondary Search | 28 | 0.07 | 0.16 | 0.05 | 0.30 |
| Y2 | Time to Remove/Rescue Person | 27 | 0.01 | 0.05 | 0.03 | 0.13 |
| Z1 | Position Aerial Appliance | 60 | 0.02 | 0.54 | 0.32 | 1.6 |
| Z21 | Set Up App. - Teleboom | 20 | 40 | 56.6 | 17.57 | 105 |
| Z22 | Set Up App. - TT Ladder | 6 | 35 | 292 | 221.1 | 607 |
| Z23 | Set Up App - Platform | 33 | 35 | 145.8 | 59.3 | 210 |
| Z3 | Conduct Safety Procedures | 59 | 160 | 62.9 | 33.7 | 160 |
| Z5 | Charge Monitor | 59 | 6 | 31.5 | 25 | 130 |

| Graph | Task | Sample: | Norm Mean | Norm SD |
|---|---|---|---|---|
| M | Dismount Appliance & don BA | 259 | 4.406 | 0.382 |
| N | Don BA & Hazardous Incident Suit | 40 | 6.255 | 0.481 |
| O1 | Flush Hydrant | 124 | 3.324 | 0.578 |
| O2 | Obtain Hazardous Material Info. | 49 | 6.406 | 0.542 |
| O3 | Decontamination Unit Set Up | 7 | 6.611 | 0.240 |
| O4 | Assemble Misc. Safety Equip. | 7 | 5.578 | 0.433 |
| P1 | Remove Hydrant Equip. | 125 | 3.346 | 0.520 |
| P2 | Remove High Rise Pack or Similar | 39 | 2.513 | 0.425 |
| Q1 | Horiz. Travel in Turnout Gear | 244 | 0.684 | 0.569 |
| Q2 | Horiz. Travel in Turnout w/ Equip | 159 | 0.491 | 0.595 |
| Q3 | Horiz. Travel in Turnout w/w/o Equip. | 113 | 0.252 | 0.394 |
| Q4 | Horiz. Travel in Full Hazard Suit/BA | 48 | -0.363 | 0.594 |
| T1 | Ascend Stairs in BA w/ Equip. | 73 | -0.165 | 0.454 |
| T2 | Ascend Stairs with High Pressure Hose | 33 | -0.880 | 0.541 |
| T3 | Ascend Stairs w/ 65mm. Dia. Hose | 34 | -0.430 | 0.418 |
| T4 | Ascend Stairs w/ 38mm. Dia. Hose | 33 | -0.319 | 0.341 |
| T5 | Descend Stairs in BA | 68 | -0.128 | 0.442 |
| T6 | Rest Breaks | 11 | 0.532 | 0.421 |
| V11 | Rem., Conn & Charge 90mm Hyd to App. | 3 |  |  |
| V21 | Remove & Connect 65mm. (App to Hose) | 82 | 3.587 | 0.415 |
| V22 | Remove & Connect 38mm. (App to Branch) | 36 | 3.409 | 0.440 |
| V3 | Remove & Connect 65mm. (App to Boost) | 39 | 3.747 | 0.365 |

| Graph | Task | Sample: | Norm. Mean | Norm. SD |
|---|---|---|---|---|
| V41 | Charge 65mm. from Appliance | 119 | 2.834 | 0.594 |
| V42 | Charge 38mm. from Appliance | 37 | 2.780 | 0.517 |
| V51 | Connect 65mm. to Boosted Hyd & Charge | 52 | 3.918 | 0.583 |
| V52 | Connect 38mm. to Boosted Hyd & Charge | 28 | 3.624 | 0.416 |
| X1 | Position Appliance | 84 | -0.002 | 0.421 |
| X2 | Rem. Suction & Connect to Tank | 85 | 2.848 | 0.388 |
| X3 | Prime Suction Hose from Tank | 39 | 2.980 | 0.594 |
| X4 | Secure for Open Water Drop | 49 | 4.447 | 0.520 |
| X5 | Lower Suct. Hose to Open Water & Prime | 48 | 3.941 | 0.574 |
| Y1 | Complete Secondary Search | 28 | -1.879 | 0.305 |
| Y2 | Time to Remove/Rescue Person | 27 | -3.149 | 0.555 |
| Z1 | Position Aerial Appliance | 60 | -0.767 | 0.549 |
| Z21 | Set Up App. - Teleboom | 20 | 3.990 | 0.303 |
| Z22 | Set Up App. - TT Ladder | 6 | 5.450 | 0.673 |
| Z23 | Set Up App - Platform | 33 | 4.906 | 0.391 |
| Z3 | Conduct Safety Procedures | 59 | 4.015 | 0.502 |
| Z41 | Elevate & Maneuver Teleboom 180 Deg. | 22 | -2.269 | 0.352 |
| Z42 | Elevate & Maneuver TT Lad. 180 Deg. | 7 |  |  |
| Z43 | Elevate & Maneuver Platform 180 Deg. | 34 | -2.200 | 0.400 |
| Z5 | Charge Monitor | 59 | 3.206 | 0.699 |

1q

| Procedure | Hose | Sample | Mean | SD | Min. | Max | Mode |
|---|---|---|---|---|---|---|---|
| Remove/Conn./Charge from Hyd. to App. | 65 | | 60.4 | 30.2 | | | |
| | 90 | | 144.7 | 90.2 | | | |
| Remove/Conn. from Hyd. to Branch | 38 | | 33.3 | 15.4 | | | |
| | 65 | | 39.4 | 17.4 | | | |
| Remove/Conn. from App. to Booster | 65 | 39 | 45.3 | 17.1 | 17.5 | 80 | 45 |
| Remove/Conn. from App. to Branch | 38 | 36 | 33.3 | 15.4 | 2 | 70.7 | 45 |
| | 65 | 82 | 39.4 | 17.4 | 6.0 | 80.0 | 30 |
| Charge Delivery Hose from App. | 38 | | 18.4 | 10.2 | | | |
| | 65 | | 20.3 | 13.2 | | | |
| Connect to boosted hyd. and charge | 38 | | 40.9 | 17.8 | | | |
| | 65 | | 59.6 | 37.9 | | | |

Table E.1: Time to Lay, Connect and Charge Hose (per 30 m length)

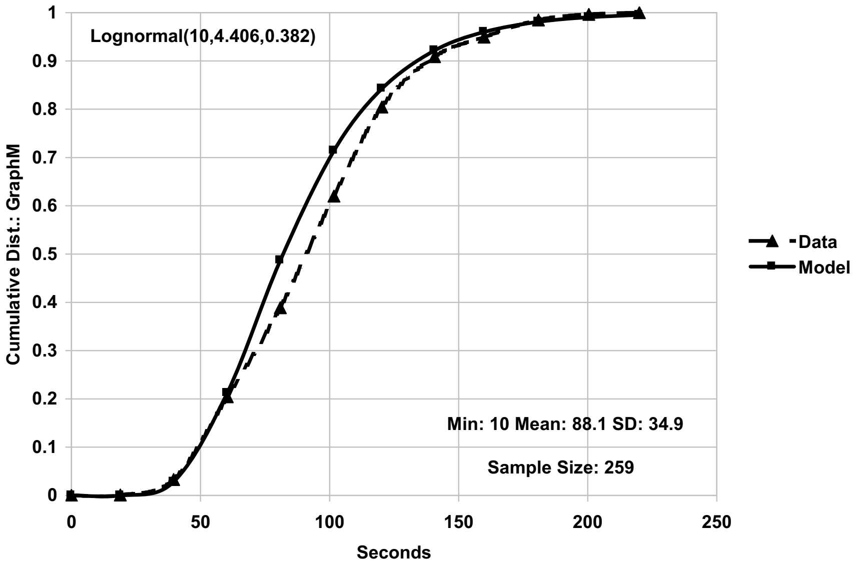

Figure E.1: Dismount Appliance and Don BA - Aust.

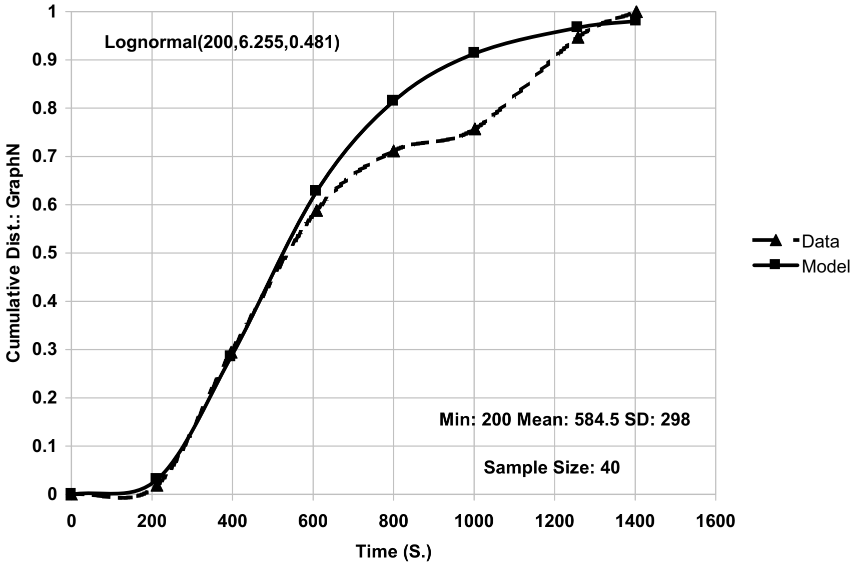

Figure E.2: Don BA and Hazardous Incident Suit - Aust.

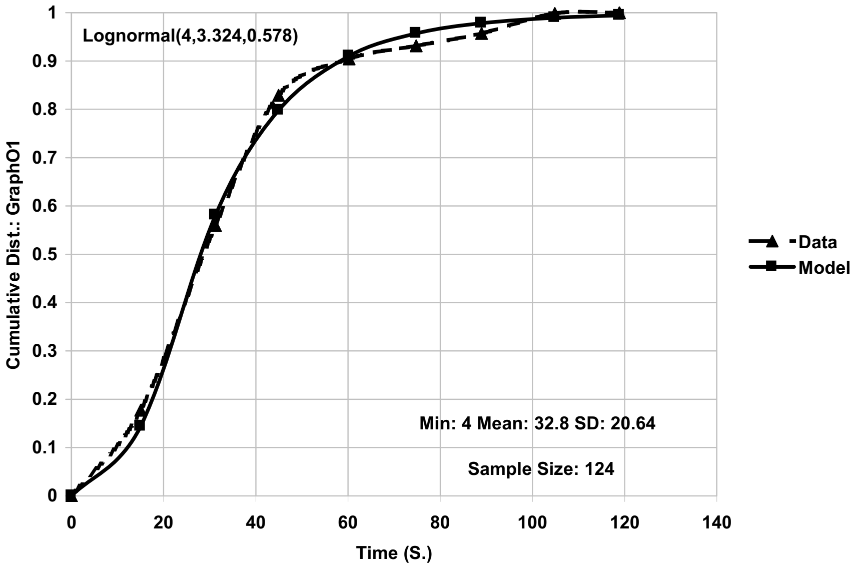

Figure E.3: Flush Hydrant - Aust.

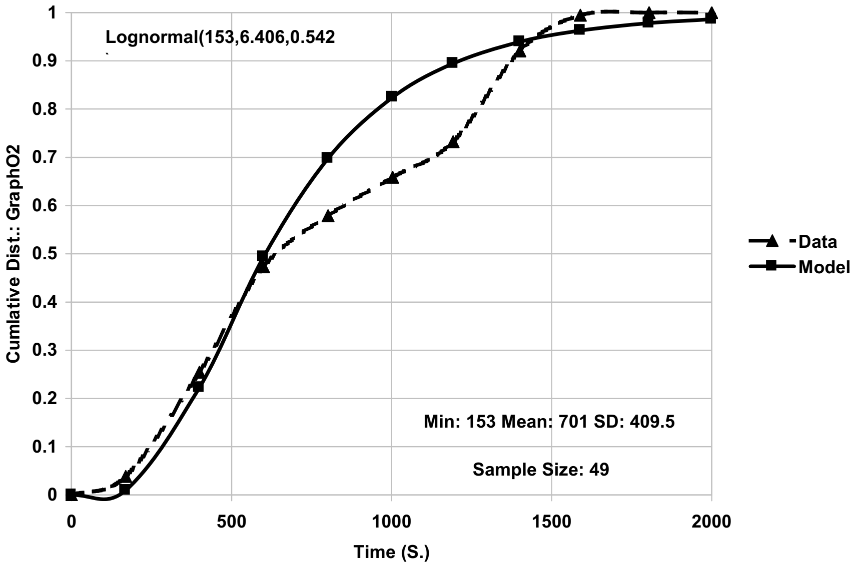

Figure E.4: Obtain Hazardous Material Info - Aust.

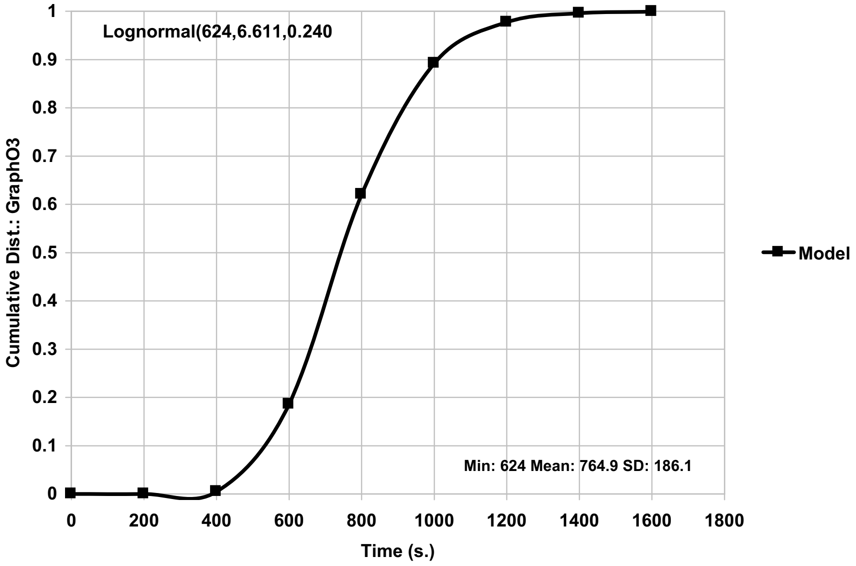

Figure E.5: Decontamination Unit Set Up - Aust.

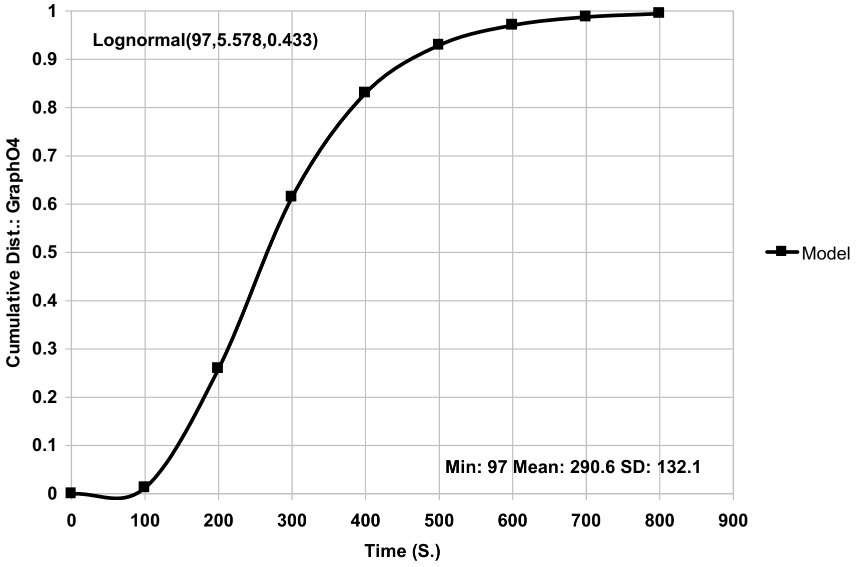

Figure E.6: Assemble Miscellaneous Safety Equipment - Aust.

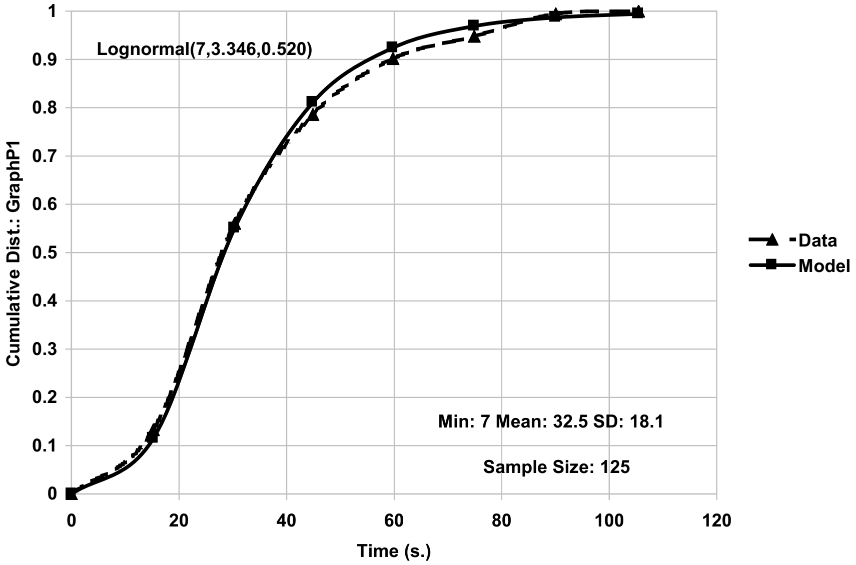

Figure E.7: Remove Hydrant Equipment - Aust.

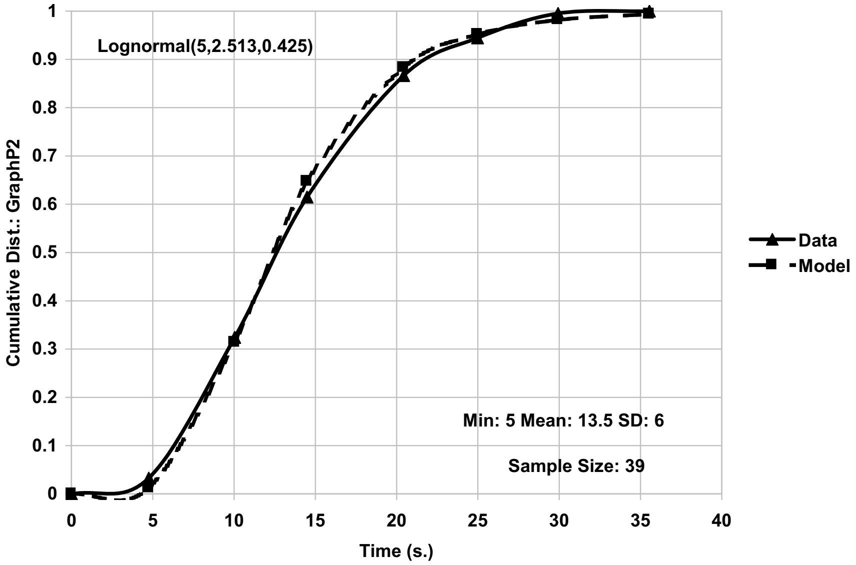

Figure E.8: Time to Remove High Rise Pack or Similar - Aust.

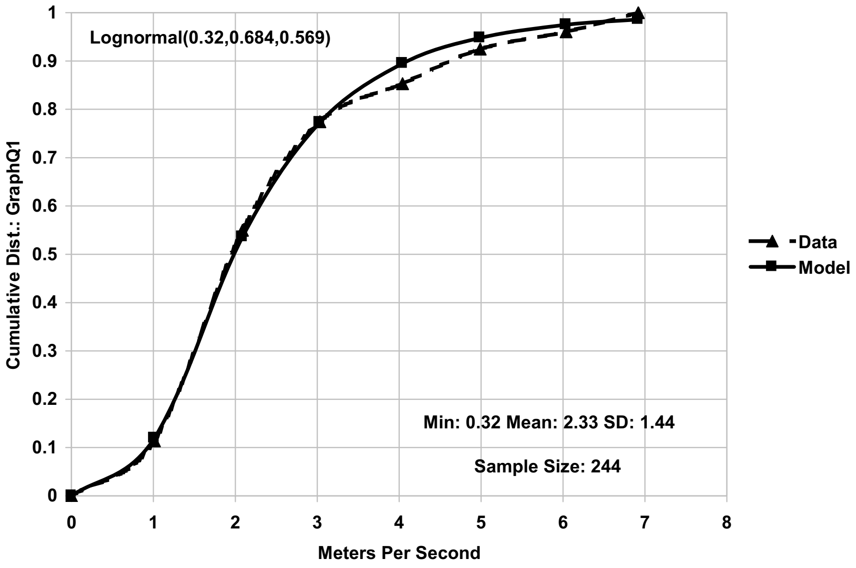

Figure E.9: Horizontal Travel in Turnout Uniform - Aust.

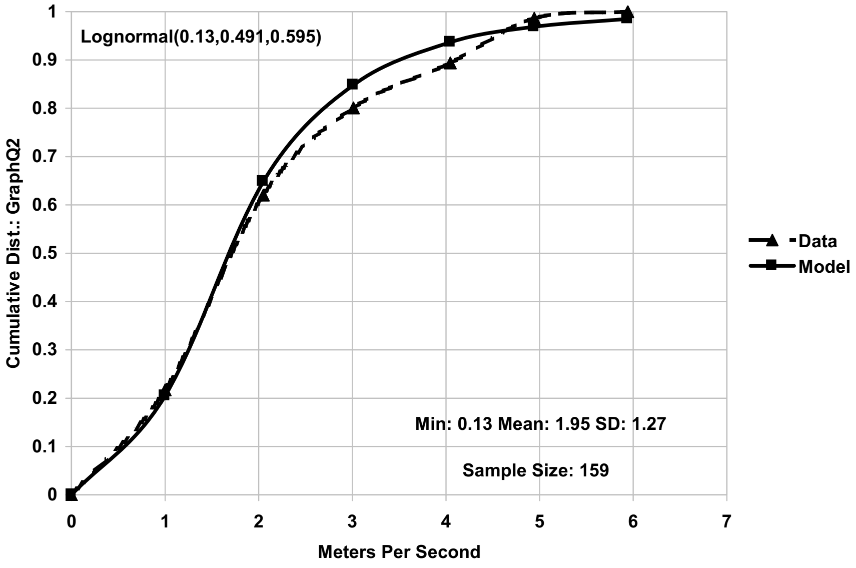

Figure E.10: Horizontal Travel in Turnout Uniform with Equipment - Aust.

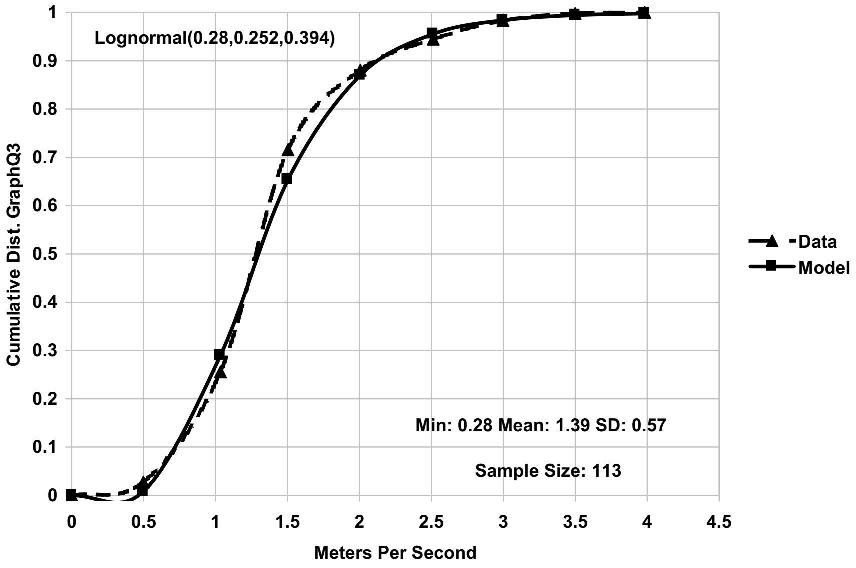

Figure E.11: Hor. Travel in Turnout & BA With/Without Equipment - Aust.

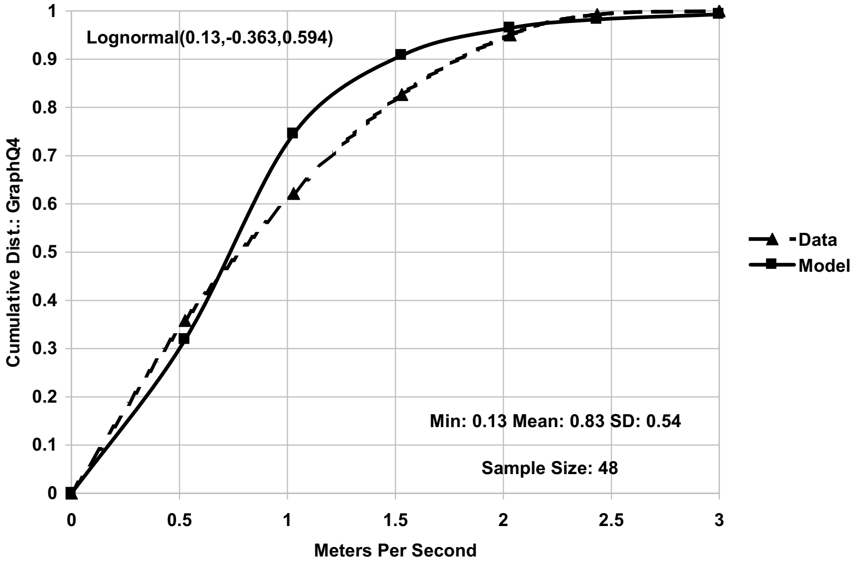

Figure E.12: Hor. Travel in Full Hazardous Incident Suit in BA - Aust.

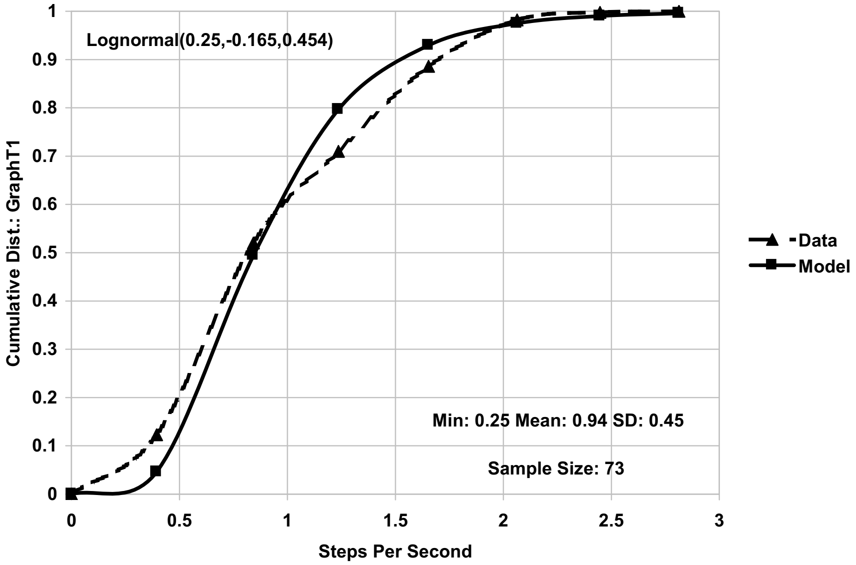

Figure E.13: Ascend Stairs in BA w/ Equipment - Aust.

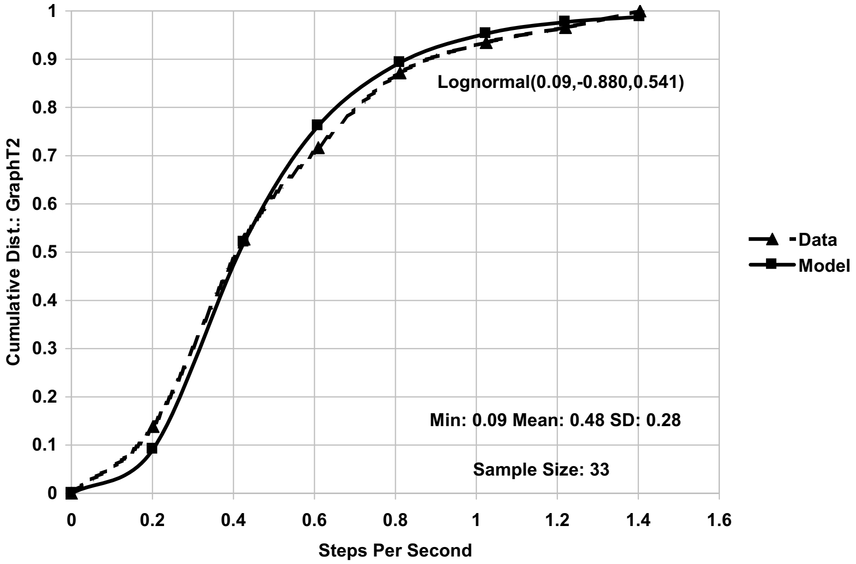

Figure E.14: Ascend Stairs with High Pressure Hose - Aust.

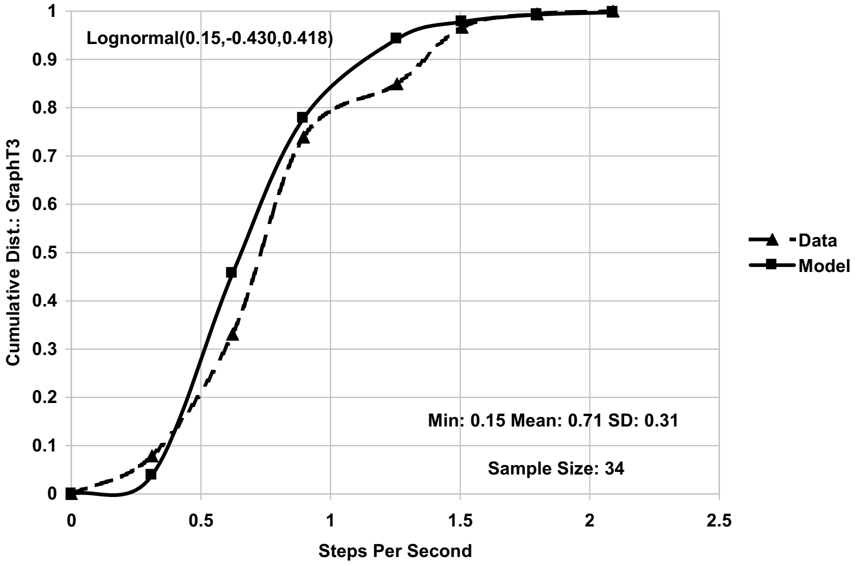

Figure E.15: Ascend Stairs with 65 mm Hose - Aust.

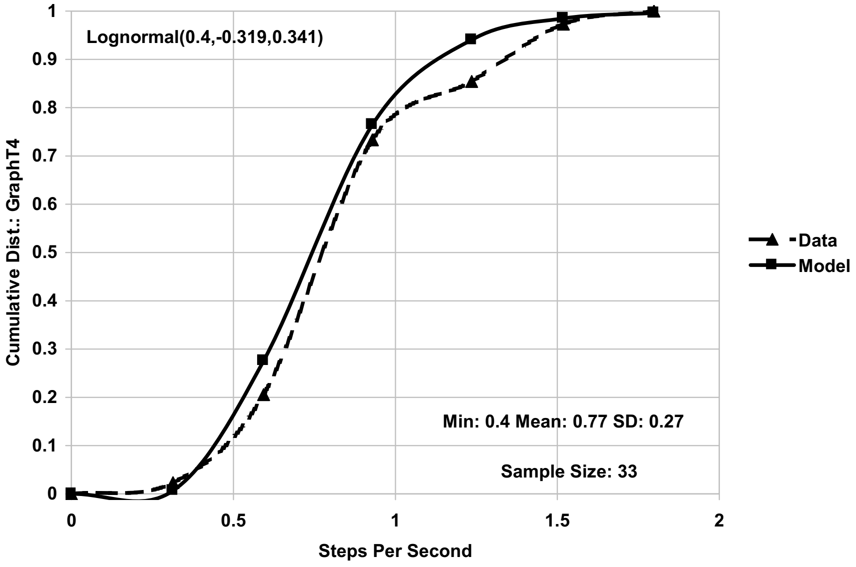

Figure E.16: Ascend Stairs with 38 mm Hose - Aust.

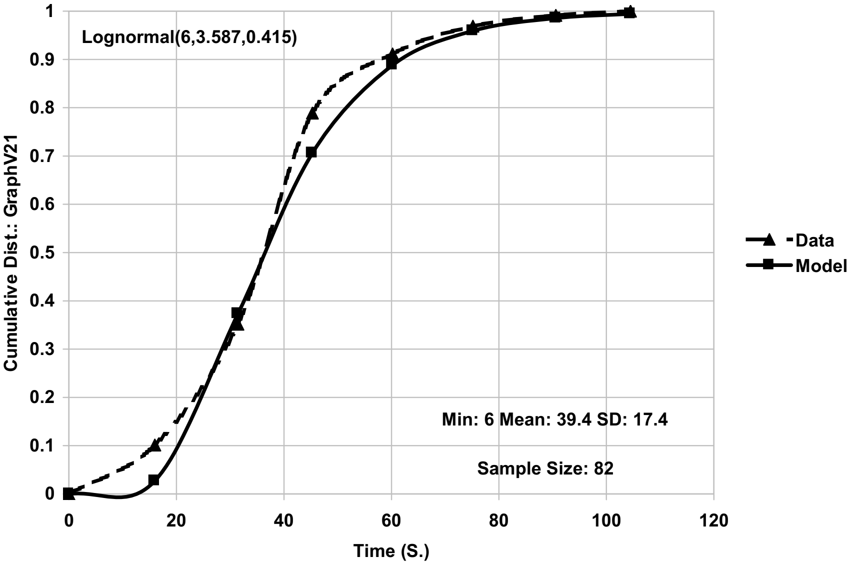

Figure E.17: Remove & Connect 65 mm Hose - App. to Branch - Aust.

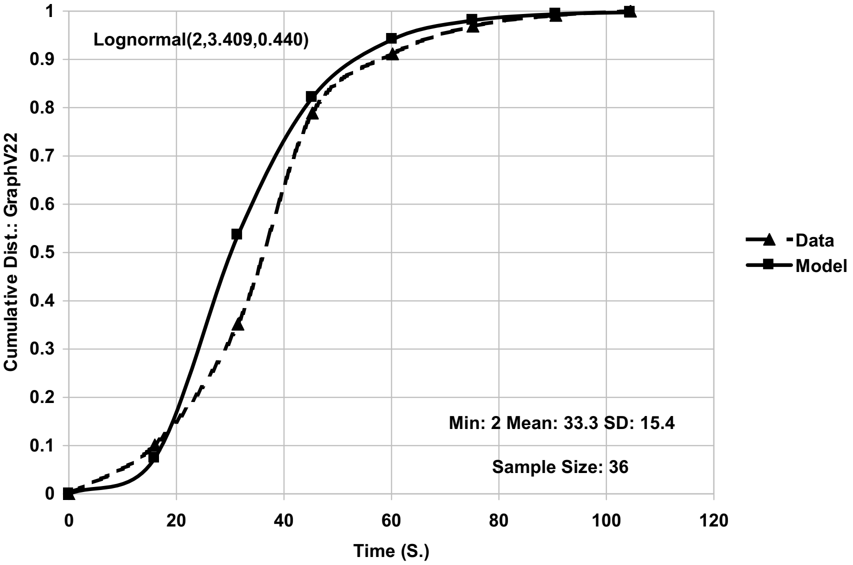

Figure E.18: Remove & Connect 38 mm Hose from App. to Branch - Aust.

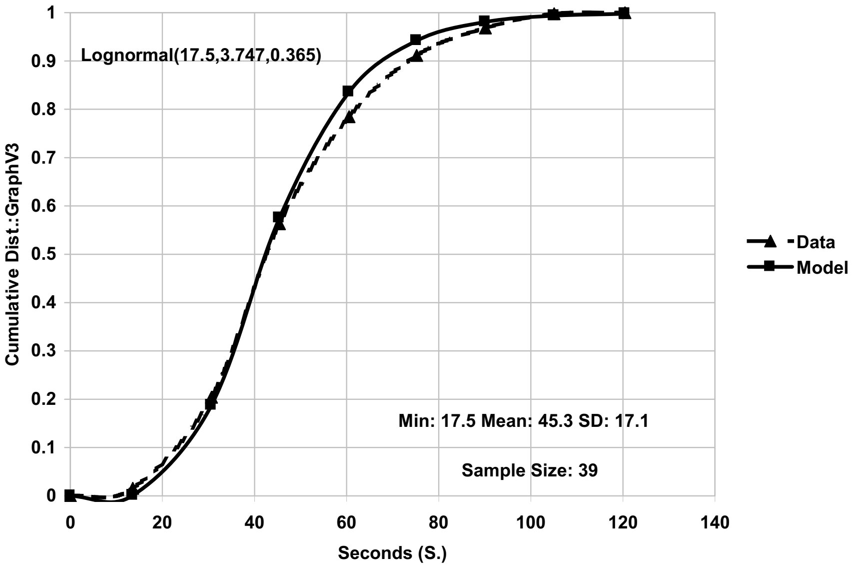

Figure E.19: Remove and Connect 65 mm Hose - App. to Boost Conn. - Aust.

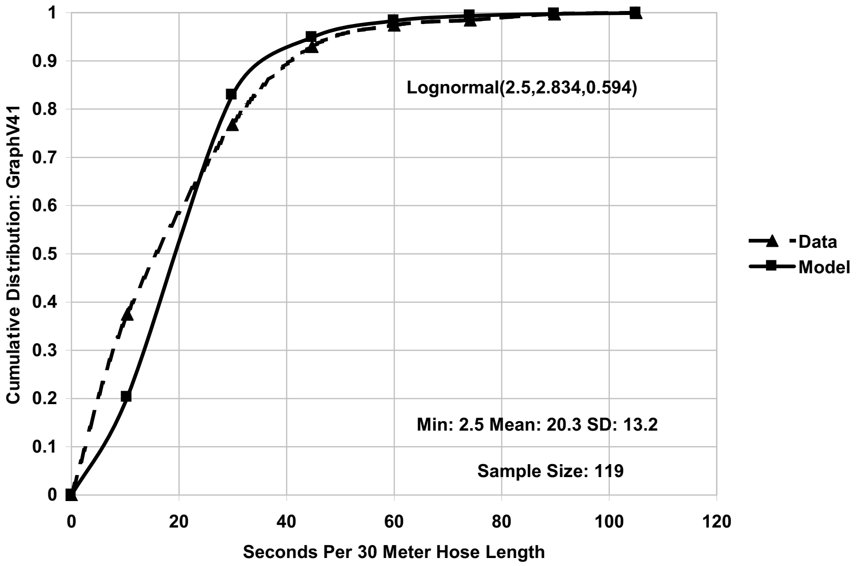

Figure E.20: Charge 65 mm. Delivery Hose from Appliance - Aust.

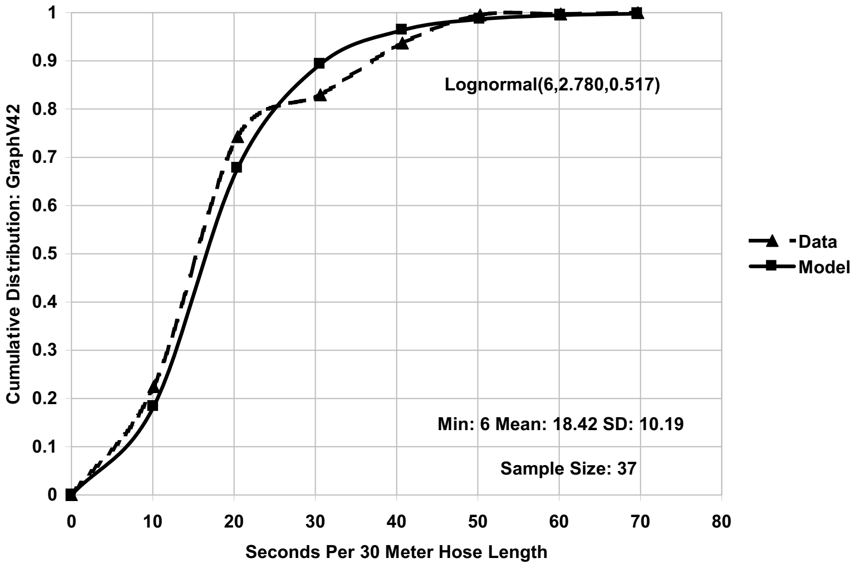

Figure E.21: Charge 38mm Delivery Hose from Appliance - Aust.

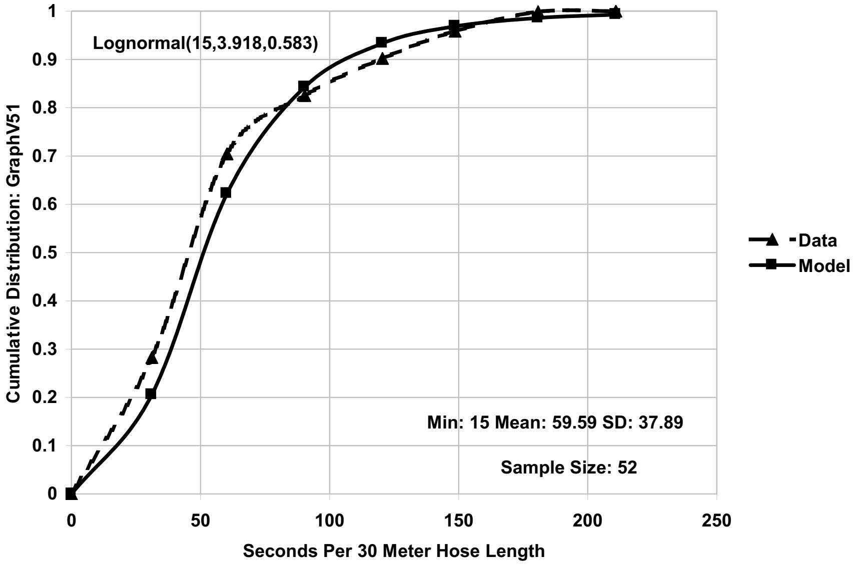

Figure E.22: Connect 65 mm Hose to Boosted Hydrant and Charge - Aust.

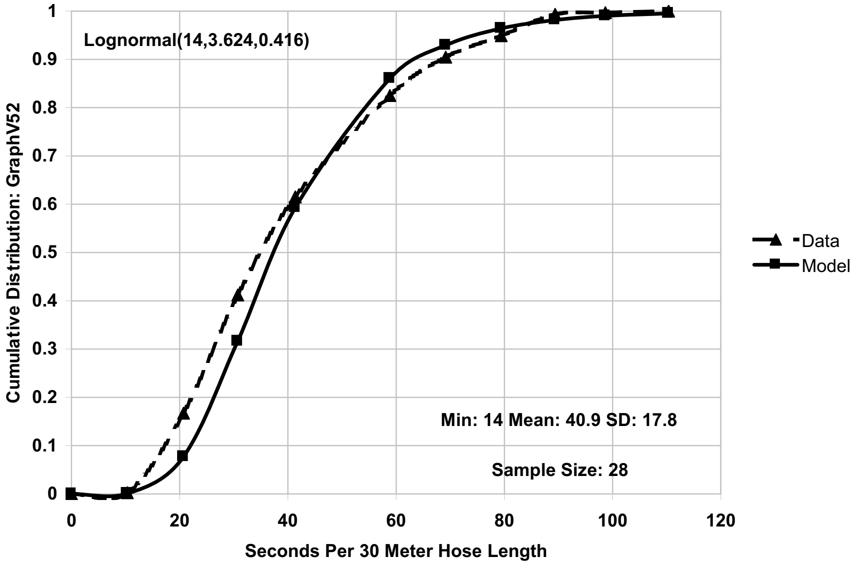

Figure E.23: Connect 38 mm Hose to Boosted Hydrant and Charge - Aust.

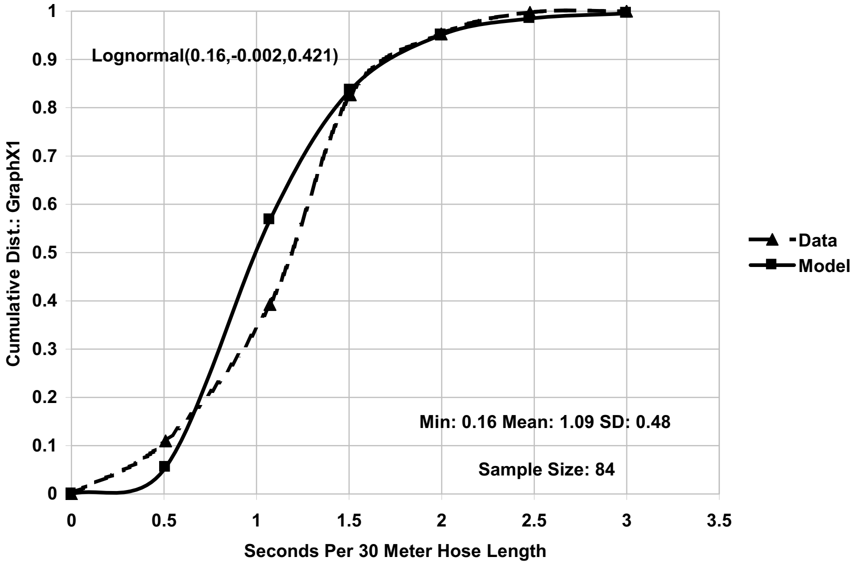

Figure E.24: Time to Position Appliance - Aust.

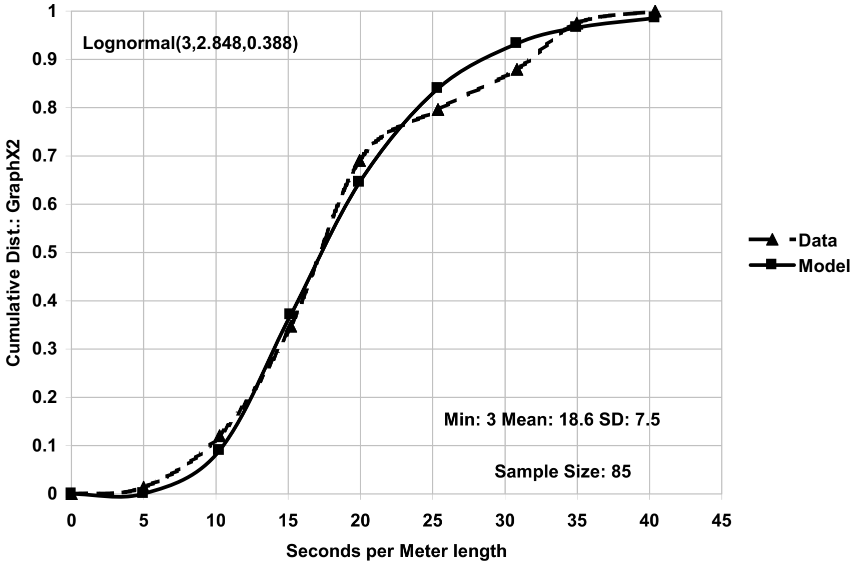

Figure E.25: Time to Remove Suction Hose and Connect to Tank - Aust.

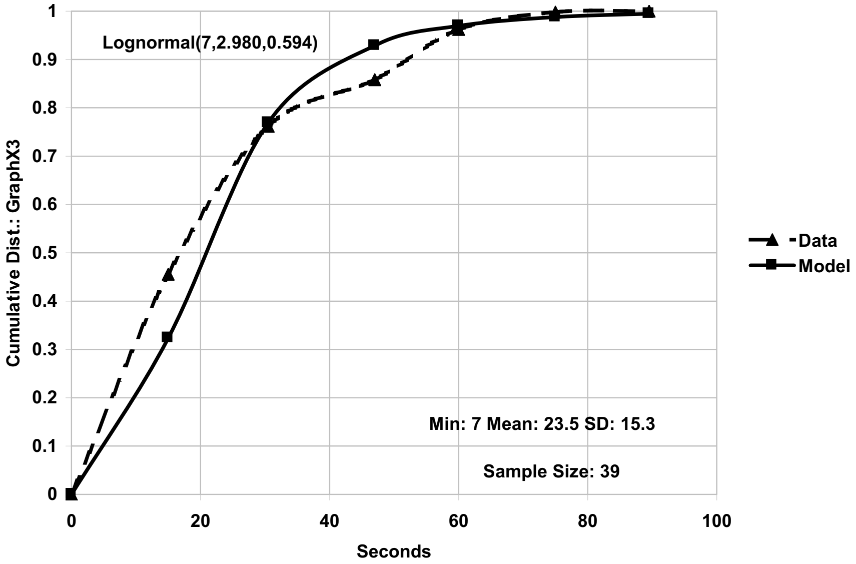

Figure E.26: Time to Prime Suction Hose From Tank - Aust.

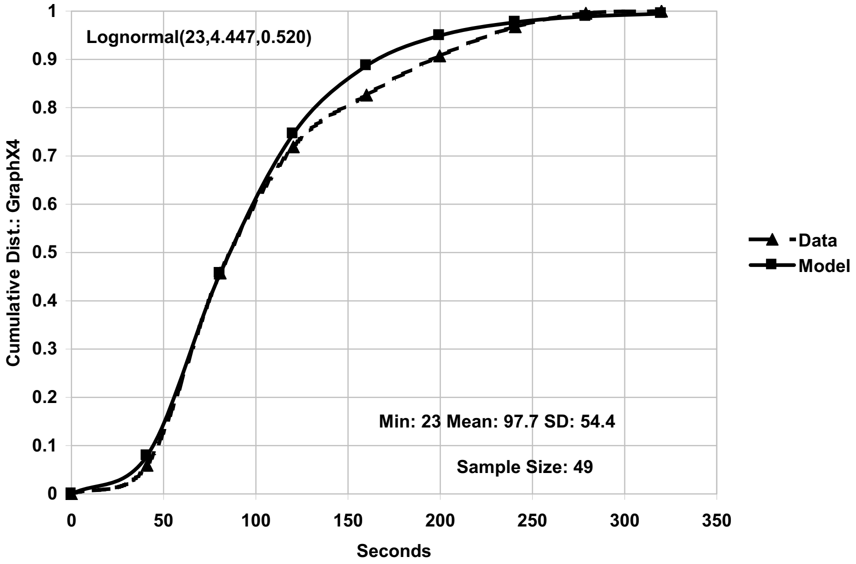

Figure E.27: Time to Secure Suction for Open Water Drop - Aust.

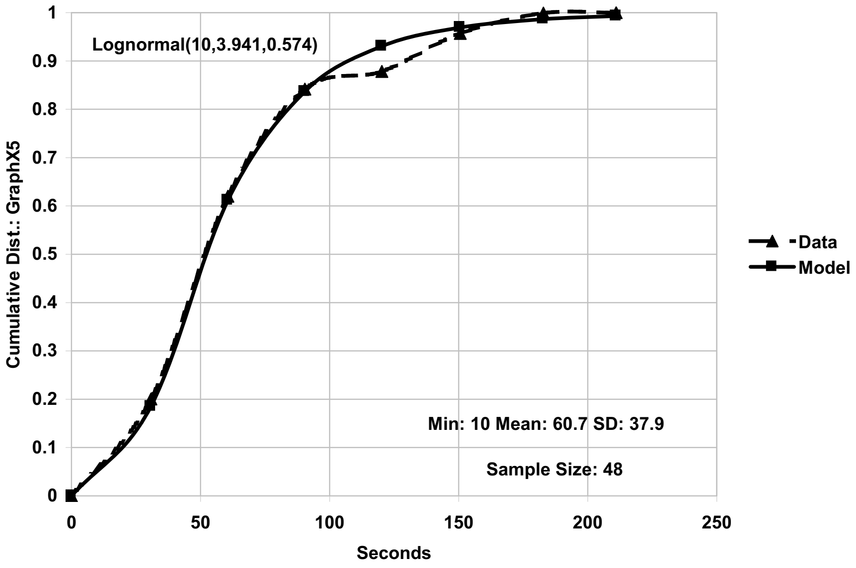

Figure E.28: Time to Lower Suction Hose into Open Water and Prime - Aust.

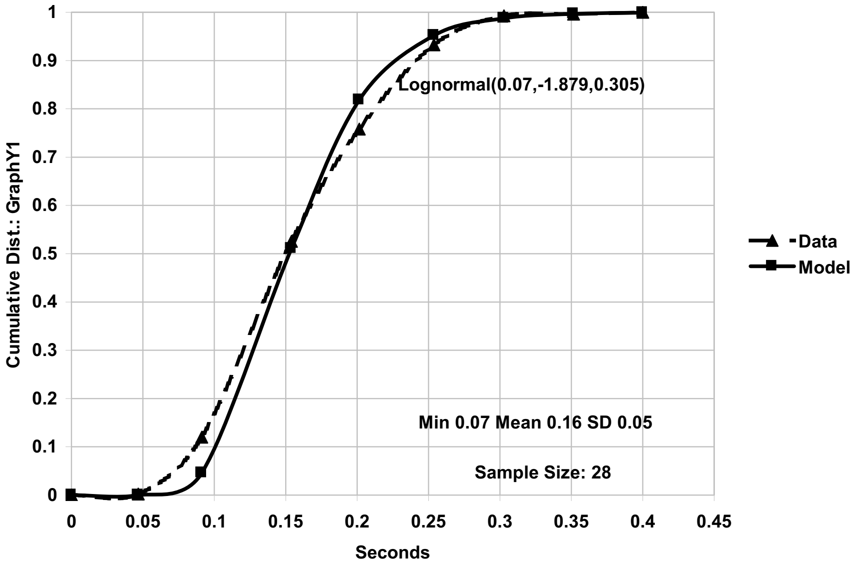

Figure E.29: Time to Complete Secondary Search - Aust.

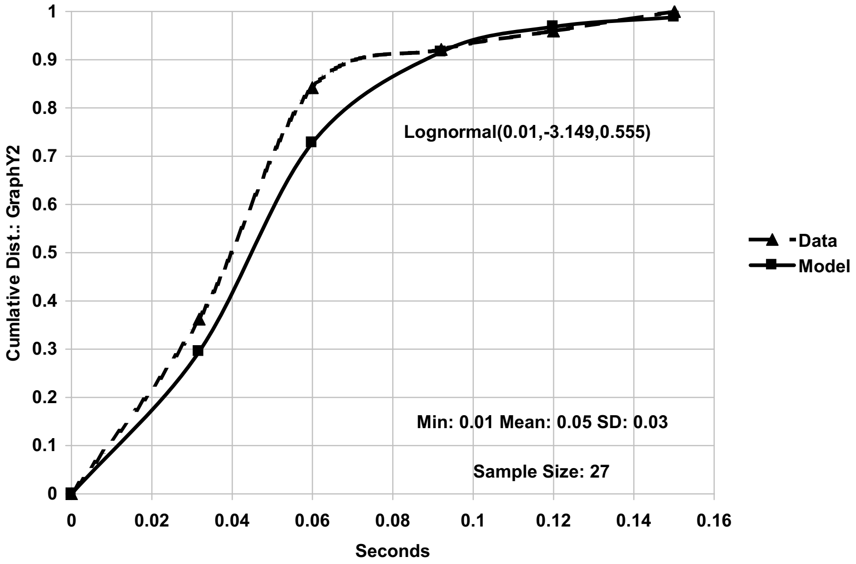

Figure E.30: Time to Remove/Rescue Person - Aust.

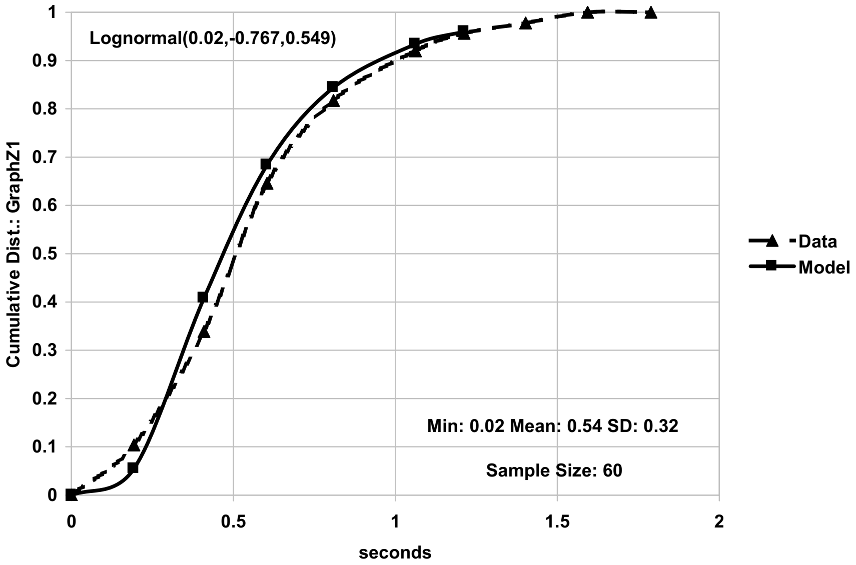

Figure E.31: Time to Position Aerial Appliance - Aust.

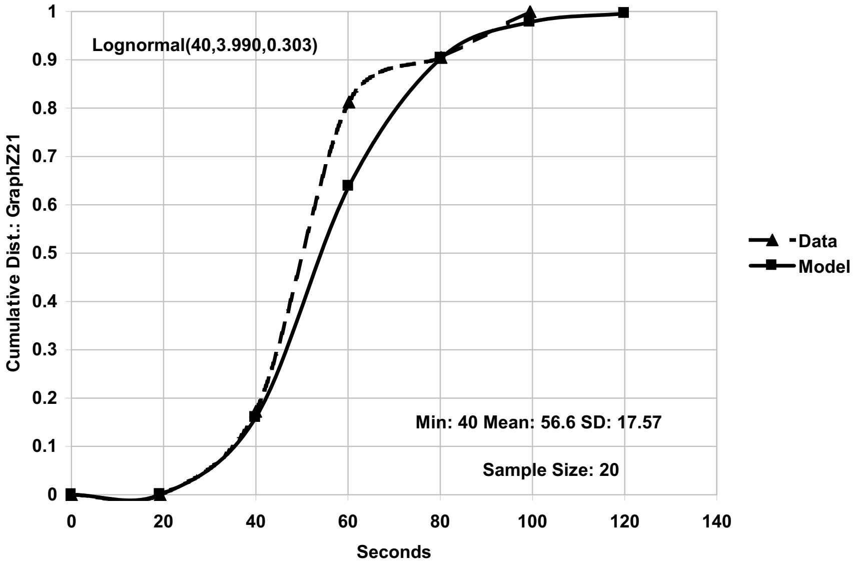

Figure E.32: Time to Set Up Teleboom (Prep. for Use) - Aust.

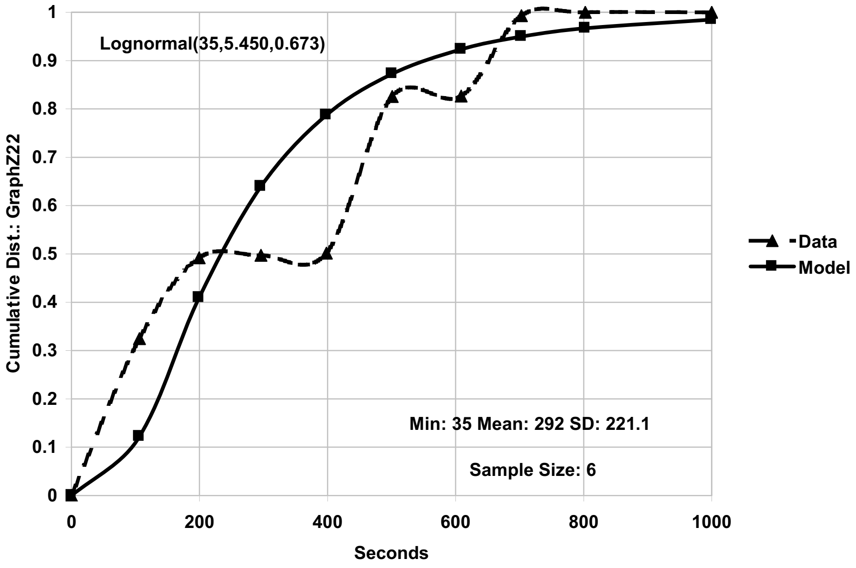

Figure E.33: Time to Set Up TT Ladder for Use - Aust.

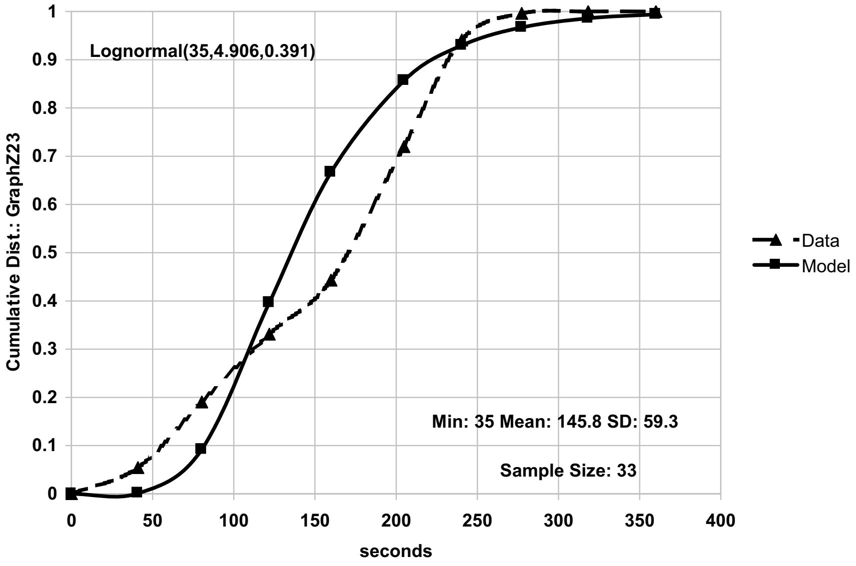

Figure E.34: Time to Set Up Platform (Prep. for Use) - Aust.

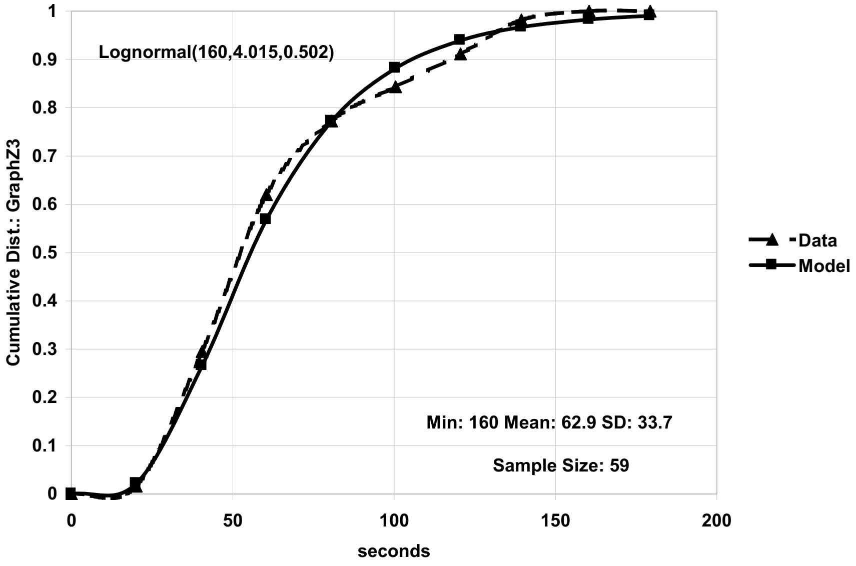

Figure E.35: Time to Conduct Safety Procedures - Aust.

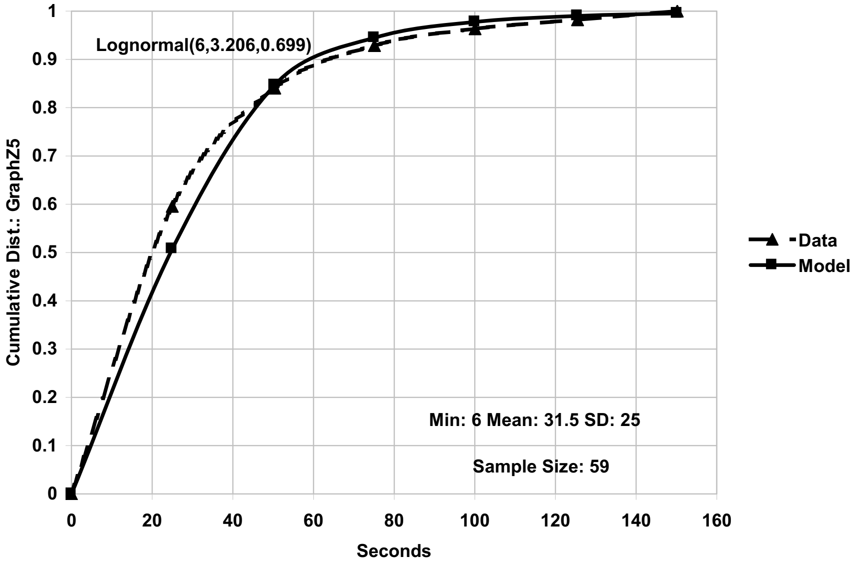

Figure E.36: Time to Charge Monitor - Aust.

# Appendix F

# GPSS Input Files

## F.1 Establish Water Supply - Two, Three and Four Man Forward Hose Lays

```
SIMULATE                          *base time unit: 1 second
* WATER SUPPLY
*/////////////////////////////////////////////////////////////////////
* SIMULATION OF A FORWARD LAY
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
* This is for 2 TO 4 men initially
* IS THE MOST CURRENT 12/19/2000 9:06AM
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
STORAGE    S$MEN,2            *Supply 2 Men Initially
STORAGE    S$TOTAL,1
RTIME    TABLE      M1,180,10,20
GENERATE                          *PROVIDE A TRANSACTION WHENEVER NEEDED
GATE LR    NEXT1                  *WAIT UNTIL PRECEDING ITERATION IS FINISHED
LOGIC S    NEXT1                  *SHUT GATE ON FOLLOWING TRANSACTION
LOGIC S    BOOLFF1
LOGIC S    BOOLFF2
LOGIC S    FF3PO3
LOGIC S    FF3CFW
SPLIT      1,PUMP                 *SEND OFFSPRING TO HANDLE PUMP
ENTER      TOTAL,1
ENTER      MEN,1                  *GET MEN FOR SUBPROJECT 1-TO-2
QUEUE      HYD12
*Wrap Hydrant wraphydr           3 15+RVLNOR(1,7.29,44.2)
ADVANCE    15+RVLNOR(1,7.29,44.2)
*Connect Hose to Hydrant conhohyd           4 13+RVLNOR(1,13.9,80.8)
ADVANCE    3+RVLNOR(1,13.9,80.8)
DEPART     HYD12
LOGIC R    BOOLFF1
GATE LR    BOOLFF2                *CALL FOR HYDRANT WATER
ADVANCE    16+RVLNOR(1,13.9,38.3) *OPEN HYDRANT
*/////////////////////////////////////////////////////////////////////
*  ATTACK LINE
*  Assisting if not primary
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*Proceed to Truck(50m) - Horiz. Travel in Turnout w/ Equip m/s
ADVANCE    (50/(0.13+RVLNOR(1,1.95,1.6)))
*Get Hose From Mattydale gehosmat           3 12+RVLNOR(1,20.6,72.1)
ATTK1    ADVANCE    12+RVLNOR(1,20.6,72.1)
*Extend Uncharged Attack 150'exatho15           3 28+RVLNOR(1,14.6,434)
ADVANCE    28+RVLNOR(1,14.6,434)
*Call and Receive Water Calrecwa           3 8+RVLNOR(1,18.1,267)
ADVANCE    8+RVLNOR(1,18.1,267)
*GO SIGNAL COMPLETION OF 2FF PUMP
LEAVE      MEN,1                  *FREE THE MEN
TRANSFER   ,NODE1                 *GO SIGNAL COMPLETION HYDRANT*
NODE1    ASSEMBLE   2                      *WAIT FOR COMPLETION OF FINAL SUBPROJECTS
LOGIC R    NEXT1                  *OPEN GATE FOR THE NEXT ITERATION
LEAVE      TOTAL,1
TABULATE   RTIME
TERMINATE  1                      *CURRENT ITERATION IS FINISHED
PUMP     ADVANCE    RVTRI(5,20,30,40)      *PARK
```

```
TRANSFER   BOTH,GOT4,NOTT4        *IF THERE ARE 4FF, GO TO THE 4FF MODEL
NOTT4    TRANSFER   BOTH,GOT3,NOTT3        *IF THERE ARE 3FF, GO, OTHERWISE CONTINUE
*222222222222222222222222222222222222222222222222222222222
NOTT3    ENTER      MEN,1                  *ONE FIREFIGHTER
QUEUE      PUMP12
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE(Alight Truck)
*Clamp Supply Hose clsuho 3 14+RVLNOR(1,12,61.8)
ADVANCE    14+RVLNOR(1,12,61.8)
LOGIC R    BOOLFF2
GATE LR    BOOLFF1
*Disconnect Hose from Bed dishobed           4 12+RVLNOR(1,18.7,211)
ADVANCE    12+RVLNOR(1,18.7,211)
*Bring 2.5’ Hose to Side of truck Bring 4 4+RVLNOR(1,4.84,21.1)
ADVANCE    4+RVLNOR(1,4.84,21.1)
*Connect Hose from Bed conhosbe           4 5+RVLNOR(1,30.9,668)
ADVANCE    5+RVLNOR(1,30.9,668)
DEPART     PUMP12
LEAVE      MEN,1                  *FREE THE MEN
TRANSFER   ,NODE1                 *GO SIGNAL COMPLETION OF PUMP
*333333333333333333333333333333333333333333333333333333333
GOT3     ENTER      MEN,2
SPLIT      1,FF33
QUEUE      PUMP23
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE(Alight Truck)
*Clamp Supply Hose clsuho 3 14+RVLNOR(1,12,61.8)
ADVANCE    14+RVLNOR(1,12,61.8)
LOGIC R    BOOLFF2
GATE LR    BOOLFF1
*Disconnect Hose from Bed dishobed           4 12+RVLNOR(1,18.7,211)
ADVANCE    12+RVLNOR(1,18.7,211)
*Bring 2.5’ Hose to Side of truck Bring 4 4+RVLNOR(1,4.84,21.1)
ADVANCE    4+RVLNOR(1,4.84,21.1)
*Connect Hose from Bed conhosbe           4 5+RVLNOR(1,30.9,668)
ADVANCE    5+RVLNOR(1,30.9,668)
DEPART     PUMP23
TRANSFER   ,NODE2                 *GO SIGNAL COMPLETION 3FF
FF33     QUEUE      PUMP33
*/////////////////////////////////////////////////////////////////////
*  ATTACK LINE
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*Get Hose From Mattydale gehosmat           3 12+RVLNOR(1,20.6,72.1)
ATTK2    ADVANCE    12+RVLNOR(1,20.6,72.1)
*Ext Uncharged Attack 150’exatho15           3 28+RVLNOR(1,14.6,434)
ADVANCE    28+RVLNOR(1,14.6,434)
*Call and Receive Water Calrecwa           3 8+RVLNOR(1,18.1,267)
ADVANCE    8+RVLNOR(1,18.1,267)
DEPART     PUMP33
TRANSFER   ,NODE2                 *GO SIGNAL COMPLETION OF 2FF PUMP
NODE2    ASSEMBLE   2
LEAVE      MEN,2
*          LOGIC R    BOOLFF2
```

```
*          GATE LR    BOOLFF1                *CALL FOR HYDRANT WATER
TRANSFER   ,NODE1
*444444444444444444444444444444444444444444444444444444444
GOT4     ENTER      MEN,3                  *GOT 3 MEN (Fourth at Hydrant)
SPLIT      1,FF4                  *ACTIONS OF FF1
QUEUE      PUMP14
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE(Alight Truck)
*Clamp Supply Hose clsuho 3 14+RVLNOR(1,12,61.8)
ADVANCE    14+RVLNOR(1,12,61.8)
LOGIC R    BOOLFF2
GATE LR    BOOLFF1
*Disconnect Hose from Bed dishobed           4 12+RVLNOR(1,18.7,211)
ADVANCE    12+RVLNOR(1,18.7,211)
*Bring 2.5’ Hose to Side of truck Bring 4 4+RVLNOR(1,4.84,21.1)
ADVANCE    4+RVLNOR(1,4.84,21.1)
*Connect Hose from Bed conhosbe           4 5+RVLNOR(1,30.9,668)
ADVANCE    5+RVLNOR(1,30.9,668)
DEPART     PUMP14
TRANSFER   ,NODE3                 *GO SIGNAL COMPLETION 3FF
*-----------------------------------------------------
FF4      SPLIT      1,FF44                 *ACTIONS OF FF3 AND 4
QUEUE      PUMP24
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE (Alight Truck)
LOGIC R    FF3PO3
GATE LR    FF3CFW                 *CFW AT BEGIN PO3
DEPART     PUMP24
TRANSFER   ,NODE3                 *GO SIGNAL COMPLETION 3FF
*
FF44     QUEUE      PUMP44
*/////////////////////////////////////////////////////////////////////
*  ATTACK LINE
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*Get Hose From Mattydale gehosmat           3 12+RVLNOR(1,20.6,72.1)
ATTK3    ADVANCE    12+RVLNOR(1,20.6,72.1)
*Extend Uncharged Attack 150’exatho15           3 28+RVLNOR(1,14.6,434)
ADVANCE    28+RVLNOR(1,14.6,434)
*Call and Receive Water Calrecwa           3 8+RVLNOR(1,18.1,267)
ADVANCE    8+RVLNOR(1,18.1,267)
DEPART     PUMP33
*          TRANSFER   ,NODE2                 *GO SIGNAL COMPLETION OF 2FF PUMP
DEPART     PUMP44
TRANSFER   ,NODE3                 *GO SIGNAL COMPLETION OF 2FF PUMP
*
NODE3    ASSEMBLE   3
LOGIC R    BOOLFF2
GATE LR    BOOLFF1                *CALL FOR HYDRANT WATER
LEAVE      MEN,3
TRANSFER   ,NODE1
START      1000                   *SIMULATE FOR A MANPOWER LEVEL OF 5
END
```

## F.2 Establish Water Supply - Two, Three and Four Man Reverse Hose Lays

```
SIMULATE                          *base time unit: 1 second
* WATER SUPPLY
*/////////////////////////////////////////////////////////////////////
* SIMULATION OF A REVERSE LAY
*\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
* This is for 2 TO 4 men initially
* IS THE MOST CURRENT 12/19/2000 9:06AM
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
STORAGE    S$MEN,2            *Supply 2 Men Initially
STORAGE    S$TOTAL,1
RTIME    TABLE      M1,180,10,20
GENERATE                          *PROVIDE A TRANSACTION WHENEVER NEEDED
GATE LR    NEXT1                  *WAIT UNTIL PRECEDING ITERATION IS FINISHED
LOGIC S    NEXT1                  *SHUT GATE ON FOLLOWING TRANSACTION
LOGIC S    BOOLFF1
LOGIC S    BOOLFF2
LOGIC S    FF3PO3
LOGIC S    FF3CFW
SPLIT      1,PUMP                 *SEND OFFSPRING TO HANDLE PUMP
ENTER      TOTAL,1
ENTER      MEN,1                  *GET MEN FOR SUBPROJECT 1-TO-2
QUEUE      HYD12
*Wrap Hydrant wraphydr           3 15+RVLNOR(1,7.29,44.2)
ADVANCE    15+RVLNOR(1,7.29,44.2)
*Connect Hose to Hydrant conhohyd           4 13+RVLNOR(1,13.9,80.8)
ADVANCE    3+RVLNOR(1,13.9,80.8)
DEPART     HYD12
LOGIC R    BOOLFF1
GATE LR    BOOLFF2                *CALL FOR HYDRANT WATER
ADVANCE    16+RVLNOR(1,13.9,38.3) *OPEN HYDRANT
*////////////////////////////////////////////////////////////////////
*  ATTACK LINE
*  Assisting if not primary
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*Proceed to Truck(50m) - Horiz. Travel in Turnout w/ Equip m/s
ADVANCE    (50/(0.13+RVLNOR(1,1.95,1.6)))
*Get Hose From Mattydale gehosmat           3 12+RVLNOR(1,20.6,72.1)
ATTK1    ADVANCE    12+RVLNOR(1,20.6,72.1)
*Extend Uncharged Attack 150'exatho15           3 28+RVLNOR(1,14.6,434)
ADVANCE    28+RVLNOR(1,14.6,434)
*Call and Receive Water Calrecwa           3 8+RVLNOR(1,18.1,267)
ADVANCE    8+RVLNOR(1,18.1,267)
*GO SIGNAL COMPLETION OF 2FF PUMP
LEAVE      MEN,1                  *FREE THE MEN
TRANSFER  ,NODE1                  *GO SIGNAL COMPLETION HYDRANT*
NODE1    ASSEMBLE   2                      *WAIT FOR COMPLETION OF FINAL SUBPROJECTS
LOGIC R    NEXT1                  *OPEN GATE FOR THE NEXT ITERATION
LEAVE      TOTAL,1
TABULATE   RTIME
TERMINATE  1                      *CURRENT ITERATION IS FINISHED
PUMP     ADVANCE    RVTRI(5,20,30,40)      *PARK
```

```
TRANSFER   BOTH,GOT4,NOTT4        *IF THERE ARE 4FF, GO TO THE 4FF MODEL
NOTT4    TRANSFER   BOTH,GOT3,NOTT3        *IF THERE ARE 3FF, GO, OTHERWISE CONTINUE
*222222222222222222222222222222222222222222222222222222222
NOTT3    ENTER      MEN,1                  *ONE FIREFIGHTER
QUEUE      PUMP12
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE(Alight Truck)
*Clamp Supply Hose clsuho 3 14+RVLNOR(1,12,61.8)
ADVANCE    14+RVLNOR(1,12,61.8)
LOGIC R    BOOLFF2
GATE LR    BOOLFF1
*Disconnect Hose from Bed dishobed           4 12+RVLNOR(1,18.7,211)
ADVANCE    12+RVLNOR(1,18.7,211)
*Bring 2.5' Hose to Side of truck Bring 4 4+RVLNOR(1,4.84,21.1)
ADVANCE    4+RVLNOR(1,4.84,21.1)
*Connect Hose from Bed conhosbe           4 5+RVLNOR(1,30.9,668)
ADVANCE    5+RVLNOR(1,30.9,668)
DEPART     PUMP12
LEAVE      MEN,1                  *FREE THE MEN
TRANSFER   ,NODE1                 *GO SIGNAL COMPLETION OF PUMP
*333333333333333333333333333333333333333333333333333333333
GOT3     ENTER      MEN,2
SPLIT      1,FF33
QUEUE      PUMP23
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE(Alight Truck)
*Clamp Supply Hose clsuho 3 14+RVLNOR(1,12,61.8)
ADVANCE    14+RVLNOR(1,12,61.8)
LOGIC R    BOOLFF2
GATE LR    BOOLFF1
*Disconnect Hose from Bed dishobed           4 12+RVLNOR(1,18.7,211)
ADVANCE    12+RVLNOR(1,18.7,211)
*Bring 2.5' Hose to Side of truck Bring 4 4+RVLNOR(1,4.84,21.1)
ADVANCE    4+RVLNOR(1,4.84,21.1)
*Connect Hose from Bed conhosbe           4 5+RVLNOR(1,30.9,668)
ADVANCE    5+RVLNOR(1,30.9,668)
DEPART     PUMP23
TRANSFER   ,NODE2                 *GO SIGNAL COMPLETION 3FF
FF33     QUEUE      PUMP33
*////////////////////////////////////////////////////////////////////
*  ATTACK LINE
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*Get Hose From Mattydale gehosmat           3 12+RVLNOR(1,20.6,72.1)
ATTK2    ADVANCE    12+RVLNOR(1,20.6,72.1)
*Ext Uncharged Attack 150'exatho15           3 28+RVLNOR(1,14.6,434)
ADVANCE    28+RVLNOR(1,14.6,434)
*Call and Receive Water Calrecwa           3 8+RVLNOR(1,18.1,267)
ADVANCE    8+RVLNOR(1,18.1,267)
DEPART     PUMP33
TRANSFER   ,NODE2                 *GO SIGNAL COMPLETION OF 2FF PUMP
NODE2    ASSEMBLE   2
LEAVE      MEN,2
*          LOGIC R    BOOLFF2
```

```
*          GATE LR    BOOLFF1                *CALL FOR HYDRANT WATER
TRANSFER   ,NODE1
*444444444444444444444444444444444444444444444444444444444
GOT4     ENTER      MEN,3                  *GOT 3 MEN (Fourth at Hydrant)
SPLIT      1,FF4                  *ACTIONS OF FF1
QUEUE      PUMP14
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE(Alight Truck)
*Clamp Supply Hose clsuho 3 14+RVLNOR(1,12,61.8)
ADVANCE    14+RVLNOR(1,12,61.8)
LOGIC R    BOOLFF2
GATE LR    BOOLFF1
*Disconnect Hose from Bed dishobed           4 12+RVLNOR(1,18.7,211)
ADVANCE    12+RVLNOR(1,18.7,211)
*Bring 2.5' Hose to Side of truck Bring 4 4+RVLNOR(1,4.84,21.1)
ADVANCE    4+RVLNOR(1,4.84,21.1)
*Connect Hose from Bed conhosbe           4 5+RVLNOR(1,30.9,668)
ADVANCE    5+RVLNOR(1,30.9,668)
DEPART     PUMP14
TRANSFER   ,NODE3                 *GO SIGNAL COMPLETION 3FF
*--------------------------------------------------------
FF4      SPLIT      1,FF44                 *ACTIONS OF FF3 AND 4
QUEUE      PUMP24
ADVANCE    3+RVLNOR(1,8.33,24.8)  *EXIT ENGINE (Alight Truck)
LOGIC R    FF3PO3
GATE LR    FF3CFW                 *CFW AT BEGIN PO3
DEPART     PUMP24
TRANSFER   ,NODE3                 *GO SIGNAL COMPLETION 3FF
*
FF44     QUEUE      PUMP44
*////////////////////////////////////////////////////////////////////
*  ATTACK LINE
* \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
*Get Hose From Mattydale gehosmat           3 12+RVLNOR(1,20.6,72.1)
ATTK3    ADVANCE    12+RVLNOR(1,20.6,72.1)
*Extend Uncharged Attack 150'exatho15           3 28+RVLNOR(1,14.6,434)
ADVANCE    28+RVLNOR(1,14.6,434)
*Call and Receive Water Calrecwa           3 8+RVLNOR(1,18.1,267)
ADVANCE    8+RVLNOR(1,18.1,267)
DEPART     PUMP33
*          TRANSFER   ,NODE2                 *GO SIGNAL COMPLETION OF 2FF PUMP
DEPART     PUMP44
TRANSFER   ,NODE3                 *GO SIGNAL COMPLETION OF 2FF PUMP
*
NODE3    ASSEMBLE   3
LOGIC R    BOOLFF2
GATE LR    BOOLFF1                *CALL FOR HYDRANT WATER
LEAVE      MEN,3
TRANSFER   ,NODE1
START      1000                   *SIMULATE FOR A MANPOWER LEVEL OF 5
END
```

# Appendix G

# Doors

| Type of Door | Procedure | Min.(s.) | Max.(s.) | Ave. |
|---|---|---|---|---|
| Glass Door, Metal Frame | Impact | | | 60 |
| | Pry | 60 | 120 | 90 |
| | Power | DNA | | |
| Metal Door, Metal Frame, No Window | Impact | 120 | 420 | |
| | Pry | 60 | 120 | |
| | Power | | | 60 |
| Metal Door, Metal Frame, Small Window | Impact | 120 | 420 | 300 |
| | Pry | 120 | 180 | 150 |
| | Power | 60 | 120 | |
| Wood Door, Wood Frame, Panels | Impact | <60 | <60 | <60 |
| | Pry | DNA | | |
| | Power | DNA | | |
| Wood Door, Metal Frame, No Window | Impact | | | 60 |
| | Pry | | | 60 |
| | Power | DNA | | |
| Wood Door, Wood Frame, Small Window | Impact | DNA | | |
| | Pry | DNA | | |
| | Power | 60 | 120 | 150 |
| Wood Door, Metal Frame, Large Window | Impact | | 60 | <60 |
| | Pry | | | 60 |
| | Power | DNA | | |
| Wood Door, Wood Frame, Glazed | Impact | | | 60 |
| | Pry | | | 60 |
| | Power | DNA | | |

Table G.1: Estimated Time to Force Entry (Seconds)

Figure G.1: Glass Door, Metal Frame

Figure G.2: Metal Door, Metal Frame, No Window

Figure G.3: Metal Door, Metal Frame, Small Window

Figure G.4: Wood Door, Wood Frame, Panels

Figure G.5: Wood Door, Metal Frame, No Window

Figure G.6: Wood Door, Wood Frame, Small Window

Figure G.7: Wood Door, Metal Frame, Large Window

Figure G.8: Wood Door, Wood Frame, Glazed

## Appendix H

# Data - Moving Charged Hose

Figure H.1: Firefighter Passes 50' Cone

One piece of missing data concerned the movement of charged attack hose. This test was conducted by video taping firefighters moving charged hose past cones placed at 50' intervals. The results are summarized in the Table H.1. Photographs taken from some of the video are shown in Figures H.1 and H.2.

Figure H.2: Extension of Charged Hose

In the cases where two firefighters extended the charged hose the second firefighter always grabbed the hose at the 100' link. In other words after the second 50' length was pulled. Only one firefighter was responsible for moving the hose over the first 100' in these tests.

The amount of time it took one firefighter to extend the hose over the second 50' was always greater than the first. This makes sense in the context of work. The overall weight being moved

|  | 2 Firefighters |  |  | 3 Firefighters |
|---|---|---|---|---|
| Distance | Test 1 | Test 2 | Test 3 | Test 4 |
| 1st 50' Interval | 6 | 6 | 6 | 6 |
| 2nd 50' Interval | 9 | 8 | 7 | 6 |
| 3rd 50' Interval | 8 | 7 | 8 | 8 |
| 4th 50' Interval | 9 | 11 | 9 | 9 |

Table H.1: Moving Charged Hose

was greater when the hose was being extended over the second 50' length than over the first.

Three firefighters were utilized in the fourth test. The time to extend the first and second 50' section was identical. For the first 150' in this case there was one man per 50' hose length.

It was not possible to obtain data for a single firefighter extending a charged hose over 200 feet. The fire officers refused to allow this test to be performed.

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