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Design of Multi Agent Based Crowd Injury Model

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DESIGN OF MULTI AGENT BASED CROWD INJURY MODEL

by

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ABSTRACT

DESIGN OF MULTI AGENT BASED CROWD INJURY MODEL

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A major concern of many government agencies is to predict and control the behavior of crowds in different situations. Many times such gatherings are legal, legitimate, and peaceful. But there are times when they can turn violent, run out of control, result in material damages and even casualties. It then becomes the duty of governments to bring them under control using a variety of techniques, including non-lethal and lethal weapons, if necessary.

In order to aid decision makers on the course of action in crowd control, there are modeling and simulation tools that can provide guidelines by giving programmed rules to computer animated characters and to observe behaviors over time in appropriate scenarios. A crowd is a group of people attending a public gathering, with some joint purpose, such as protesting government or celebrating an event. In some countries these kinds of activities are the only way to express public's displeasure with their governments. The governments' reactions to such activities may or may not be tolerant. For these reasons, such situations must be eliminated by recognizing when and how they occur and then providing guidelines to mitigate them.

Police or military forces use non-lethal weapons (NLWs), such as plastic bullets or clubs, to accomplish their job. In order to simulate the results of such actions in a computer, there is a need to determine the physical effects of NLWs over the individuals in the crowd.

In this dissertation, a fuzzy logic based crowd injury model for determining the physical effects of NLWs is proposed. Fuzzy logic concepts can be applied to a problem by using linguistic rules, which are determined by problem domain experts. In this case, a

group of police and military officers were consulted for a set of injury model rules and those rules were then included in the simulation platform. As a proof of concept, a prototype system was implemented using the Repast Simphony agent based simulation toolkit. Simulation results illustrated the effectiveness of the simulation framework.

To my children, Bensu and Cuneyt.

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I would like to thank my parents, four sisters, and three brothers. They were always supporting me and encouraging me with their best wishes.

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CHAPTER 1

INTRODUCTION

1.1 Motivation for the Dissertation Research

A major concern of many government agencies is to predict and control the behavior of a crowd upon different events. "*A crowd is a group of significant number of individuals gathering for an event, doing same activities for a specific duration, and eventually dispersing due to fatigue, the closure of the event, or involuntarily*" [1]. To resolve most crowd related problems, it is necessary to influence, orient and control human flow by providing several control measures [2]. For these reasons such situations must be eliminated by recognizing when and how they occur and then providing guidelines to mitigate them. Modeling and simulation are tools that can provide these guidelines by giving programmed rules to computer animated characters and observing their behaviors over time in appropriate scenarios [3-4].

"*In the last decade the threat has changed and future engagements are expected to often involve lighter forces in urban setting.*" [5]. Several military simulations have been developed for different problem domains to reduce the cost of education and for safety issues. However, crowd models are absent from those military simulations. New military simulations including crowd models are needed to simulate real urban area operations [6-7].

To meet that requirement, The Virginia Modeling Analysis and Simulation Center (VMASC) developed a multi-phase military simulation project that includes crowd modeling. For military simulations, certain military standards, defined by the Department of Defense, such as High Level Architecture (HLA) would normally be met by a crowd modeling project [8]. A crowd behavior cognitive model, as a part of crowd modeling, is still under development. The aim of the cognitive model is to simulate crowd behavior under different circumstances.

In situations where crowd control is warranted, military or police forces are used to manage the crowd and non-lethal weapons (NLW) may be optional tools. To make the simulation more realistic, an injury model should be developed for different types of non-lethal weapons [9]. The physical effects of each non-lethal weapon should be defined in this injury model. The injury model has a close relationship with the crowd behavior cognitive model since the effects of the non-lethal weapons also affect the psychology of the crowd and become a decision making criteria [10-11].

In this dissertation, a multi-agent based model of crowd behavior is described by using certain methods. Possible physical effects of the non-lethal weapons on the individuals in a crowd were simulated based on the PMFserv injury model [12]. A novel multi agent based crowd injury model, which uses the fuzzy logic concept as its background, was also designed in this dissertation.

1.2 Summary of Dissertation Contributions

In this dissertation research, the physical effects of non-lethal weapons over individuals in a crowd have been simulated by using a novel fuzzy logic design in the Repast agent-based simulation toolkit. In order to simulate the physical effects of lethal or non-lethal weapons, a mathematical model is needed and the PMFserv Injury Model developed by Silverman [12] is used for such purpose.

The PMFserv Injury Model provides solutions for two types of non-lethal weapons including club and rubber bullets. However, there are nine different types of non-lethal weapons in the crowd modeling project. In this dissertation, we first implemented the PMFserv Injury Model using Repast to simulate the results for these two types of NLWs. Then, a novel fuzzy logic injury model was developed to cover the other types of NLWs. This fuzzy logic model was also implemented in Repast Simphony for the proof of concept and reasonable results have been achieved.

1.3 Specific Objectives

The specific objective of this research is to design a novel multi agent based crowd injury model based on fuzzy logic. Another objective is to implement the proposed model using the multi agent based simulation toolkit--Repast Simphony, and to test it for certain cases to show its effectiveness.

1.4 Organization of the Dissertation

The remaining chapters of this dissertation are organized as follows,

Chapter II introduces the research background and related work. The PMFserv injury model, which forms the basis of this dissertation, is discussed in this chapter. This chapter also presents the work done by McKenzie [15], the incorporation of the PMF based injury model into the multi agent crowd model and the crowd cognitive model. The High Level Architecture (HLA), Fuzzy Logic concept, Agent Based Simulation (ABS) and ABS toolkits with an emphasis on Repast Simphony, behavior modeling and simulation framework are also discussed.

Chapter III discusses the Unified Modeling Language (UML) design of the PMFserv Injury Model including the use case, sequence, activity and class models. An implementation of the PMFserv Injury Model in Repast Simphony and the test cases are also presented.

Chapter IV outlines the design and implementation of a fuzzy logic injury model, which determines the effects of non-lethal weapons on crowd individuals. The most important part of a fuzzy logic design is the determination of rules of its inference system that requires domain expert knowledge.

Chapter V presents experimental results, Chapter VI presents a discussion on the results, and Chapter VII concludes this dissertation.

CHAPTER 2

BACKGROUND AND RELATED WORK

2.1 Agent Design - An Injury Model Proposed by Silverman

Silverman conducted a complete literature review for injury model design based on lethal and non-lethal weapons including its design, implementation and testing as briefly listed below.

In the reservoir model [12], each agent has an energy reservoir with a capacity decided by its reservoir level. If the level of the energy reservoir is below the predefined threshold, the agent cannot do some specific tasks [13-14]. Five different parameters are defined based on the Performance Moderator Functions (PMF) to decide an agent's energy reservoir level [12],

- Exertion
- Nourishment
- Injury
- Sleep
- Environmental Conditions

In this work, the motive capacity of an agent is divided into the following five categories [12],

- Healthy
- Slowed and Dazed
- Limping Badly
- Incapacitated
- Dead

The parameters of an injury model can be defined using the following formula [12].

$$SI = f(Wt, Wc, R, B, E, V, t) \quad (2.1)$$

Where:

SI : Severity of the injury

Wt : Weapon type

Wc : Weapon capacity

R : Distance from the source/injurer

B : Part of the body affected

E : Effort by the injurer

V : Vulnerability of the injured

T : Time

Lookup tables are used to decide the values of the parameters which are used to calculate the motive capacity of an agent. Another key concept of the model is the "Golden Hour" concept that is used to decide whether the injury will get better or worse one hour from the onset of the injury. It is defined based on the combination of the weapon type and weapon capacity. If the Golden Hour score > 1, then the injured person will get worse. Otherwise, the injured person will get better. If the Golden Hour score is equal to one, there is no change. For example, Silverman assumed that the Golden Hour score was larger than one for all types of guns while it was smaller than one for a small club. The final version of the formula then becomes [12]:

$$SI(t) = SI_0 * \psi(t) \tag{2.2}$$

where

SI_0 : Time independent component (severity at the time of injury occurred)

$\psi(t)$: Time variation factor

$$SI_0 = SWt * SWc * SB * SV \tag{2.3}$$

Here, time variation factor is decided based on the Golden Hour concept.

$$\psi(t) = 1\text{-}e^{(-K_2*T)} \tag{2.4}$$

where

$$K_2 = 1\text{- Golden Hour score} \tag{2.5}$$

2.2 Incorporation of the PMF-Based Injury Model into a Multi-Agent Representation of the Crowd Behavior Model

In a riot, military or police forces use non-lethal weapons to manage the crowd. McKenzie defined the types of these weapons and their physical effects on an activist [15-16]. In addition, the integration of the PMFserv Injury Model and the crowd federate was proposed.

A crowd federate is the combination of the cognitive layer, the physical layer and the crowd behavior API [15]. Each layer has its own specific tasks. The cognitive layer receives stimuli from the physical layer and decides a suitable behavior as a response to the stimuli. Behaviors are carried out by the physical layer after receiving a decision from the cognitive layer [17]. The physical layer also senses the environment for stimuli and sends them to the cognitive layer. Another task of the crowd behavior layer is to communicate with other federates via a Runtime Infrastructure (RTI). Figure 2.1 summarizes the architecture of the crowd federate.

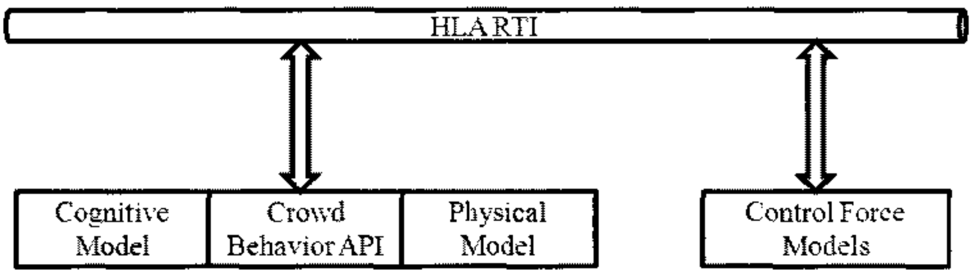


Figure 2.1 Crowd Federate Architecture.

The Extended Markup Language Remote Procedure Call (XMLRPC) is used for integration purposes between Crowd Federate and PMFserv [18]. XMLRPC is a set program which is used to call a remote procedure from different platforms over the internet. It uses the HTTP protocol for transportation and XML standards for encoding purposes. A rubber bullet is used as a NLW and is aimed at the chest area for proof of concept. Once the health value is lower than a predefined threshold, the individual from the crowd falls to the ground. The individual then starts to recover and starts moving again after its health value is above the threshold.

The most important part of this work is the definitions of the non-lethal weapons and their possible effects on crowd individuals. There are several non-lethal weapons to be used on crowded rebels by law-enforcements. They are categorized into nine basic types by McKenzie as follows [15]:

2.2.1. Personal Armor and Shields

This category consists of those protection equipments rather than weapons such as face mask, shield and other clothes. Figure 2.2 [19] shows examples of personal armor and shields.

(a)Personal Armor.

(b)Shields.

Figure 2.2 Personal Armor and Shields.

Even though there are no specific injuries associated with these kinds of components, they have psychological effects on the crowd when they notice the law-enforcement equipped with these gear.

2.2.2. Audio Equipment

Audio equipment is not often viewed as weapons like Personal Armor and Shields are. Audio equipment is usually voice amplification equipment, which allow law-enforcement to communicate internally with each other and/or externally with the crowd, independent of environmental audio level. Figure 2.3 [20] shows an example of an audio amplifier.

These weapons also do not have any physical effect but they may have psychological effects on the crowd.

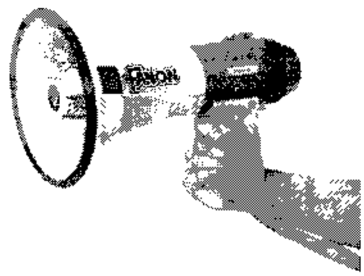


Figure 2.3 Audio Amplifier.

2.2.3. Short-Range Direct Contact NWLs

Any hand-wielded weapons which gets in contact with an individual in a crowd in direct-touch range or a very short-range is classified in this group, for example batons and disposable restraint systems. Figure 2.4 [21] shows a club and a double cuff disposable restraint. They can slow down or harm the individuals if applied effectively.

(a) Club. (b) Double Cuff Disposable Restraint.

Figure 2.4 Club and Double Cuff Disposable Restraint.

2.2.4. Handheld Short-Range Chemical Dispensers

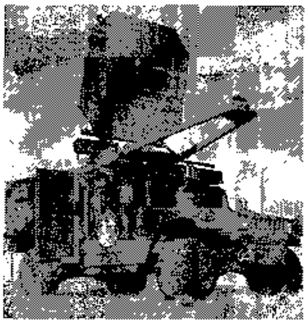
Handheld short-range chemical dispensers are a group of single operator, handheld chemical dispensers who affect several people at the same time. The lifetime of these chemicals are short and their effect on individuals should be calculated once for all entities at the moment being fired. Figure 2.5 [22] shows a chemical spray used by police.

Figure 2.5 Chemical Spray.

The individuals in the crowd can be put out of action for a time period with these weapons so a Golden Hour value of less than 1 is appropriate.

2.2.5. Direct Long-Range Non-Persistent

This category includes rubber bullets and active denial systems together with other long distance dispensers of various non-persistent materials. Some of those weapons are directly fired to a target in order to affect only that target. Figure 2.6 [23] shows an active denial system and some rubber bullets [15-24]. Living human agents react immediately in pain and the recovery period is usually short.



(a) Active Denial System.

(b) Rubber Bullet.

Figure 2.6 Active Denial System and Rubber Bullet.

2.2.6. Indirect Long-Range Non-Persistent

Indirect long-range, non-persistent weapons have the same properties as direct long-range non-persistent weapons, but they affect multiple people in a specific area. Rubber ball grenades and disorienting flash-bang rounds are examples of this type of less-lethal weapons. Figure 2.7 [25-26] shows the rubber ball grenades and the flash bang rounds.

(a) Rubber Ball Grenades.

(b) Flash-Bang Round.

Figure 2.7 Rubber Ball Grenades and Flash Bang Rounds.

Reaction and recovery periods are short as are those of direct long-range non-persistent weapons.

2.2.7. Long-Range Persistent

Long-range persistent weapons include persistent materials, such as gases, at long distance. These materials may either be thrown or be cartridge in nature. Figure 2.8 [27] shows color gases and cartridge.

(a) Color Gases. (b) Gas Cartridge.

Figure 2.8 Color Gases and Cartridge.

These types also have short reaction and recovery periods. However, these kinds of weapon forces are expected to be able to keep the area clear for a longer period of time, allowing the crowd to escape from the area. The crowd can join in another area if they are motivated.

2.2.8. Deployed Hindrances

Deployed hindrances are passive weapons in nature. Once they are installed in an area, they perform their functions without changing their states. Tire-damaging spike strips or sticky foam are examples of this kind. Figure 2.9 [28] shows an example of a spike.

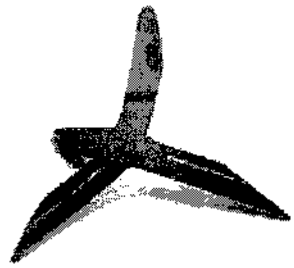


Figure 2.9 Spike.

The individuals from the crowd can be disabled for a period of time that would be dictated by a Golden Hour value of less than 1.

2.2.9. Deployed Weapons

Deployed weapons need to be installed in an area before usage much like deployed hindrances. They must be triggered before functioning by the control force at a certain location. However, they function only if some events are triggered, and they are usually disabled after the first usage. Rubber ball grenades with triggering timers are examples of this type. "*Reaction, injury, and recovery would be dictated by one of the above associated categories*" [15].

2.3 Crowd Cognitive Model

This model is still under development by McKenzie and Nguyen [1]. In this model, social structures are determined at three levels [29]. Crowd factions are considered as large scale structures and their purpose in a crowd event is highly abstract [30-31]. Individuals in crowd clusters are located in a specific area and they are affected by same stimuli. Individuals of Family/Friends/Acquaintances (FFA groups) move together during the crowd event. All structures in all levels have their own leader to guide its members. Figure 2.10 shows the group types and their hierarchical relationship in a crowd event [32-33].

Instead of participating in an event alone, individuals get together as a family, friends or acquaintances to support crowd events. They reach their objectives as a group by making decisions on the group level [34]. "*The crowd behavior cognitive model architecture has to be able to handle influences of a social (group) identity and individual* *(personal) identities in decision-making, leading to a multi-resolution approach towards modeling crowd behavior*" [29-35].

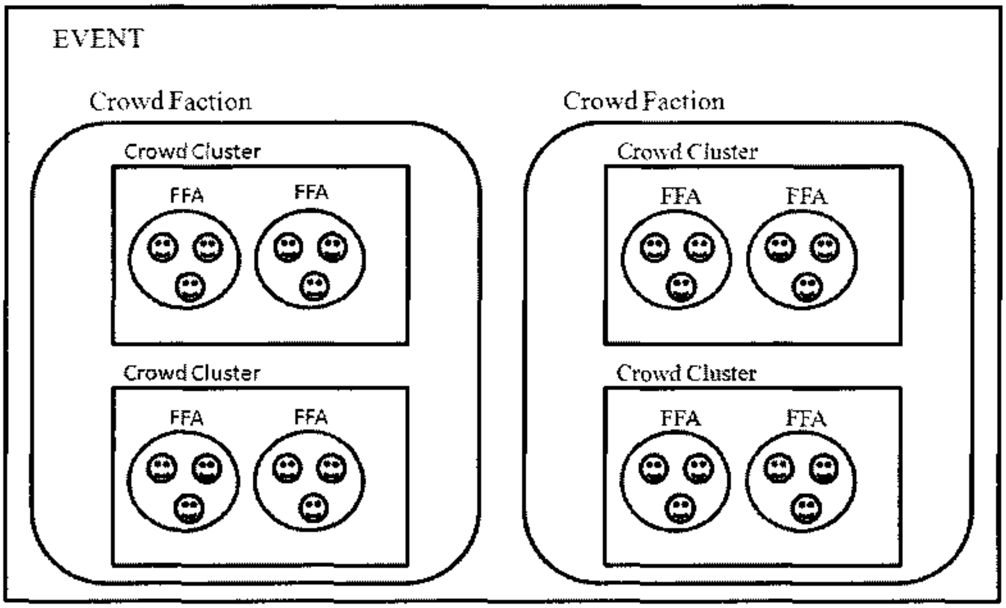


Figure 2.10 Crowd Structure.

2.4 High Level Architecture (HLA)

HLA was developed by the US Department of Defense to provide a general architecture for military simulations. The key responsibility of HLA is to define interoperability standards among different simulation projects [36]. The baseline definition of the HLA includes the HLA Rules, the HLA Interface specification, and the HLA object model template [37].

Figure 2.11 shows the main functional components of a HLA federation. Federates are any kind of simulations working on HLA backbone. Each federate in a HLA can represent specific tasks but they must have common capabilities to establish data exchange by using runtime infrastructure (RTI) services [38]. Each federate might be written in different programming languages and may run on different platforms [12].

All communications among the simulations are done via RTI. RTI is an operating system that provides not only a set of services supporting the simulations but also federation management support functions [39].

The HLA runtime interface specification provides a standard way for federates to interact with RTI, to invoke RTI services to support runtime interactions among federates, and to respond to requests from RTI [36]. This interface is implementation independent and is independent of the specific object models and data exchange requirements of any federation [40].

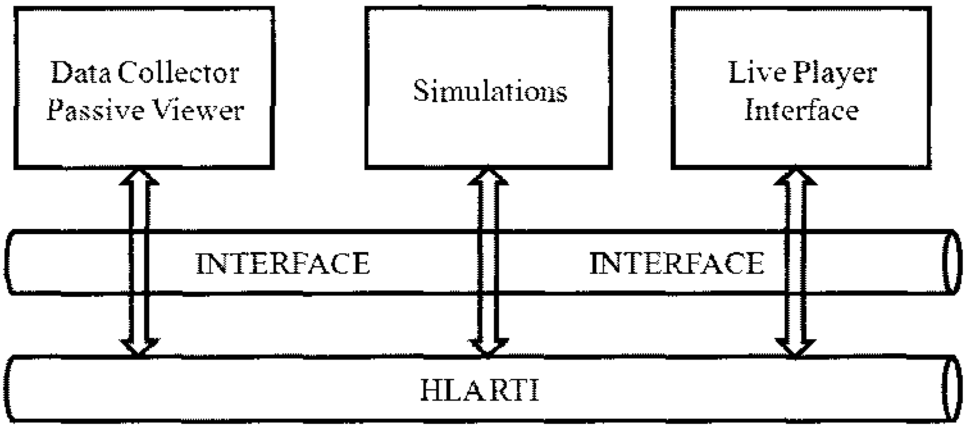


Figure 2.11 HLA Components.

2.4.1 HLA Object Models

"HLA object models are descriptions of the essential sharable elements of the simulation or federation in 'object' terms." [37] Since HLA provides the interoperability, object models are intended to focus on the description of the critical aspects of simulations and federations, which are shared across federation. All federates are required to document their object model by using standard object model template [41], providing open information for the community to facilitate the reuse of simulations [42].

2.4.2 HLA Interface Specification

The HLA interface specification is the descriptions of six runtime services provided by RTI to the federations. Each service has its own responsibilities [37-43]. These services are:

- Federation management service
- Declaration management service
- Object management service
- Ownership management service
- Time management service
- Data distribution management service

2.4.3 HLA Rules

HLA has several mandatory standards defined by HLA rules. Rules are divided into two groups: Federation and federate rules. All federations must have their own Federation Object Model (FOM) which is created by using the Object Model Template (OMT) [44]. Federates use RTI to exchange information between each other [45]. "*Based on the information, federates must import and export information, transfer object attribute ownership, updates attributes and utilize the time management services of the RTI when managing local time.*" [37]

2.5 Fuzzy Logic

Fuzzy logic was proposed in 1965 by Zadeh [46]. In the crisp logic concept, everything is considered as "black or white", i.e. "1 or 0". On the other hand, the fuzzy logic concept pays attention to the "grays". "*The question Zadeh always insists upon asking is, to what degree is something true or false*?" [47]. A real world problem can be defined as its inputs and outputs by using linguistic variables in fuzzy logic. It is used especially when ambiguity is common and when it is difficult to model the problem domain [48].

Fuzzy logic is defined in three phases. In the first phase, crisp input values must be fuzzyfied by using membership functions. Each input variable gets different membership values within the range of [0, 1] in this phase. There are several membership functions such as trapezoidal, Gaussian and triangular. In the second phase, a rule based inference system is used. The min-max inference method is often used. After the inference process, all output variables get membership values within the range of [0, 1].

The key point of the fuzzy logic system is the definitions of the rules. All rules must be defined by domain experts to resolve a problem accurately [49-50]. Rules are defined as the IF-THEN structure. In the last phase, output variables must be defuzzified to get crisp values. Max, singleton, average and centroid are candidate methods for defuzzification [51]. A simple fuzzy logic washing machine could be designed as follows,

There are two types of fuzzy inference system in Matlab: Mamdani and Sugeno. In this example, Mamdani type fuzzy inference system is used for illustration as shown in Figure 2.12.

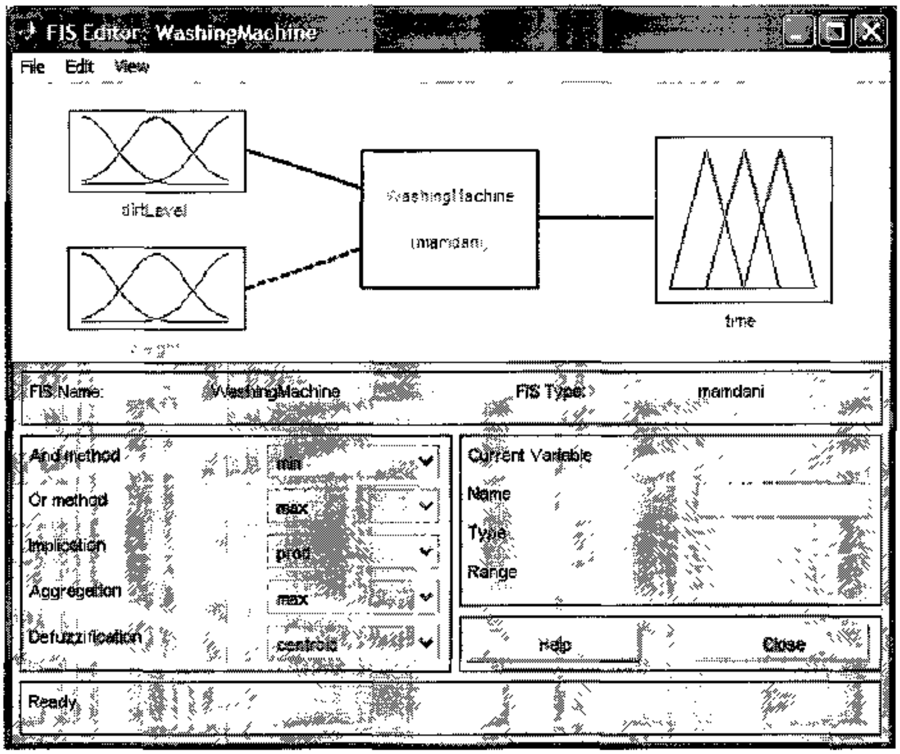


Figure 2.12 Washing Machine Fuzzy Logic Design in Matlab.

The duration of the washing process is determined as a function of dirt level and weight features of the clothes. The fuzzy set concept is a set without strictly defined boundaries [52-53]. The elements of a fuzzy set are the degrees of membership for the inputs and the outputs of the system. Fuzzy sets for the input *dirtLevel* are *low, normal, high*, for the input *weight* are *light, normal, heavy* and for the output *time* are *short, normal and long*. Each fuzzy set has a specific membership function which is triangular in this example. Here, crisp value ranges must be determined for all inputs and outputs. The *dirtLevel* input gets a crisp value within the range of [0 and 10], the *weight* input gets a value within the range of [0 and 9] and the output *time* gets a value within the range of [0 and 5]. The *weight* input has the unit of kilogram and the *time* output has the unit of hour. The crisp input values are converted into degrees of membership for each fuzzy set. Figures 2.13, 2.14 and 2.15 show the fuzzy sets and the membership functions for the variables *dirtLevel*, *weight* and *time*, respectively.

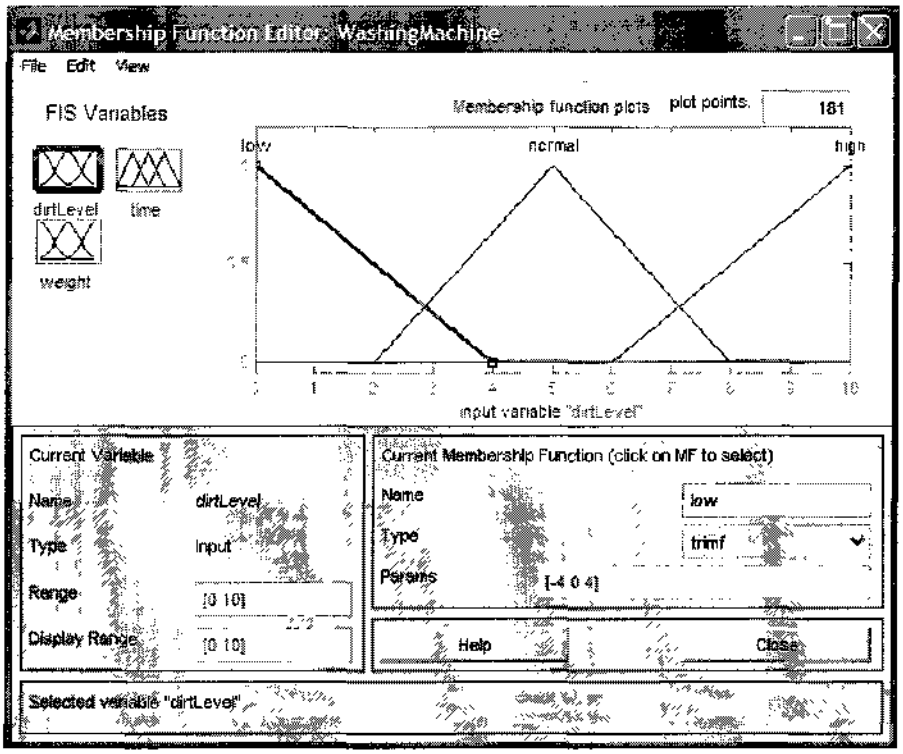


Figure 2.13 Membership Functions of Dirtlevel Input.

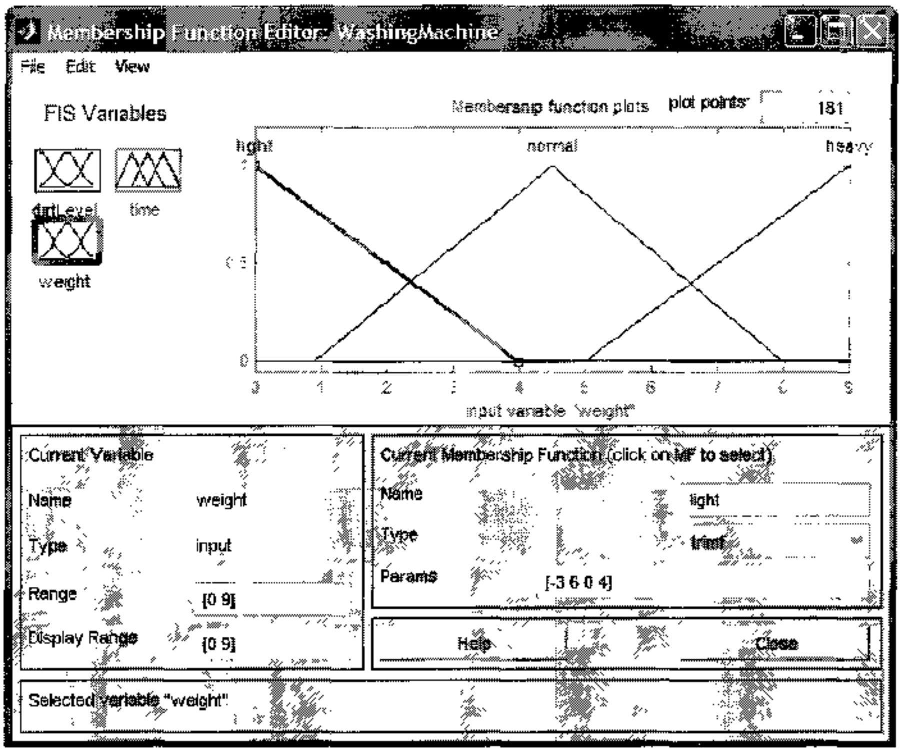


Figure 2.14 Membership Functions of Weight Input.

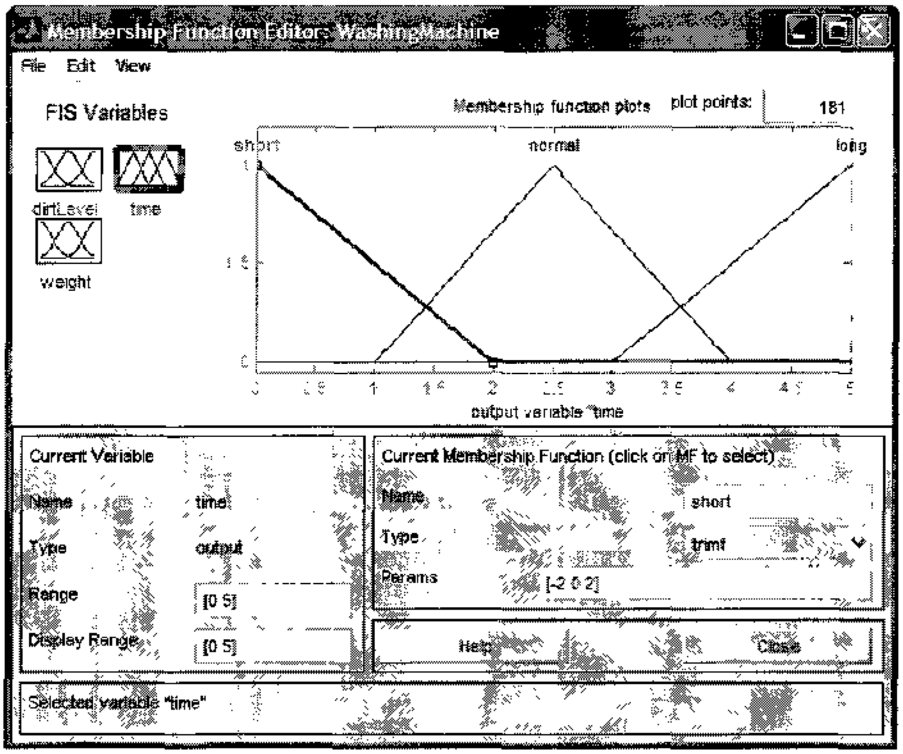


Figure 2.15 Membership Functions of Time Output.

After the membership values of the input variables have been determined, the fuzzy inference process is done based on fuzzy rules. Definition for the fuzzy rules is very important and must be done by domain expert. A fuzzy rule consists of two parts: an antecedent part and a consequent part, as shown in Figure 2.16.

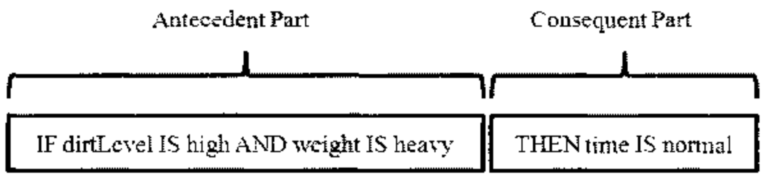


Figure 2.16 Rule Structure.

A weight value within the range of 0 and 1 should be assigned to each rule. Fuzzy operators AND and OR connect the input variables to shape the antecedent part of the rule. There are two methods for the AND operator: minimum and product; while the OR operator has the maximum and probabilistic OR. Each rule supports the output to a different degree. The antecedent part states the degree of support of the rule once fuzzy operators are applied. Figure 2.17 shows the rules used by inference process in washing machine example. On the other hand, Figure 2.18 shows the mesh surface produced by Matlab.

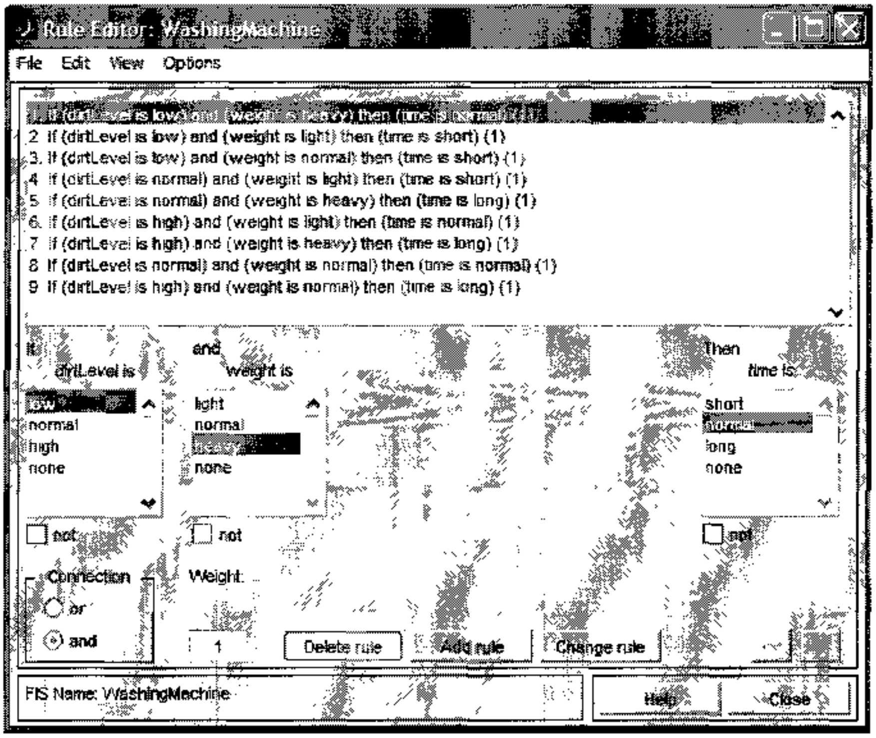


Figure 2.17 Fuzzy Logic Rules for Washing Machine.

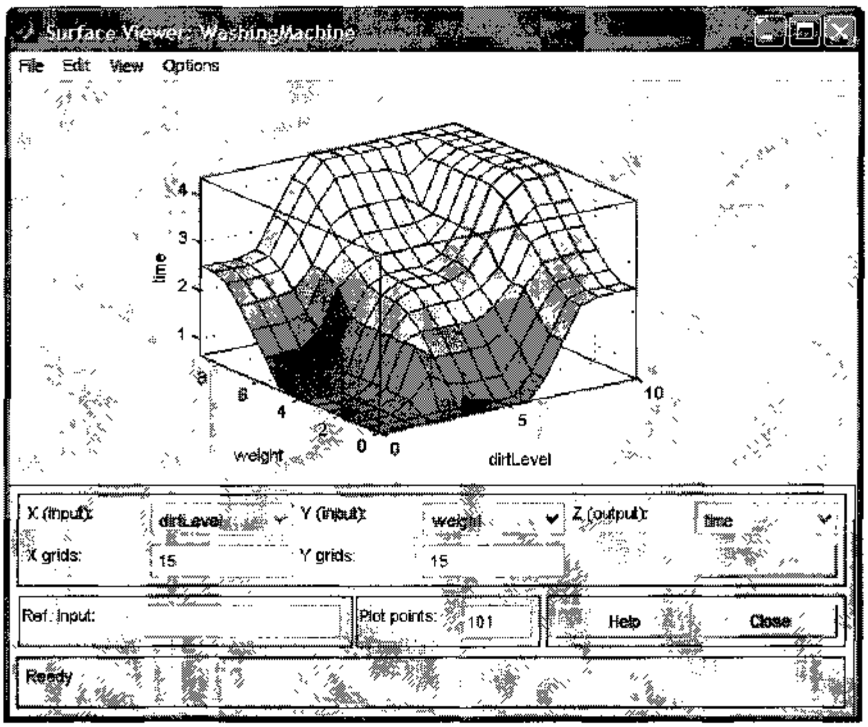


Figure 2.18 Washing Machine Mesh Surface.

To identify the output fuzzy set, all of the rules are combined in the aggregation process. There are three methods for aggregation: maximum, probabilistic or, and summation.

The last phase of a fuzzy logic design is the defuzzification process. In this process, crisp values of all output variables are produced from the fuzzy sets. The centroid method is the most used defuzzification method in this phase. Figure 2.19 and Figure 2.20 show how the crisp output values are produced for the sample crisp input values.

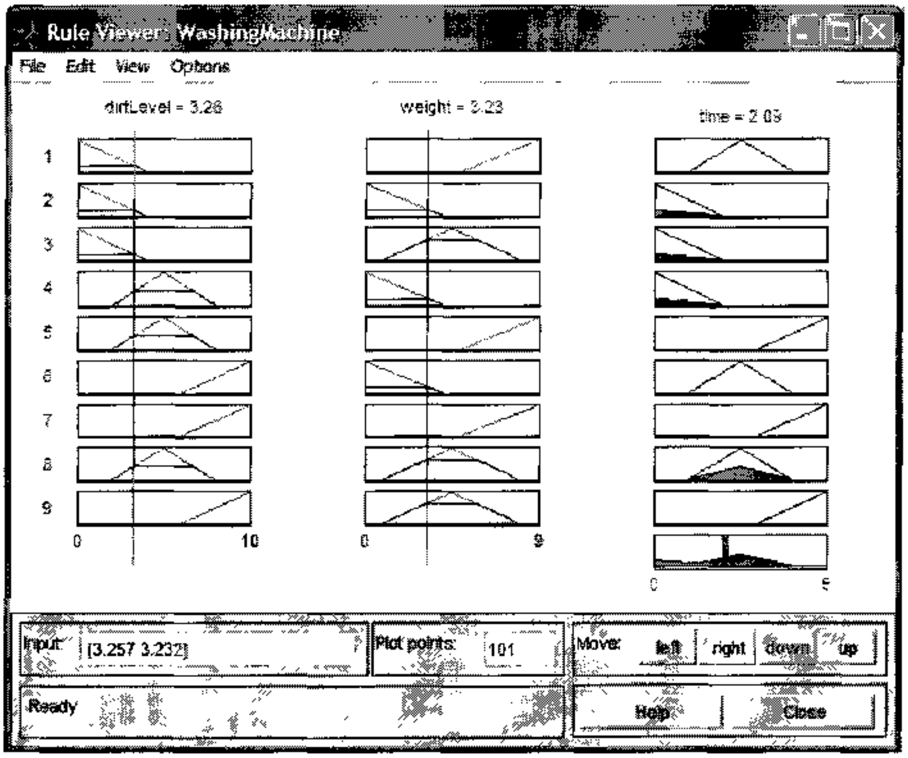


Figure 2.19 Sample Output for Inputs: Dirtlevel =3.26 and Weight=3.23.

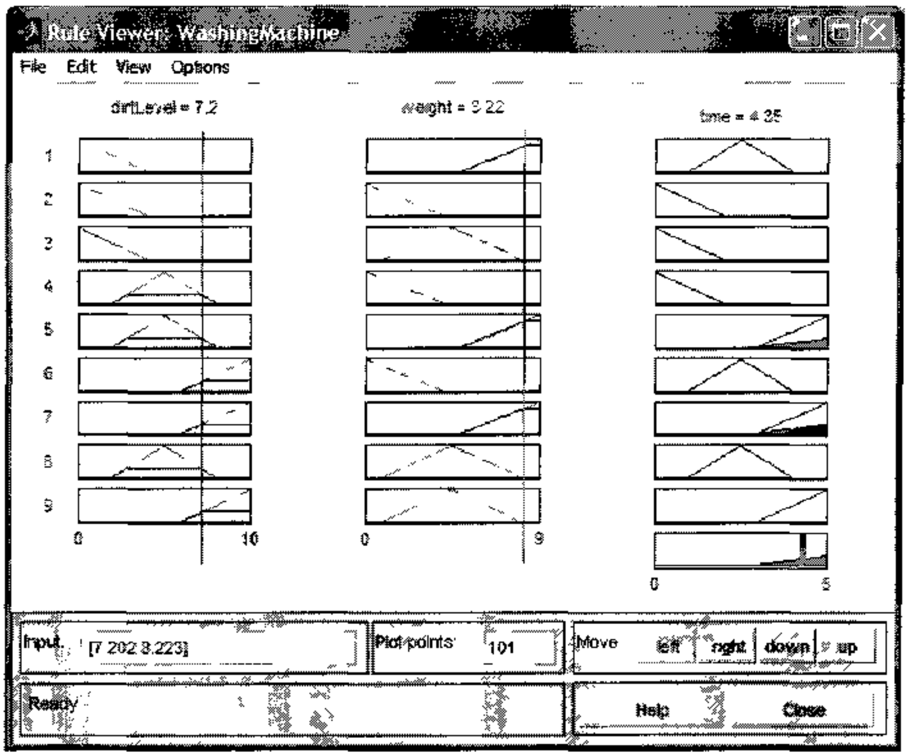


Figure 2.20 Sample Output for Inputs: Dirtlevel =7 2 and Weight=8.22.

Basic features of fuzzy logic include:

- It is based on natural language
- It is easy to understand
- It needs problem domain knowledge
- It can model nonlinear functions
- It is flexible.

Fuzzy logic can be used in different applications such as decision support, industrial process control and consumer products [54].

2.6 Agent Based Simulation

Agent based simulation (ABS) is often used to simulate the behavior of an autonomous agent and the interactions among a group of agents to illustrate their effects on a system as a whole. The systems to be simulated may vary from micro to macro levels and the behavior of an autonomous agent may produce very complex behaviors. It is sometimes called agent based modeling (ABM) or multi-agent systems. Although it was developed in the 1940s, ABM was not used frequently until the 1990s because of its computational complexity [40].

Each agent has its own behaviors and objectives depending on the system in which it participates [55]. It also has an adaptation capability to change its behavior in a changing environment [56]. An agent always senses its environment and makes independent decision to reach its objectives in order to be autonomous. An agent has several features, as follows [57-58].

- It could be considered as an individual with some features and rules in addition to its boundary to shape its behaviors and decision systems.
- An agent is an autonomous structure which can decide what to do under changing circumstances.
- It has one or more objectives to achieve. It always checks if the objectives are achieved after a behavior being conducted and tries to manipulate its behavior to achieve its goals.
- It lives in an environment in which it interacts with the other agents, as well as the environments itself. It is aware of what is happening in the surrounding areas.
- It has learning capabilities. By using its memory, it can have experience.

Because of their complexity, most real life systems cannot be modeled by using mathematical equations. Although agents have simple rules to make decision, complex systems can be modeled by using different types of agents [59]. The whole system is much larger than the summation of the agent capabilities. If an agent is considered as "1", for example, and three agents are used in a system, the total value of the system is usually not equal to "3" but may be equal to 111 [60-61]. Sometimes, a simple agent-based model can express complex behaviors and provide valuable information about the real-world systems. An agent has a capability of taking independent decisions that means it is an active component for the decision systems [4].

One of the most attractive features of ABM is its ease of implementation. It is easy to implement but on the other hand, it is really difficult to decide the concepts used in the system. To model a complex system, a deep system analysis must be conducted. In this analysis, types of agents, rules of each agent type should be defined.

ABM has several benefits. ABM can be in charge of extraordinary events [62]. An extraordinary event can occur as a result of the communication between the agents. But, by using their adaptive decision making features, agents can have responsibility of the emerging problems [63]. For example, in a battlefield simulation, the behavior of an opponent cannot be predicted. It is not easy to understand and to predict the unfriendly behaviors in a battle game. ABM is a new approach to model emergent phenomena [64]. With ABM, one can model and simulate the behaviors of the system's agents and their interactions, capturing emergence from the bottom up when the simulation is run [65].

ABM can describe a system naturally. In many cases, ABM is most natural for describing and simulating a system composed of behavioral entities. Whether one is attempting to describe a traffic jam, the battlefield, or how an organization works, ABM makes the model seem closer to reality [66].

Agent Based Modeling is flexible. Systems can be modeled in a wide range from simple to more complex structures by using ABM. A system can be extended by adding new agent types or by changing the number of agents in a specific agent type. The rules of interaction between the agents and the ability to adaptation to changing environment can be controlled easily in ABM. In addition, the ability of changing levels of description is another type of flexibility [67].

2.7 Agent Based Simulation Tools and Repast Simphony

There are several free open-source ABS toolkits developed by different consortia. Repast (Recursive Porous Agent Simulation Toolkit), Swarm, MASON (Multi-Agent Simulator of Neighborhoods) and NetLogo are the most popular. Many of them are developed in Java or similar programming languages. If the agent does not have a learning behavior then it is called proto-agent [68]. All the tools listed above provide proto-agent designing capabilities [69]. Those tools also provide a proto-agent interaction environment to develop complex ABM simulations.

Among the toolkits mentioned above, Repast is the most popular and widely used agent based simulation toolkit. There are three versions of Repast for different platforms. Repast Py is developed for Python scripting, Repast J is developed for Pure Java programming, and Repast .NET is developed for Microsoft .NET framework. Repast Simphony is the latest version of Repast J. Repast Simphony offers users a rich variety of features including the following [68],

- Fluid model component development using any mixture of Java, Groovy, and flowcharts in each project.
- A pure Java point-and-click model execution environment that includes built-in results logging and graphing tools.
- An extremely flexible hierarchically nested definition of space including the ability to do point-and-click and modeling and visualization of both 2D and 3D environments.
- A range of data storage "freeze dryers" for model check pointing and restoration including XML file storage, text file storage, and database storage.
- Libraries for genetic algorithms, neural networks, regression, random number generation, and specialized mathematics.
- An automated Monte Carlo simulation framework which supports multiple modes of model results optimization.
- Built-in tools for integrating external models.
- Distributed computing with Terracotta.
- Full object-oriented.

In Repast Simphony, the location of the proto-agents is called its context. Context includes all proto-agents that are used in an agent based simulation. The Repast development team has developed a structure to provide an interaction space for proto-agents and called it as projection. Another important term in Repast Simphony is "context-sensitive behavior" which controls the behavior of a proto-agent in different contexts.

Repast Simphony has a strong 3D visualization ability to show the results of simulation by using Java 3D library.

2.7.1 Context

Context is the core data structure to hold proto-agents in Repast Simphony. Any kind of object instances could be put into context. By adding several proto-agents into a context, an abstract population could be created [68]. Proto-agents are the population of the context. But context does not provide an interaction structure for proto-agents. In the crowd injury model, crowd individuals such as leaders, followers and control forces would be the population of a context. A context may contain two or more sub-contexts. Crowd factions could be thought as sub-contexts of the crowd context and clusters could be thought as sub-contexts of crowd factions [70].

Context maintains not only proto-agents but also some generic data used by proto-agents to interact with the context in which they are located. Time and coordinates are the examples of data maintained by context [57]. A tick concept is used as a time variable in Repast Simphony. The duration of each tick can be adjusted for each simulation before it is run. An agent in a context occupies a location. Sometimes it shares its room with the other agents no matter if they all come from the same agent type. A proto-agent can move from one context to another based on the changes in its situation. In this case, shifting may occur. One proto-agent can shift the other one to different context by occupying its location. Figure 2.21 shows a context and a sub-context structure.

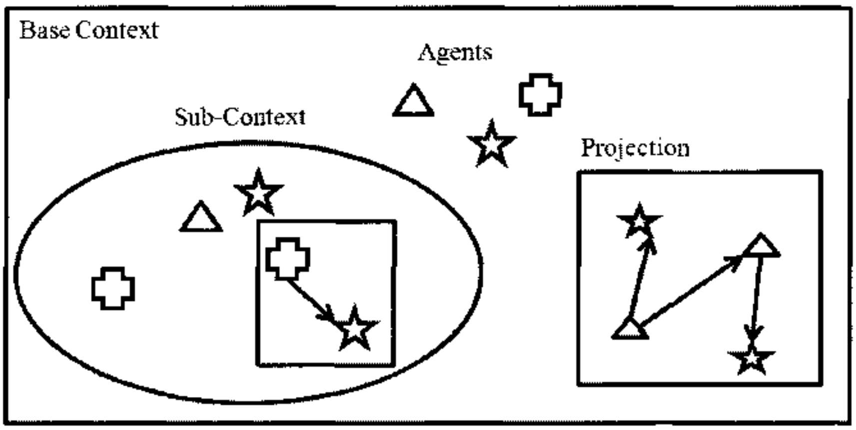


Figure 2.21 Context and Sub-Context Structures.

2.7.2 Projection

Since context does not provide an interaction structure among the proto-agents, a new structure is needed to handle that requirement. Projections are the structures to control the interactions between proto-agents in a specific context. Projections are the windows open to their environments for proto-agents. Various projections can be applied to a context to represent different types of interactions between proto-agents. That means, one proto-agent may have more than one interaction type in the same context. Grid and network projections are the mostly used projection types in Repast Simphony. Figure 2.22 shows a 3D layout example in Repast.

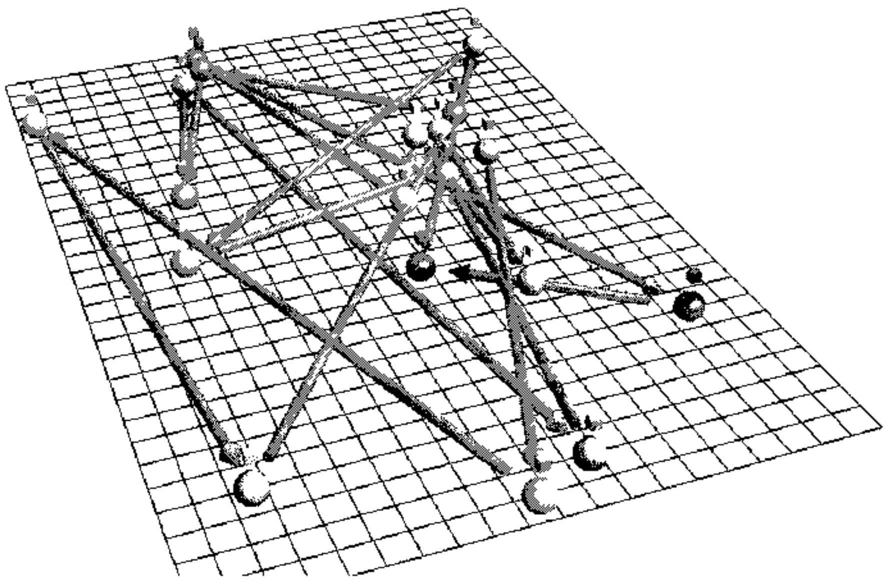


Figure 2.22 3D Layout in Repast as an Example of Projection.

2.7.3 Context-Sensitive Behavior

As mentioned above, proto-agents can shift from one context to another for different purposes. They could have different behaviors within different contexts. For example, a member of a crowd faction could behave differently from a member of another crowd faction.

"*Context-sensitive behaviors can be implemented by creating watchers or triggers for the behavior of the proto-agents. The modeler declares the particular circumstances under which a certain behavior is executed.*" [68] Watchers are used to monitor the state of an agent. Any changes appeared on an agent can be observed using watchers. Triggers can be active on any state change. Based on the state change, proto-agents decide different behaviors. Complex problems could be solved by using triggers in Repast.

2.8 Behavior Modeling and Simulation Framework for Crowd Simulation

Behavior modeling and simulation is done to design a behavior model to simulate a crowd under different circumstances such as in an emergency [2]. An agent based approach is used to represent each crowd individual's decision making process that consists of an agent's awareness of the environment and updates of some features. In an emergency situation, a person can chose to not obey the rules which regulate our daily lives, especially if the emergency endangers his or her life. Researchers try to simulate this kind of human behavior in the computer environment to predict the unwanted results of the emergency situations [2].

There are two categories broadly used to model crowd behavior. In the first category, a crowd is considered a collection of homogenous actors who behave as a result of simple rules. Cellular automata and the particle system model belong to this category. Complex human behaviors such as decision making are not handled by this kind of model. In the second category, a crowd is considered as a collection of heterogeneous actors who have decision making capabilities. An agent based model in which each individual is represented as an agent is a good example for this category.

Bayesian networks, fuzzy logic, neural networks, and BDI (Belief, Desire, Intention) are well known decision making frameworks, which are used in several applications. They almost all use a mathematical inference system as a core. The main objective of this work is to realize the natural human decision making process. A person's emotion or physical capabilities are effected by external stimulus such as climate, events and people. In this framework, the awareness of context is key. Based on the changes in the environmental variables, each agent updates its own features to save its health condition by adopting those changes. To do this job, each agent should communicate with the inference engine. Agents have several attributes in different areas such as emotional, physical and social groups. These attributes determine the decision making and behaviors under normal or emergency circumstances.

2.8.1 Design of Behavior Modeling Framework

Behavior modeling consists of many works such as situation awareness, cognition, population classification and coordination between the agents. The crowd behavior module, the individual behavior module, and the physical behavior module are three modules in this framework [3]. The framework also consists of two logical layers. The upper layer is responsible for sensing the environment and making decisions on the behavior of the agent. The crowd behavior module and the individual behavior module lie on this layer. The physical behavior module stands on the lower layer and this layer is responsible for the delivery of the sensor information gathered from the environment to the upper layer. Another task done by this layer is the execution of the selected behaviors as basic actions [2].

The crowd behavior module monitors the social relationships among the agents and commits the required group and crowd level feature updates of the agent. The individual behavior module evaluates the sensor information supplied by the lower layer and makes related changes on the individual level features. The final behavior of the agent is defined after the evaluation process of all of the attributes of the agent and it is sent to the lower layer to be executed. The physical behavior module converts the final behavior of the agent into simple actions such as run forward, turn, stand still and walk forward [6-7].

2.8.2 Development of Behavior Model

The first step of the simulation is the generation of the population by using the crowd initializer. In this step, all agent types are created with different internal parameters such as age, roles and social relationships. Once agents are created, they can sense the virtual environment via the situation awareness module to see what is happening nearby. The virtual environment is supplied by the virtual world database. Any changes in the virtual environment may affect the attributes of the agents that play very important roles in the decision making process [71]. The changes on the attributes are evaluated by the inference engine to decide what to do in the next step. Possible behaviors are stored in the behavior repository and the inference engine selects the suitable behavior from that repository [72]. Behaviors are executed by the behavior execution module in the simulation. Figure 2.23 shows the crowd simulation architecture.

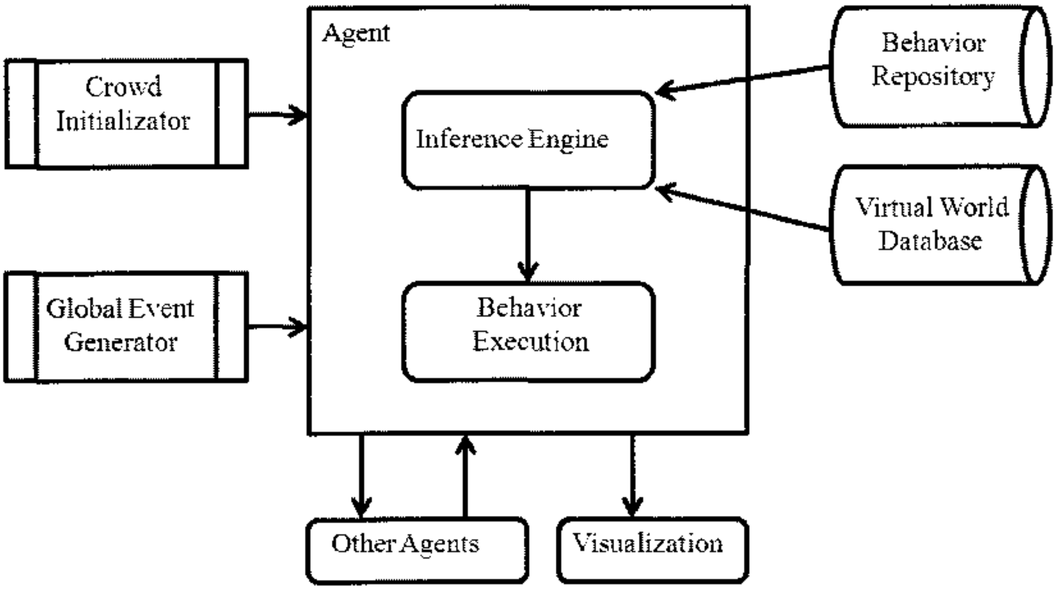


Figure 2.23 Crowd Simulation Architecture.

The situation awareness module uses different methods to obtain the information about the environment through sensing, reasoning and memory. Sensing is done by the query of certain radius in the virtual world database. The results of the query might be external objects (sales, threat), significant objects (shop, exit) and relevant people (family, acquaintances, leaders and casualties). The reasoning method observes the spatial domain and the present situations of the other agents to decide the distance from the threat or emotional states of near agents. An agent has a list that contains the virtual objects it is encountered [56-16].

An agent has two types of attributes: static and dynamic. Static attributes are used to save the characteristic features of the agent while dynamic attributes are used to save emotional, physiological ones. Dynamic attributes might be changed by the effects of external events and these attributes affect the individual and group level behaviors. Static and dynamic attributes are listed as follows [2],

Static Attributes:

- Knowledge Level
- Attraction Tendency
- Threat Vulnerability
- Time Pressure Susceptibility
- Relationship Type
- Group Id
- Altruism Level
- Avoidance Level

Dynamic Attributes:

- Physiological
  - Health Level
  - Energy Level
  - Sensing Range
  - Walking Speed
- Emotional
  - Attraction Intensity
  - Panic Intensity
- Social Group Attributes.

CHAPTER 3

IMPLEMENTATION OF THE PMFSERV INJURY MODEL FOR MULTI-AGENT CROWDS

The objective of this dissertation is to develop a multi-agent crowd simulation to visualize the effects of non-lethal weapons on crowd individuals by using the Repast Simphony multi-agent simulation toolkit. The injury model has a close relationship with the crowd cognitive model, which is still under development. Both models share some structures such as the crowd and group structures.

The PMFserv injury model is the base of this work to determine the effects of NLWs [73]. PMFserv uses lookup tables to store the parameter values of the injury formula. Equivalent java classes are created in Repast in this design. NLW types are defined based on McKenzie's work [12]. PMFserv was designed for five types of weapons not covering all the NLW types defined by McKenzie. Therefore, the definition was extended to cover all the types. Crisp logic was used in PMFserv to simulate injury models while a fuzzy logic design is utilized to make the simulation more realistic in this dissertation.

Design of the injury model was done by using the UML that is a common language in software engineering. Visual paradigm UML 6.4 (enterprise edition) was selected as the UML development platform in this work. All details must be considered and all cases must be handled in this phase.

In Repast implementation phase, the grid projection style was selected to represent crowd and control forces for simplicity. After the grid projection implementation, all the agents could be put on a geographic information system (GIS) base [74]. Both projections were used to calculate the distance between the control forces and crowd individuals.

The following sections include the UML design of this work.

3.1 UML Design

UML is used to specify, visualize and document the artifacts of an object-oriented software-intensive system [75]. UML offers a standard way to write a system's blueprints including conceptual components such as,

- Actors,
- Business processes, and
- System's components, and activities.

A weapon effects system is a part of the implementation of crowd injury model. It receives the information including weapon type, part of body and distance from the physical system and, after the calculations are made based on PMFserv injury model and then sends the motive capacity of the individual to the physical system. The weapon effect system also sends the stimuli to the cognition system. The cognition system accepts stimuli from the other systems and decides an appropriate behavior for the individual [76-77].

3.1.1 Use Case Diagram

In software engineering, a use case diagram in the UML is a type of behavioral diagram defined by and created from a use-case analysis. Its purpose is to present a graphical overview of the functionality provided by a system in terms of actors, their goals (represented as use cases), and any dependencies between those use cases [78]. The main purpose of a use case diagram is to show what system functions are performed for which actor. Roles of the actors in the system can be depicted. Figure 3.1 shows the injury model use case diagram [79].

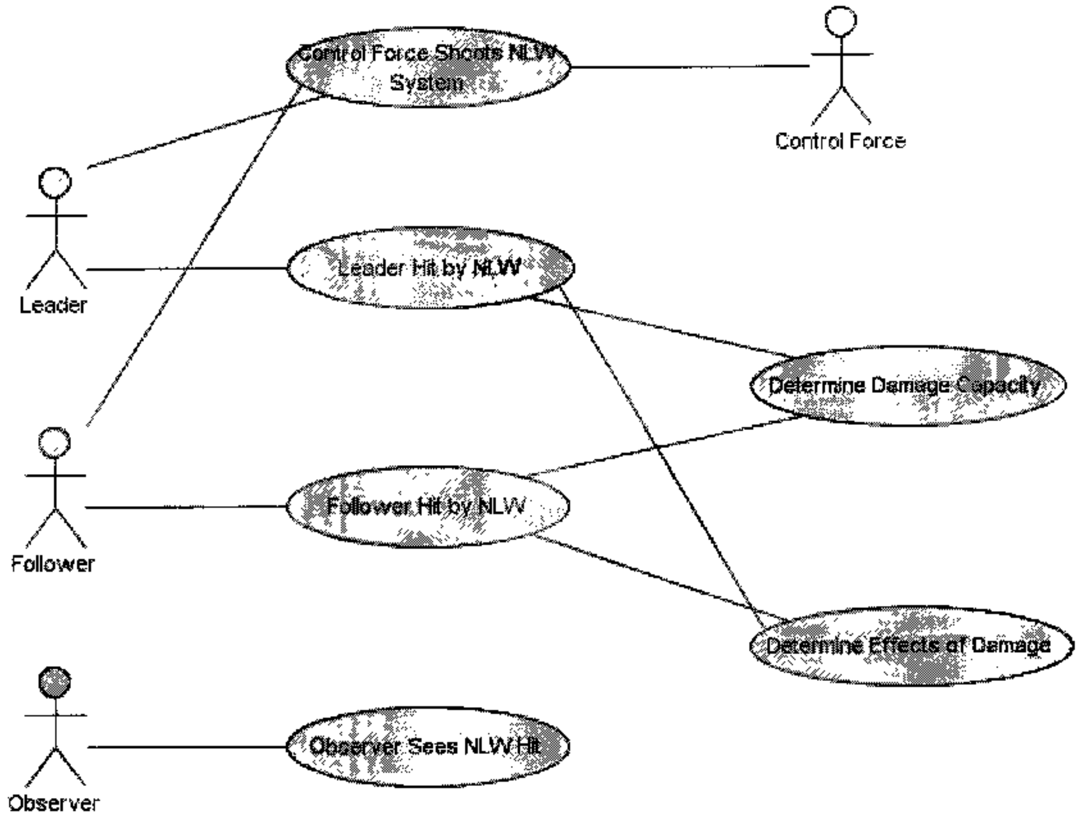


Figure 3.1 The Injury Model Use Case Diagram.

Use Case: Control Force Shoots NLW System

The objective of this use case is the activation of the NLW system. Control forces initiate this use case. They can choose any of the systems to activate based on the situation. This use case determines the amount/extent of force applied to the target. The target may be a leader, a follower, or a group. A control force sends information, such as target and amount/extent of force to be applied, as a message to this use case.

In addition to the target information, some special parameters specific to nine different weapon categories are needed by this use case. Table 3.1 shows the weapon scores and Table 3.2 shows weapon capacity scores imported from the PMFserv Injury Model [12].

Table 3.1 Weapon Type Scores.

Weapon Type	**Score**
Club	85
Gun	100
Rubber Bullet	40

Table 3.2 Weapon Capacity Scores.

Weapon Capacity	**Score**
Large	**20**
Medium	18
Small	15

Use Case: Leader Hit By NLW

The objective of this use case is to determine the motive capacity of a leader based on the damage inflicted. A leader initiates this use case when hit by an NLW. The leader sends its personal and NLW system information to this use case as a message. This use case has an association with the other use cases: "Determine Damage Capacity" and "Determine Effects of Damage". It initiates "Determine Damage Capacity" use case. It receives damage range value from this use case and initiates "Determine Effects of Damage" use case. It receives health/damage status from this use case and sends it to a leader agent [80].

In the PMFserv injury model, look up tables are used to decide the vulnerability score of an injured leader based on age and health status. The younger and healthier the leader is, the lower vulnerability score he gets. Table 3.3 shows the vulnerability scores for a leader/follower while Table 3.4 shows body part scores [12].

Table 3.3 Vulnerability Scores.

Vulnerability	**Score**
Old/ Infirm	1.2
Young / Healthy	1.1

Table 3.4 Body Part Scores

Body Part	Score
Head	50
Limbs	25
Trunk	40

Use Case: Follower Hit By NLW

The objective of this use case is to determine the motive capacity of a follower based the damage. A follower initiates this use case when hit by an NLW. The follower sends its personal and NLW system information to this use case as a message. This use case has an association with the other use cases: "Determine Damage Capacity" and "Determine Effects of Damage". It initiates the "Determine Damage Capacity" use case by sending the target and NLW information as a message. It receives the damage range from this use case and initiates the "Determine Effects of Damage" use case by sending status of agent and damage range information as a message. It receives health/damage status from this use case and sends it to the leader agent.

In the PMFserv injury model look up tables are used to decide the vulnerability score of an injured follower based on age and health status. The younger and healthier a follower is, the lower vulnerability score received.

Use Case: Observer Sees NLW Hit

The objective of this use case is the determination of the cognitive attitude of the observer. An observer initiates this use case. The crowd injury model creates a communication channel with the crowd cognitive model via this use case. Behavior of the observer is decided by the cognitive model [81].

Use Case: Determine Damage Capacity

The objective of this use case is to determine the range value of damage that can occur based on target and NLW systems. Either the "Follower Hit by NLW" or **the** "Leader Hit by NLW" use cases can initiate this use case. This use case determines the damage range and sends it back as a response. Based on the distance between the control force and the follower/leader, the weapon efficiency is decided.

Use Case: Determine Effects of Damage

The objective of this use case is to determine the effects of damage based on damage range and status of an agent. Either the "Follower Hit by NLW" or the "Leader Hit by NLW" use case can initiate this use case. They send damage range value and status of the agent to this use case. This use case determines the health/damage status and sends it back.

This use case decides the motive capacity of agent based on the PMFserv Injury formula as [12],

$$SI(t) = SI_0 * \psi(t) \quad (3.1)$$

SI_0 : Time independent component

$\psi(t)$: Time variation factor

$$SI_0 : = SW_t * SW_c * SB * SV \quad (3.2)$$

Time variation factor is decided based on the Golden Hour concept.

$$\psi(t) = 1 - e^{(-K2*T)} \quad (3.3)$$

where

$$K_2 = 1 - \text{Golden Hour score} \quad (3.4)$$

Table 3.5 shows overall scores and corresponding motive capacities.

Table 3.5 Overall Scores and Correspondence Motive Capacities.

Score	Motive Capacity	Score Range (SI_0)	
		From	To
1	Healthy	0	20000
2	Slowed and Dazed	20000	40000
3	Limping Badly	40000	60000
4	Incapacitated	60000	80000
5	Dead	80000	120000

3.1.2 Activity Diagram

An activity diagram is a loosely defined diagram for showing workflows of stepwise activities and actions, with support for choice, iteration and concurrency. In the UML, an activity diagram can be used to describe the business and operational step-by-step workflows of components in a system. The activity diagram shows the overall flow of control [82].

In this dissertation's injury model, activities start with the activation of the NLW system by a control force. A control force shoots the NLW system and the system determines if the target is hit. If the target is missed, the observer in the system become aware of the shot of the NLW. The observer can change his/her mind based on the power of NLW shot and his/her mood to decide if he/she wants to run away from the area. Therefore, mood status of the observer must be updated in this case [83].

If the target is hit, the system then decides if the target is a leader or a follower. In both conditions, parallel activities can occur. The observer can see this hit and change her/his mood based on effects of NLW on the target. The observer can also determine the damage capacity of the NLW system on the target and compute the exact effects of the NLW system on the target. Once the effects of NLW system are determined, the system updates or changes the health and mood status for all agents. Figure 3.2 shows the injury model activity diagram [79].

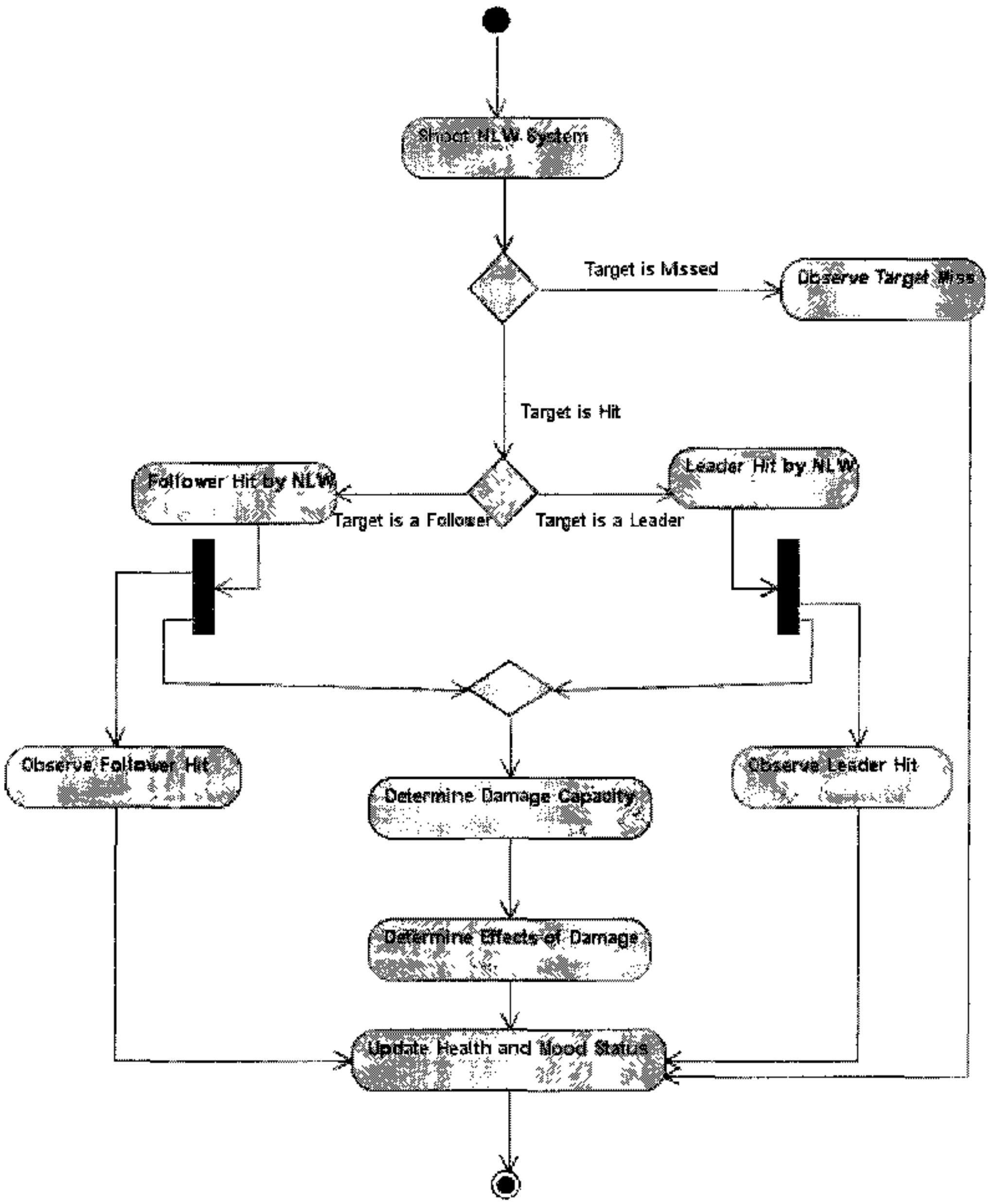


Figure 3.2 Injury Model Activity Diagram

3.1.3 Sequence Diagram

A sequence diagram in UML is an interaction diagram that shows how processes operate with one and another and in what order. Sequence diagrams are sometimes called event-trace diagrams, event scenarios or timing diagrams [84].

In this design, there are two sequence diagram scenarios depending upon whether the target is hit or not. Figure 3.3 shows the scenario when the target is hit. A control force agent sends a message to the NLW System to activate it. This message includes weapon type and weapon capacity information. Because the target is hit, the NLW system sends a hit message to an individual, who could be a follower or a leader. The individual then will require the damage range information that is determined by the damage determination system based on which part of the body is affected and the vulnerability information sent by the individual. The damage range determination system then sends a message to the effect determination system for determining the effects of the NLW system [85].

All parameters including the distance between the NLW system and the individual are now available for the effect determination system to determine the effects of NLW system. Once determined, the determination system then sends the motive capacity information to the individual and the individual agent updates its motive capacity. Observer agents are informed about the hit message sent by the individual and they then send an observeNLWHit message to themselves. After that, they update their mood status depending upon the new motive capacity of the individual [79].

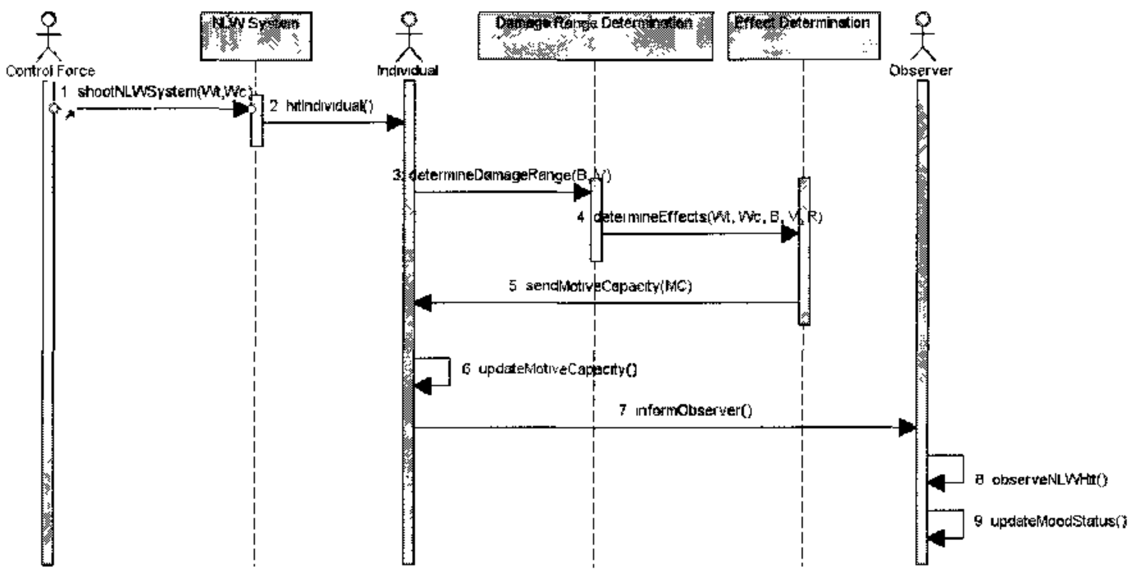


Figure 3.3 Injury Model Sequence Diagram Case 1: Target Hit.

Figure 3.4 shows the second scenario: Missed Target. In this case, a control force sends a message to the NLW system again to activate it and inform the NLW system that the target was missed. Observer agents are informed about the missed target via a message sent by the NLW system and they send an observeNLWMiss message to themselves. After that, they update their mood status depending upon the weapon type [79].

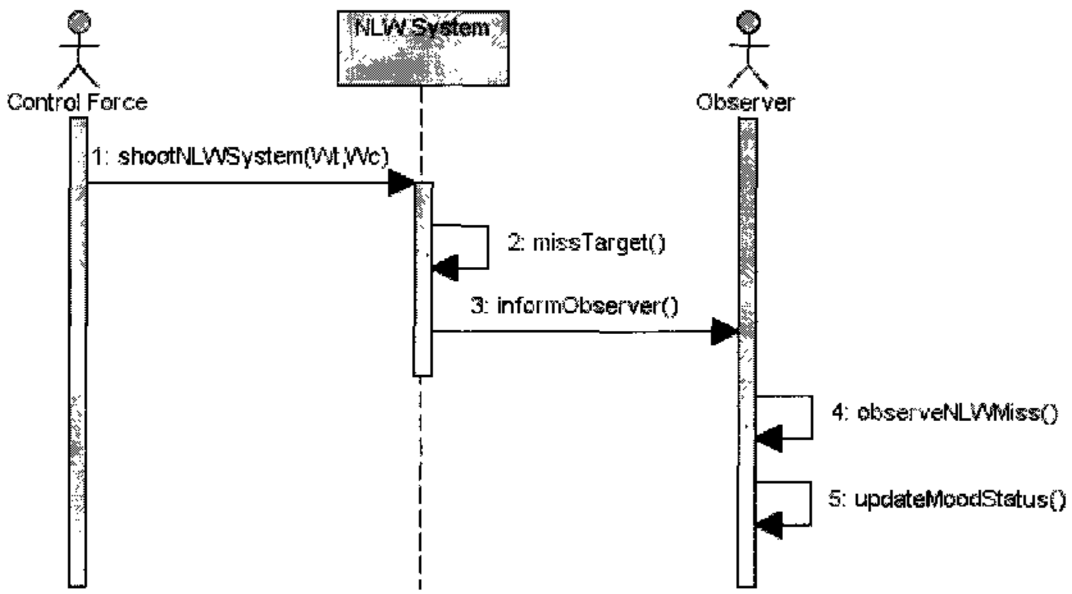


Figure 3.4 Injury Model Sequence Diagram Case 2: Missed Target.

3.1.4 Classes

There are two agent classes in this work: police and resister. A police agent is used to represent control forces while a resister agent is used to represent crowd individual in a riot [86]. In addition, the ModelInitializer class is used in the initialization phase in the simulation. Repast Simphony allows the users to create thousands of these agents which are very important to simulate real riot activities. Attributes and methods of these classes could be found in the following part [87].

Class: Police

Attributes:

- *weaponType<int>:* This attribute is used to represent the weapon type used by the police agent. 1 for Club, 2 for Rubber Bullet, and 3 for Gun.
- *weaponCapacity<double>:* This attribute is used to save the capacity of the weapon used by police agent. The value range of this attribute is 0 and 20.
- *hasShot<boolean>:* This attribute is used to see if the police agent has shot or not.
- *effort<double>:* This attribute is used save the effort value applied by police agent.

Methods:

- *initialize():* This method is used to initialize some of the attributes. In this method, weaponType, weaponCapacity, and effort attributes get their values within their ranges.
- *step():* This method is used to shoot at the resister agent in the simulation.

Class: Resister

Attributes:

- *distance<double>:* This attribute is used is to save the distance between the resister agent and the police agent.
- *hours<int>:* This attributes is used to save how many hours past after being shot and used in Golden Hour concept.
- *motiveCapacity<String>:* This attribute is used to save the motive capacity of the resister agent.
- *motiveCapacityCode<int>:* This attribute is used for statistical purposes.
- *partOfBody<double>:* This attribute is used to save the affected body part value of the resister.
- *police<Police>:* This attribute is used by the police agent that engaged on the resister agent.
- *severityOfInjury<double>:* This attribute is used to save severity of injury onthe resister agent.

- *vulnerability<double>:* This attribute is used to save the vulnerability of the resister agent.

Methods:

All of the attributes above have getter and setter methods.

- *distance():* This method is used to calculate the distance between the resister agent and the police agent.
- *initialize():*This method is used to initialize some of the attributes. In this method, partOfBody and vulnerability attributes get their values within their ranges.
- *move():* This method is used for movement of the resister agent. If the resister agent is shot by the police agent and its motive capacity allows then it moves away from the police agent.
- *GoldenHour():* This method is used for Golden Hour concept. It updates the severityOfInjury attribute based on Golden Hour principles.
- *shoot(Police):* This method watches the police agent taken as the parameter. If the police has shot then this method calculates the severity of injury based on the fuzzy logic model.
- *step():* This method allows the resister agent to move each tick.

3.2 Implementation

In the last two decades, researchers have proposed and developed many models to simulate pedestrian crowds. Those include micro level analysis models [88-48], micro simulation of cellular automata models based on some predefined rules [89], and multi-agent models simulating a crowd where each agent has its own behavior and interacts with other nearby agents [90-91].

Projections are the structures to manage the interactions between agents in a certain context. They are the windows open to their environment for the agents [72]. In this model, a 2D grid projection and a "Crowd Network" projection are used to control the interactions between agents. Two types of NLWs, clubs and rubber bullets, are used as weapon types for the proof of concept in this model. They are assigned to police agents as weapon types just after initialization process of crowd and control force populations. Vulnerabilities of resister agents are also assigned at this step. Figure 3.5 shows the initialization step.

Police agents may be related to more than one resister agent as target. 3D display type is selected as display type to take advantage of 3D visualization of the Repast Simphony toolkit. Spheres represent police agents while cones represent resister agents. Arrows represent relationships between police and resister agents. Any properties of an agent can be set as label of this agent in Repast. In this model, the name of the police agent is set as a label for police agents and the motive capacity of resister agent is set as the label of resister agents. The movement of resister agent based on its motive capacity is tested in this implementation. If the motive capacity of a resister agent is incapacitated or dead, it cannot move. Otherwise, it can move one pixel towards any direction in each step [79].

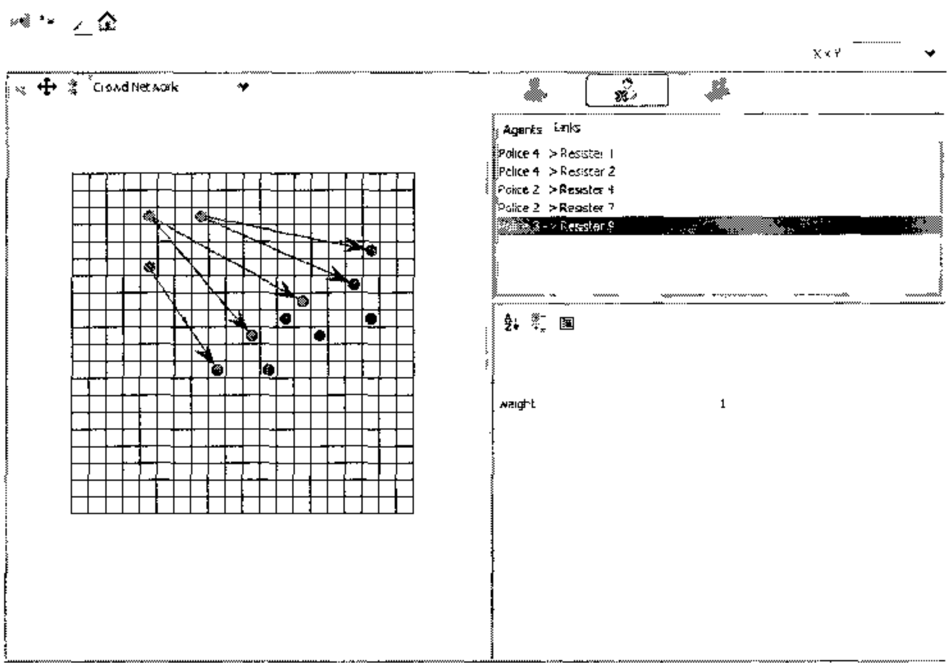


Figure 3.5 Agent and Network Initialization Step.

Three police agents are created as control forces for the crowd event and nine resister agents are created as crowd. The motive capacities of all resister agents are set to "healthy" in the initialization process. Figure 3.6 shows 3D visualization of agents after initialization step [79].

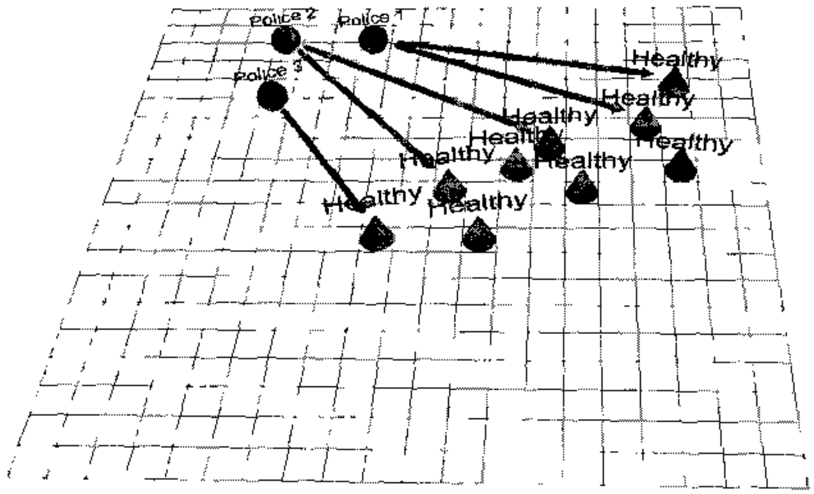


Figure 3.6 3D Visualization of the Agents after the Initialization Step.

One of the police agent is armed with the small rubber bullets, another is armed with the large rubber bullets, and the last one is armed with the small clubs. In this work, all the resisters are assumed to be in the effective ranges of all weapon types. Therefore, there is no distance calculation to check if a resister is in the effective range. After the first shot, the motive capacities of all resister agents are recalculated. Figure 3.7 shows the motive capacities of the resister agents [79].

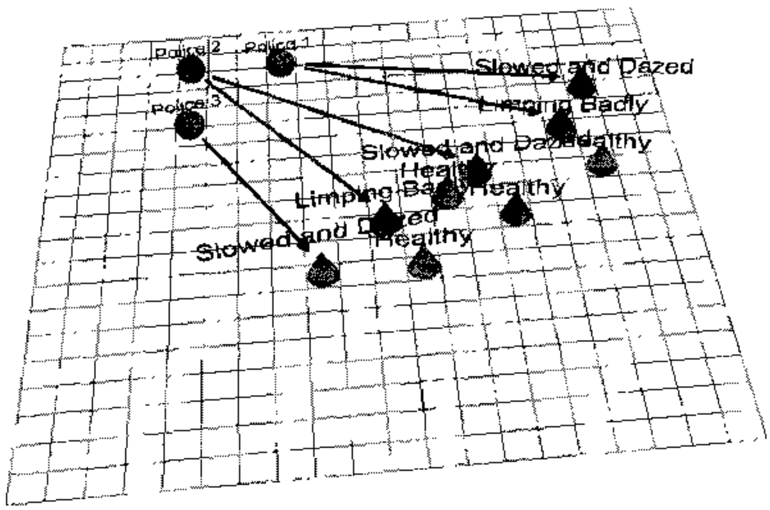


Figure 3.7 3D Visualization of the Agents after the First Shot.

If a resister is not shot by any armed forces then there is no change on its motive capacity. For all resister agents, vulnerability is set to 1.1 or 1.2 and the effected part of body is set to head region for this trial. Figure 3.8 shows how the resister agents move. They normally have to move in the opposite direction of police agents but for this trial they moved randomly. After 60 ticks, the Golden Hour concept is applied to motive capacities of resister agents. Figure 3.8 shows how the motive capacities of the resister agents were changed after the Golden Hour concept was applied [79].

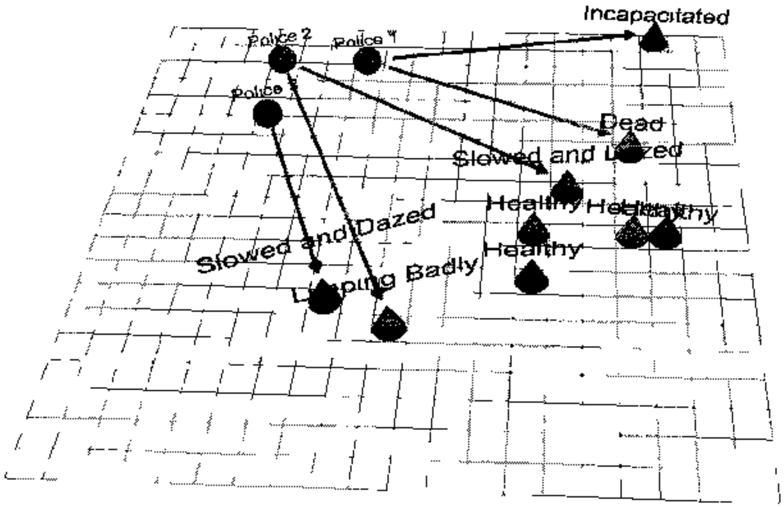


Figure 3.8 3D Visualization of the Agents after the Golden Hour.

3.3 Summary

Modeling and simulating pedestrian crowd behaviors, especially in emergency cases, have been an active research topic in recent years. It is important to predict the motions of the crowd in the case of extreme events like usage of non-lethal weapons. Therefore, utilization of some simulation mechanisms is necessary. Multi-agent based simulations have some advantages over traditional numerical simulation techniques, which are based on stochastic and mathematical models [79]. First, a multi-agent based simulation platform provides noticeable visual displays in which the simulation designers can visually estimate pedestrian's behaviors in the simulation environment. Second, simulation designers can dynamically trace how the global structure emerges as a result of the agents' individual interactions.

CHAPTER 4

FUZZY LOGIC CROWD INJURY MODEL

Although the PMFserv injury model is a mathematical model, it is not easy to determine the physical effects of NLWs. A fuzzy logic model is proposed for this purpose [92]. First, the inputs and the outputs for the fuzzy logic model are defined. In this model, there are six inputs and one output. The inputs of the model are the same as inputs of the PMFserv injury model including weapon type, weapon capacity, effort applied by injurer, part of body affected, vulnerability of the crowd individual and distance between the control force and the resister. The output of the model is the motive capacity of the crowd individual. Figure 4.1 shows the fuzzy logic design of the model [93].

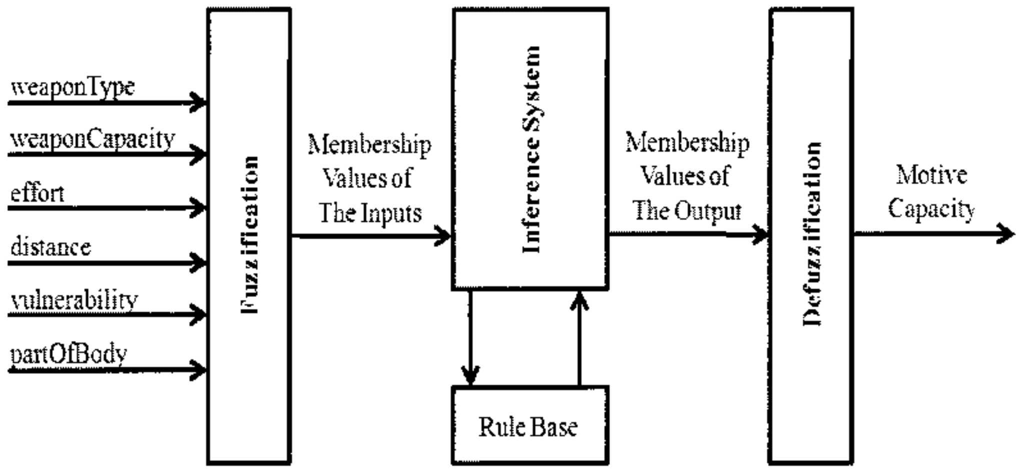


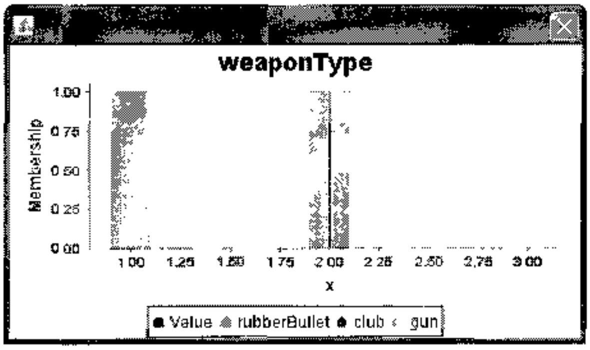
Figure 4.1 Fuzzy Logic Design of the Model.

JFuzzyLogic is an open source fuzzy logic library written in Java by Cingolani [94]. It is used as an external Java library in Repast Simphony and this dissertation's method is developed based on the JFuzzyLogic library. A fuzzy control language file is created containing at least one function block consists of inputs, outputs, fuzzy sets, membership functions, rules and defuzzification methods [95].

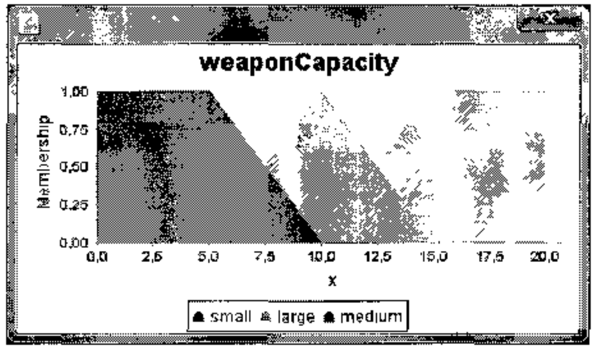
Data types of those inputs and output are defined in the variable declaration part. The next part in the file defines how the input values will be fuzzyfied according to the membership functions. The boundaries of crisp values for each input and output variables define their universe of discourses, which are indicators of sensitivity. The wider a universe of discourse for an input is the more sensitive membership value it has.

Table 4.1 Attributes of Inputs and Outputs

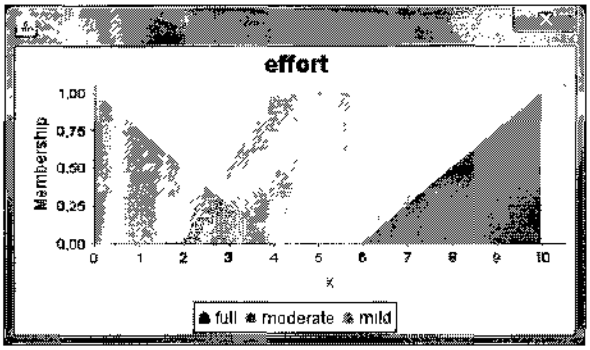
Inputs			
Input Name	**Universe of Discourse**	**Fuzzy Sets**	**Membership Function**
weaponCapacity	[0, 20]	Small Medium Large	Trapezoidal Triangular Trapezoidal
effort	[0, 10]	Mild Moderate Full	Triangular Trapezoidal Triangular
distance	[0, 3]	Close Moderate Far	Triangular Trapezoidal Trapezoidal
partOfBody	[0, 50]	Limbs Trunk Head	Trapezoidal Trapezoidal Trapezoidal
vulnerability	[0, 10]	Healthy Unfirm	Trapezoidal Trapezoidal
Output			
motiveCapacity	[0, 50]	Healthy Slowed and Dazed Limping Badly Incapacitated Dead	Trapezoidal Triangular Triangular Triangular Trapezoidal



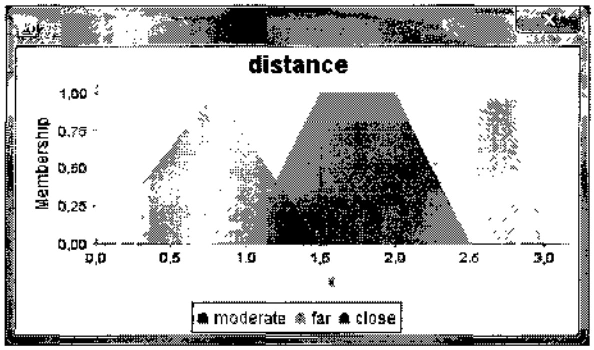
(a) Membership Functions of Weapontype Input.



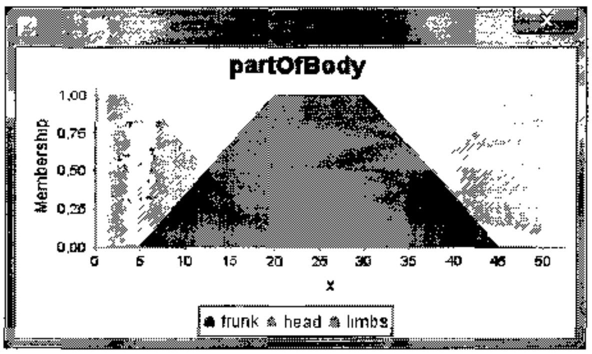
(b) Membership Functions of Weaponcapacity Input.



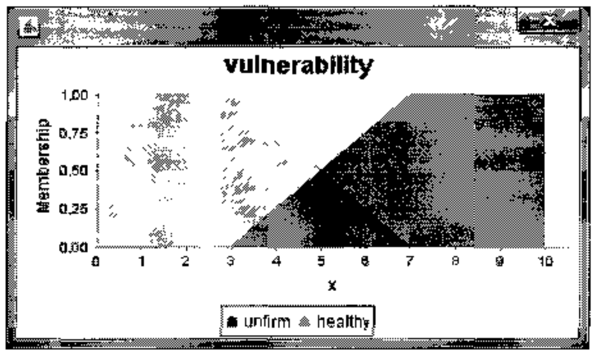
(c) Membership Functions of Effort Input.



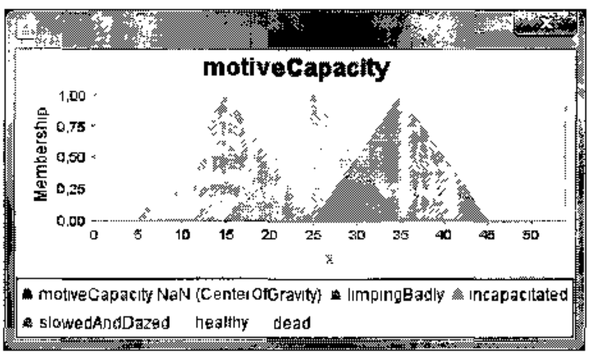
(d) Membership Functions of Distance Input.



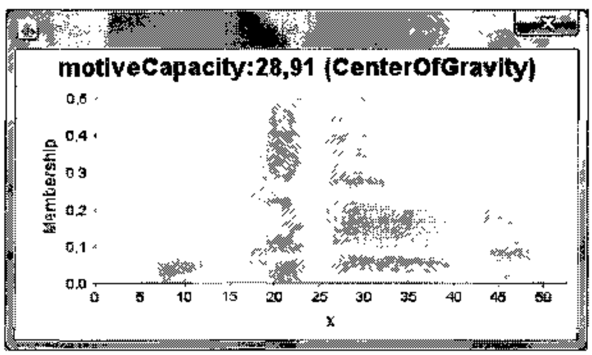
(e) Membership Functions of Partofbody Input.



(f) Membership Functions of Vulnerability Input.



(g) Membership Functions of Motivecapacity.



(h) Crisp Motivecapacity Value after Defuzzification.

Figure 4.2 Membership Functions of the Inputs and the Outputs.

In a fuzzy logic model, fuzzy sets and their membership functions should be defined for each input and output. Table 4.1 shows the values of discussed terms. In Figure 4.2, graphical representations of the membership functions of inputs and outputs are shown [44].

4.1 Rule Definition

The key point of fuzzy logic design is the definition of a set of rules incorporating domain knowledge [96]. In this dissertation, military security officers and police officers were invited as the domain experts for the crowd injury model. Collaborative work was conducted with the military security officers and 139 rules were defined as the inputs for the inference system as listed in the Appendix A.

Sample inputs and the corresponding output of the model are shown in Table 4.2.

Table 4.2 Sample Inputs and the Corresponding Output.

Inputs	weaponType: Club weaponCapacity: 14 distance: 1 PartOfBody: 6 effort: 7 vulnerability: 6
Output	motiveCapacity: 28.91 (Limping Badly)

The output of the fuzzy set is shaped after the implication method has been applied to the fuzzy rules. Each rule supports the output with a different degree. The degree of support for a specific rule is shaped by its antecedent part [97]. If there is only one fuzzy statement in the antecedent part, then the membership value of that statement defines the degree of support for the rule. Otherwise, the degree of support is acquired once the logic operators are applied to the membership values of the fuzzy statements in the antecedent part. Table 4.3 shows the degree of support for the selected rules.

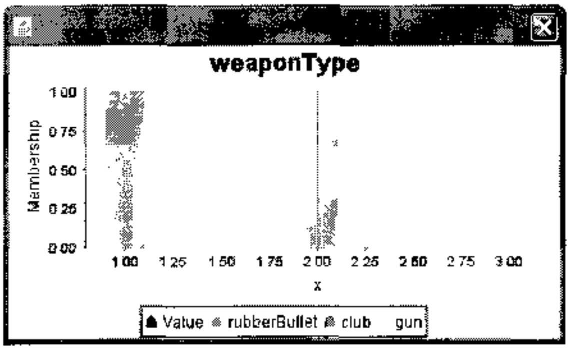
Table 4.3 Degree of Support for Selected Rules

Rule Number	Degree of Support
Rule 1	0.25
Rule 4	0.06
Rule 5	0.0
Rule 8	0.0
Rule 16	0.06

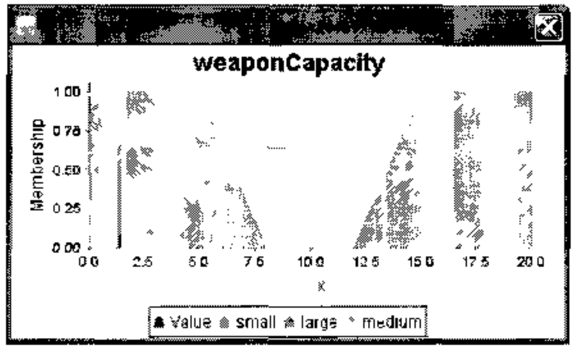
4.2 Fuzzy Logic Golden Hour Concept

The Fuzzy Logic Golden Hour concept is imported from the PMFserv injury model to decide whether the injured will get better or worse in an hour from onset of the injury. It is defined based on the combination of weapon type and weapon capacity. For example, Silverman assumes the Golden Hour score is larger than 1 for all types of guns while it is smaller than 1 for a small club. If the Golden Hour score >1, then the injured will get worse. Otherwise, the injured will become better. If it is equal to 1 then there is no change.

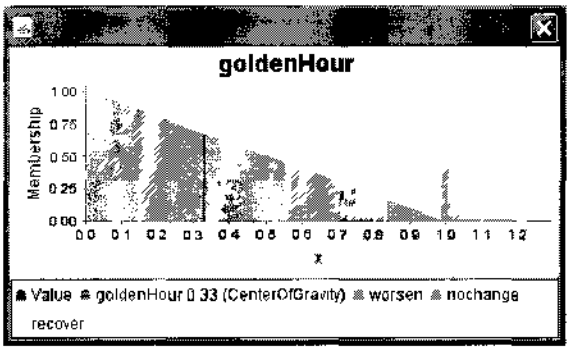
Here, the Golden Hour score is defined by the fuzzy logic method instead of lookup tables. The inputs of the model are weapon capacity and weapon type. The output of the model is the Golden Hour score. Figure 4.3 shows the membership functions of the inputs and output.



(a) Membership Function of Weapon Type.



(b) Membership Function of Weapon Capacity.



(c) Membership Function of Golden Hour.

Figure 4.3 Membership Functions of the Inputs and the Output.

Nine rules have been defined for the fuzzy logic golden hour concept as presented in Appendix B.

A test case is utilized to verify the model. In the test case, the weapon type of the police agent is selected as rubber bullet and the weapon capacity is chosen randomly as 1.5. Therefore, the weapon capacity is small and the Golden Hour score is less than 1. As a consequence, the motive capacity of the resister agent will get better by the time.

The motive capacity of the resister is decided as "Incapacitated" at the first shot in the simulation. Figure 4.4 shows the situation at the first shot.

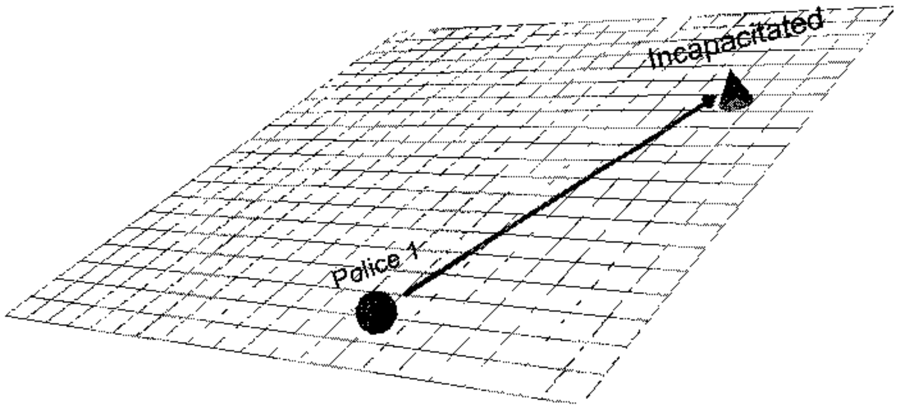


Figure 4.4 Situation after the First Shot.

The fuzzy logic Golden Hour model determines the Golden Hour score as 0.33. Since the motive capacity of the resister is "Incapacitated", it cannot move away. But it recovers after one hour then its motive capacity turned to "Limping Badly" and the resister moves away slowly. Figure 4.5 shows the situation during the first hour.

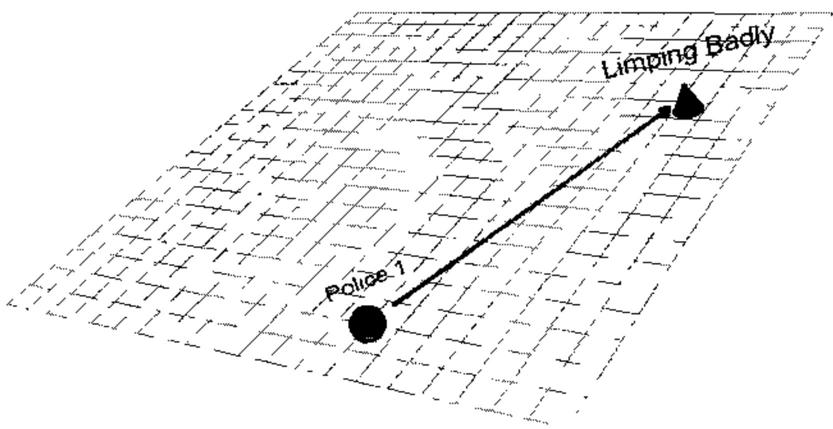


Figure 4.5 Situation in the First Hour.

In the second hour, the resister's motive capacity turned to be "Slowed and Dazed" and the resister moves away fast. Figure 4.6 shows the situation in the second hour.

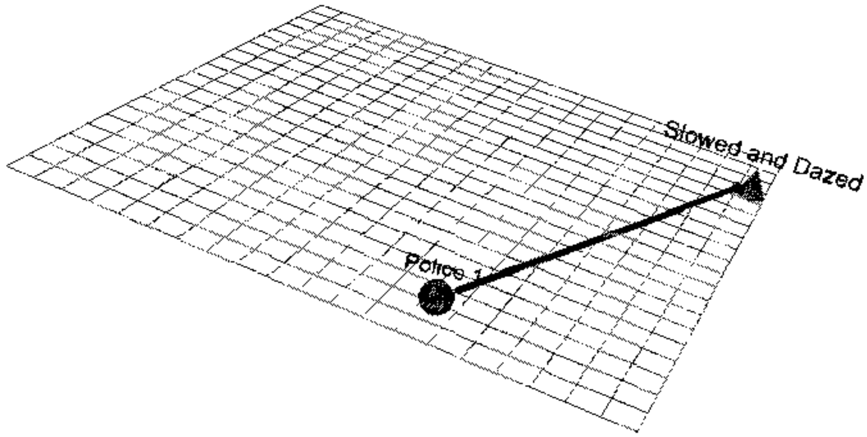


Figure 4.6 Situation in the Second Hour.

In the third hour, the motive capacity turns to healthy and the resister moves away fast. Figure 4.7 shows the situation in the third hour.

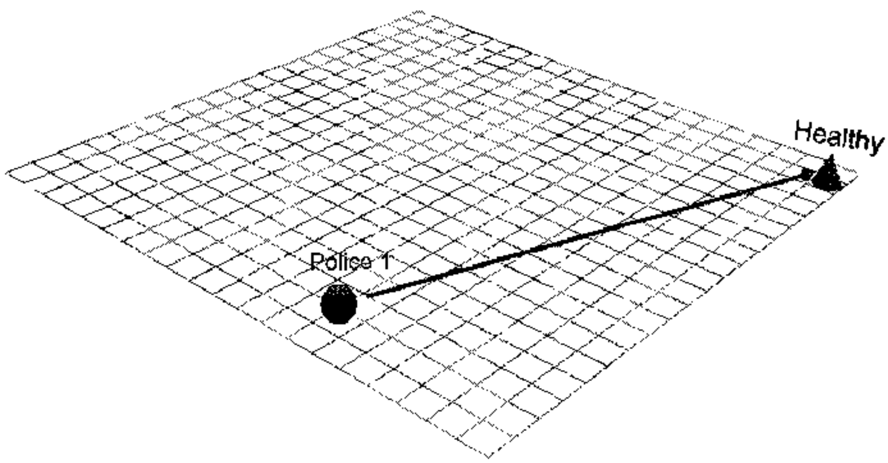


Figure 4.7 Situation in the Third Hour.

CHAPTER 5

TESTS AND RESULTS

Three types of weapons including rubber bullet, club and gun are used to test the simulation system. Eight test cases have been conducted for the weapon type rubber bullet while seven cases for the club and six cases for the gun. One of the test cases is for the mixture of these three weapon types. In total, 22 test cases were conducted 10 times. After conducting 10 times, the mean and standard deviation values were gathered for each test case and they have been reflected as "mean value ± standard deviation" to the results tables. Some of the parameters of the model are assumed to get more realistic results [98].

5.1 Assumptions

- The dimensions of the grid is assumed as 200 x 600 for the weapon types rubber bullet and gun while it is assumed as 12 x 12 for the weapon type club corresponding to their effective ranges.
- The size of each pixel is assumed to be one foot long.
- For the weapon types rubber bullet and gun, the number of police agents is 150 and the number of resister agents is 1,000. On the other hand, for the weapon type club they are assumed to be 50 and 70, respectively.
- The police agents are located on one side of the grid randomly while the resister agents are located on the other side randomly.
- The values of the input parameters (vulnerability, weapon capacity, effort and part of body) are selected randomly within the ranges shown in the tables.
- The distances between the police agents and the resister agents are calculated by the program.
- Effective ranges of the weapons are imported from the internet [99].

- Each tick is assumed to be 20 minutes long and the Golden Hour concept is applied once for every 3 ticks.
- The Golden Hour score is depended on the combination of the weapon type and the weapon capacity parameters.

5.2 Test Cases

In this test case, four police agents and seven resister agents were created. A police agent may engage more than one resister agent in this test case. Initial motive capacities of the resister agents have been set to "Healthy". Figure 5.1 shows the 3D visualization of the initial step [100].

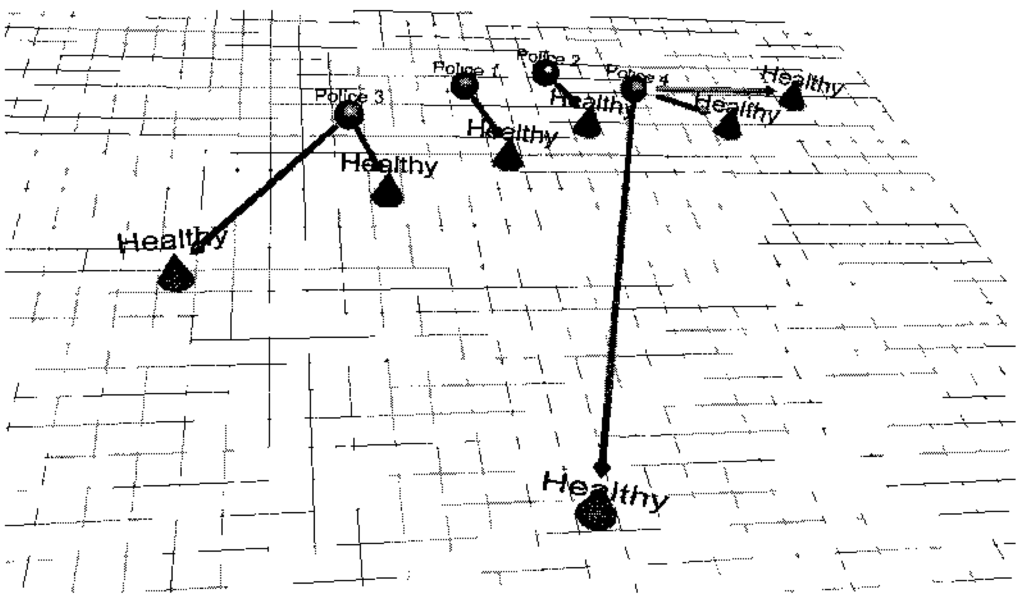


Figure 5.1 3D Visualization of the Initial Step

The fuzzy logic injury model needs six inputs and produces one output. Three of the inputs, weaponType, weaponCapacity, and effort come from police agents, two of them, vulnerability and partOfBody, come from resister agents and the last input, distance, is calculated by the program. The single output of the model is decided after the defuzzification phase and it is assigned as the motive capacity of the resister agent. Figure 5.2 shows the situation after the first engagement [91]

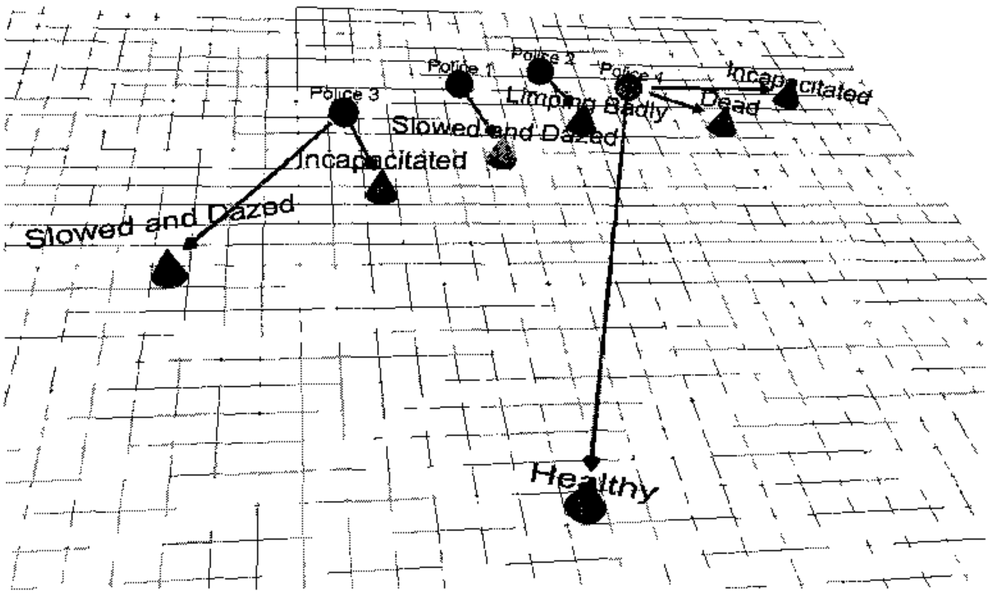


Figure 5.2 Situation After the First Engagement

Table 5.1 shows the input values and the corresponding output values for the engaged agents [91].

Table 5.1 Input Values and the Corresponding Outputs.

Agents Engaged in Each Other	**Input Values**	**Output**
Police 3 Resister 1	weaponCapacity: 16 weaponType: Club effort: 8 partOfBody: 20 vulnerability: 7 distance: 1.3	motiveCapacity: 31.6 (Slowed and Dazed)
Police 3 Resister 2	weaponCapacity: 16 weaponType: Club effort: 8 partOfBody: 15 vulnerability: 9 distance: 0.6	motiveCapacity: 19.5 (Incapacitated)
Police 1 Resister 3	weaponCapacity: 12 weaponType: Club effort: 5 partOfBody: 6 vulnerability: 4 distance: 0.6	motiveCapacity: 35.2 (Slowed and Dazed)
Police 2 Resister 4	weaponCapacity: 15 weaponType: Club effort: 6 partOfBody: 25 vulnerability: 5 distance: 0.45	motiveCapacity: 25 (Limping Badly)
Police 4 Resister 5	weaponCapacity: 17 weaponType: Club effort: 7 partOfBody: 45 vulnerability: 8 distance: 0.5	motiveCapacity: 6.9 (Dead)
Police 4 Resister 6	weaponCapacity: 17 weaponType: Club effort: 7 partOfBody: 30 vulnerability: 6 distance: 2.8	motiveCapacity: 44.5 (Healthy)

Table 5.1 (Continued)

Police 4 Resister 7	weaponCapacity: 17 weaponType: Club effort: 7 partOfBody: 30 vulnerability: 8 distance: 0.8	motiveCapacity:19.1 (Incapacitated)

5.2.1 Test Case: Rubber Bullet-1

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type rubber bullet is assumed to be large caliber with ranges from 14 to 20. Table 5.2 shows the results of that test case. It is observed that the number of dead is zero after the first shot. Based on the Golden Hour concept, the motive capacities of the resisters get worse by the time and the number of casualties increases.

Table 5.2 Results of the Test Case Rubber Bullet-1.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	14-20	35-50	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	951 ± 16	26 ± 9	20 ± 7	2 ± 2	0
1 hour later	943 ± 6	22 ± 7	32 ± 6	3 ± 2	0
2 hours later	952 ± 7	10 ± 6	18 ± 3	20 ± 4	1 ± 1
3 hours later	930 ± 5	0	0	23 ± 4	47 ± 3

5.2.2 Test Case: Rubber Bullet-2

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region and the range is from 35 to 50. The weapon type rubber bullet is assumed to be medium caliber with a range from 8 to 14. It is observed that the number of dead is much less than that in the previous test case. Table 5.3 shows the results of this test case.

Table 5.3 Results of the Test Case Rubber Bullet-2.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	8-14	35-50	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	956 ± 14	27 ±10	15 ±4	4 ±3	0
1 hour later	930 ± 6	35 ± 5	29 ± 4	6 ± 2	0
2 hours later	930 ± 6	26 ± 3	34 ± 5	10 ± 3	1 ±1
3 hours later	930 ± 6	24 ± 8	23 ± 3	20 ± 5	2 ± 1

5.2.3 Test Case: Rubber Bullet-3

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type rubber bullet is assumed to be small caliber with a range from 1 to 8. In this test case the number dead is zero even after three hours. Table 5.4 shows the results of this test case.

Table 5.4 Results of the Test Case Rubber Bullet-3.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	1-8	35-50	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	951 ± 13	27 ± 8	18 ± 5	4 ± 2	0
1 hour later	988 ± 3	5 ± 3	6 ± 2	1 ± 1	0
2 hours later	995 ± 1	5 ± 1	0	0	0
3 hours later	1000	0	0	0	0

5.2.4 Test Case: Rubber Bullet-4

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon type rubber bullet is assumed to be large caliber with a range from 14 to 20. In this test case the number casualty is zero after two hours. Table 5.5 shows the results of this test case.

Table 5.5 Results of the Test Case Rubber Bullet-4.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	14-20	20-35	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	951 ± 13	43 ± 11	6 ± 3	0	0
1 hour later	924 ± 7	34 ± 5	42 ± 6	1 ± 1	0
2 hours later	924 ± 7	0	51 ± 5	25 ± 5	0
3 hours later	924 ± 7	0	0	47 ± 5	29 ± 5

5.2.5 Test Case: Rubber Bullet-5

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon capacity of rubber bullet is assumed to be medium caliber with a range from 8 to 14. Table 5.6 shows the results of this test case.

Table 5.6 Results of the Test Case Rubber Bullet-5.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	8-14	20-35	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	955 ± 15	29 ± 11	15 ± 6	2 ± 1	0
1 hour later	926 ± 5	40 ± 5	30 ± 7	3 ± 2	0
2 hours later	926 ± 5	30 ± 5	39 ± 7	6 ± 2	0
3 hours later	926 ± 5	28 ± 5	24 ± 6	21 ± 4	1 ± 1

5.2.6 Test Case: Rubber Bullet-6

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon type rubber bullet is assumed to be small caliber with a range from 1 to 8. Table 5.7 shows the results of this test.

Table 5.7 Results of the Test Case Rubber Bullet-6.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	1-8	20-35	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	955 ± 13	22 ± 7	20 ± 5	5 ± 3	0
1 hour later	970 ± 4	22 ± 5	7 ± 3	0	0
2 hours later	996 ± 3	4 ± 3	1 ± 1	0	0
3 hours later	1000	0	0	0	0

5.2.7 Test Case: Rubber Bullet-7

In this test case, the resister agents are assumed to be old/infirm people, so their vulnerability range is from 6 to 10. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type rubber bullet is assumed to be large caliber with a range from 14 to 20. Table 5.8 shows the results of this test case.

Table 5.8 Results of the Test Case Rubber Bullet-7.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	14-20	35-50	6-10	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	950 ± 16	19 ± 7	26 ± 10	6 ± 2	0
1 hour later	925 ± 7	0	51 ± 6	22 ± 4	2 ± 2
2 hours later	925 ± 7	0	0	70 ± 8	6 ± 3
3 hours later	926 ± 7	0	0	2 ± 1	73 ± 8

5.2.8 Test Case: Rubber Bullet-8

In this test case, all the values of parameters are selected randomly within their full range. Table 5.9 shows the results of this test case.

Table 5.9 Results of the Test Case Rubber Bullet-8.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Rubber Bullet	1-20	1-50	1-10	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	951 ± 16	26 ± 9	20 ± 7	2 ± 2	0
1 hour later	943 ± 6	22 ± 7	32 ± 6	3 ± 2	0
2 hours later	952 ± 7	10 ± 6	18 ± 3	20 ± 4	0
3 hours later	953 ± 7	8 ± 6	7 ± 3	12 ± 3	19 ± 4

5.2.9 Test Case: Club-1

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type club is assumed to be large caliber with a range from 14 to 20. The effort applied by the police agent is assumed to be full with a range from 7 to 10. Table 5.10 shows the results of this test case.

Table 5.10 Results of the Test Case Club-1.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	14-20	35-50	1-5	7-10	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	31 ± 3	16 ± 3	18 ± 4	5 ± 2		0
1 hour later	31 ± 3	1 ± 1	29 ± 5	10 ± 3		0
2 hours later	31 ± 2	0	8 ± 3	28 ± 4		3 ± 2
3 hours later	31 ± 3	0	0	9 ± 3		31 ± 4

5.2.10 Test Case: Club-2

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type club is assumed to be medium caliber with a range from 8 to 14. The effort applied by the police agent is assumed to be full with a range from 7 to 10. Table 5.11 shows the results of this test case.

Table 5.11 Results of the Test Case Club-2.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	8-14	35-50	1-5	7-10	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	32 ± 2	11 ± 3	20 ± 2	7 ± 2		0
1 hour later	32 ± 2	10v 3	20 ± 2	8 ± 2		0
2 hours later	32 ± 2	7 ± 3	20 ± 2	10 ± 3		0
3 hours later	32 ± 2	7 ± 3	17 ± 2	12 ± 3		3 ± 1

5.2.11 Test Case: Club-3

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type club is assumed to be small caliber with a range from 1 to 8. The effort applied by the police agent is assumed to be full with a range from 7 to 10. Table 5.12 shows the results of this test case.

Table 5.12 Results of the Test Case Club-3.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	1-8	35-50	1-5	7-10	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	31 ± 3	11 ± 3	23 ± 3	7 ± 2		0
1 hour later	57 ± 2	7 ± 2	6 ± 2	0		0
2 hours later	70	0	0	0		0
3 hours later	70	0	0	0		0

5.2.12 Test Case: Club-4

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon type club is assumed to be large caliber with a range from 14 to 20. The effort applied by the police agent is assumed to be full with a range from 7 to 10. Table 5.13 shows the results of this test case.

Table 5.13 Results of the Test Case Club-4.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	14-20	20-35	1-5	7-10	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	31 ± 2	27 ± 3	13 ± 2	0		0
1 hour later	30 ± 2	1 ± 1	37 ± 2	1 ± 1		0
2 hours later	31 ± 2	0	11 ± 3	28 ± 3		0
3 hours later	31 ± 2	0	0	10 ± 3		29 ± 3

5.2.13 Test Case: Club-5

In this test case, the resister agents are assumed to be old/infirm people, so their vulnerability range is from 6 to 10. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon type club is assumed to be large caliber with a range from 14 to20. The effort applied by the police agent is assumed to be full with a range from 7 to 10. Table 5.14 shows the results of this test case.

Table 5.14 Results of the Test Case Club-5.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	14-20	20-35	6-10	7-10	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	32 ± 3	14 ± 3	21 ± 3	4 ± 2		0
1 hour later	32 ± 3	1 ± 1	29 ± 4	8 ± 2		0
2 hours later	32 ± 3	0	7 ± 3	32 ± 4		0
3 hours later	32 ± 3	0	0	8 ± 3		31 ± 4

5.2.14 Test Case: Club-6

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon type club is assumed to be large caliber with a range from 14 to 20. The effort applied by the police agent is assumed to be moderate with a range from 4 to 7. Table 5.15 shows the results of this test case.

Table 5.15 Results of the Test Case Club-6.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	14-20	20-35	6-10	4-7	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	31 ± 3	18 ± 5	18 ± 5	4 ± 3		0
1 hour later	31 ± 3	1 ± 1	30 ± 3	8 ± 3		0
2 hours later	30 ± 3	0	6 ± 5	33 ± 5		0
3 hours later	31 ± 3	0	0	7 ± 5		32 ± 5

5.2.15 Test Case: Club-7

In this test case, all the values of parameters are selected randomly within their full range. Table 5.16 shows the results of this test case.

Table 5.16 Results of the Test Case Club-7.

Grid Height	12					
Grid Width	12					
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Effort Range**	**Number of Policemen**	**Number of Resisters**
Club	1-20	1-50	1-10	1-10	50	70
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**		**Dead**
Before the shot	70	0	0	0		0
After the shot	31 ±4	16 ± 4	17 ± 3	6 ± 2		0
1 hour later	38 ± 4	7 ± 3	20 ± 6	5 ± 2		0
2 hours later	43 ± 5	3 ± 3	9 ± 3	14 ± 3		0
3 hours later	44 ± 4	2 ±2	4 ± 2	8 ± 3		11 ± 3

5.2.16 Test Case: Gun-1

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be the head region with a range from 35 50. The weapon type gun is assumed to be large caliber with a range from 14 to 20. Table 5.17 shows the results of this test case.

Table 5.17 Results of the Test Case Gun-1.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Gun	14-20	35-50	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	916 ± 24	2 ±2	25 ± 8	26 ± 10	31 ± 9
1 hour later	850	0	30 ± 7	64 ± 8	56 ± 4
2 hours later	850	0	0	75 ± 6	76 ± 6
3 hours later	850	0	0	0	150

5.2.17 Test Case: Gun-2

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type gun is assumed to be medium caliber with a range from 8 to 14. Table 5.18 shows the results of this test case.

Table 5.18 Results of the Test Case Gun-2.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Gun	8-14	35-50	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	903 ± 21	9 ± 6	20 ± 4	55 ± 15	13 ± 3
1 hour later	850	0	35 ± 6	93 ±4	22 ± 5
2 hours later	850	0	0	70 ± 9	81 ± 9
3 hours later	850	0	0	0	150

5.2.18 Test Case: Gun-3

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be head region with a range from 35 to 50. The weapon type gun is assumed to be small caliber with a range from 1 to 8. Table 5.19 shows the results of this test case.

Table 5.19 Results of the Test Case Gun-3.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Gun	1-8	35-50	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	905 ± 21	14 ± 6	10 ± 5	60 ± 13	12 ± 5
1 hour later	850	0	39 ± 4	90 ± 6	22 ± 5
2 hours later	850	0	0	54 ± 6	97 ± 6
3 hours later	850	0	0	0	150

5.2.19 Test Case: Gun-4

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be trunk region with a range from 20 to 35. The weapon type gun is assumed to be large caliber with a range from 14 to 20. Table 5.20 shows the results of this test case.

Table 5.20 Results of the Test Case Gun-4.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Gun	14-20	20-35	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	914 ± 12	15 ± 3	30 ± 7	39 ± 7	3 ± 2
1 hour later	850	0	38 ± 6	92 ± 7	20 ± 5
2 hours later	850	0	0	126 ± 4	25 ± 4
3 hours later	850	0	0	0	150

5.2.20 Test Case: Gun-5

In this test case, the resister agents are assumed to be young people, so their vulnerability range is from 1 to 5. Their parts of body affected are assumed to be limps region with a range from 1 to 20. The weapon type gun is assumed to be large caliber with a range from 14 to 20. Table 5.21 shows the results of this test case.

Table 5.21 Results of the Test Case Gun-5.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Gun	14-20	1-20	1-5	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	903 ± 22	10 ± 5	32 ± 9	55 ±13	0
1 hour later	850	0	39 ± 4	109 ± 4	3 ± 2
2 hours later	850	0	0	104 ± 4	46 ± 4
3 hours later	850	0	0	0	150

5.2.21 Test Case: Gun-6

In this test case, all the values of parameters are selected randomly within their full range. Table 5.22 shows the results of this test case.

Table 5.22 Results of the Test Case Gun-6.

Grid Height	600				
Grid Width	200				
Weapon Type	**Weapon Capacity Range**	**Part of Body Range**	**Vulnerability Range**	**Number of Policemen**	**Number of Resisters**
Gun	1-20	1-50	1-10	150	1000
	Healthy	**Slowed and Dazed**	**Limping Badly**	**Incapacitated**	**Dead**
Before the shot	1000	0	0	0	0
After the shot	901 ± 26	5 ± 2	29 ± 10	35 ± 7	30 ± 9
1 hour later	850	0	32 ± 6	63 ± 4	55 ± 5
2 hours later	850	0	0	67 ± 6	83 ± 6
3 hours later	850	0	0	0	150

CHAPTER 6

DISCUSSION

This chapter includes the discussion of the results gathered from the conducted test cases. It is observed from the results that the following criteria should be kept in mind to reduce the number of casualties in a riot.

The weapon type used by control forces should be selected depending on the vulnerability of the resister. Because of its lower effect factor, rubber bullets should be used as the first option for long distances. The capacity of the rubber bullet is another key factor, a small caliber is better and the limbs of the victim should be targeted. The Golden Hour score is less than 1 for this type of weapon, so the victim gets better as time passes.

For close distances, a club is a very effective NLW. But, a small club must be selected especially for the old/unhealthy resisters and the trunk region may be targeted with moderate effort. A club is very dangerous if it is targeted at the head region with full force and might be fatal in this case. The limb region cannot be targeted with this type of weapon, because the control forces may endanger themselves while trying to target the limbs. A gun must be selected as the last option because it is a lethal weapon. If there is no choice, then it must be targeted at the limb region. It is very effective even from long distances.

Another key point to reduce the casualties is the Golden Hour concept. When examining the results from the previous chapter,, the number of casualties in the first shot is reasonably less than the number of casualties after one or two hours. If the Golden Hour score is bigger than 1 for a case, the motive capacity of the victim would be worse by the time. This fact causes that the number casualties would be larger in the first or second hours. So, in a riot, emergency vehicles must be ready to take the victims to the hospitals within the first hour.

The proposed fuzzy logic injury model has several advantages:

- It is scalable. The number of resister and the number of control forces may be changed easily to predict results of various sized riot activities. By using the proposed model, control forces can decide what type of weapon should be used to save the public with minimum injury or casualty for a riot, based on the crowd profile.
- It is extendable. New weapon types may be added into the model by adding new rules into the inference system for these new weapon types. Each weapon type has its own membership function and input range in addition to weapon capacity fuzzy sets. New rules must added into the rule based inference system for this weapon type to be taken into account in a case.
- It uses experience. Experience is the most important part of this model. The rules of the inference system must defined by the expert officers. The experience of the military security and police officers directly affects the accuracy and the reliability of the model.
- It is flexible. Usually, the results of the simulation and the real cases may not overlap. Rule definitions may be easily refined after the comparison with the real results to increase the overlapping ratio.

Besides the advantages, the proposed model has some limitations such as experience. If the experience of the control forces is not sufficient then the success of the model is not guaranteed. The other limitation of the model is that the size of the crowd in a simulation depends on the performance of the platform. A crowd with hundreds of thousands of individuals cannot be handled by laptop platforms.

CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

This chapter includes the summarized major contributions of the dissertation and possible future work suggested for further improvement of the proposed method.

7.1 Conclusions

Riots have always been part of the popular scene in one part of the world or another. In 2011, certain Arab and North African countries witnessed large demonstrations, some of which have turned into riots with many deaths. It is spreading from country to country with a domino effect. These kinds of activities are the only way to express public's displeasure with their governments [101]. But the governments' reactions to the riot activities may not always be tolerant. The police and maybe the military forces, who are responsible to preserve the public law and order, may resort to using non-lethal weapon as their first choice. If the non-lethal weapons do not work then the lethal weapons may be used by the controlling forces as the last choice to reach the objective of saving the public peace with the minimum injury or casualty.

Modeling and simulating pedestrian crowd behaviors, especially in emergency cases, has been an active research topic in recent years. It is important to predict the actions of the crowd in the case of extreme events like following the use of Non-Lethal Weapons. Therefore, utilization of some simulation mechanism is necessary. Multi-agent based simulations have some advantages over traditional numerical simulation techniques, which are based on stochastic and mathematical models. First, multi-agent based simulation platform provides noticeable visual displays in which the simulation designers can visually estimate pedestrian's behaviors in the simulation environment. Second, simulation designers can dynamically trace how the global structure emerges as a result of the agents' individual interactions.

In this dissertation, a fuzzy logic based multi agent crowd injury model has been developed for that purpose. Agent based simulation solutions may be the best way to predict behavior of crowd under emergent circumstances. To get the most suitable, reliable and accurate results, simulations must be supported by well designed models. Often, it is not easy to acquire the mathematical model for certain problem domains. Here, a fuzzy logic design could be the best option since it has several advantages such as ease of understanding, flexibility and being based on natural language. But, it must be kept in mind that fuzzy logic designs need problem domain knowledge and experience.

The Fuzzy Logic Injury Model is developed based on the PMFserv Injury Model and three types of weapons (rubber bullet, club and gun) are modeled. A gun has the most significant effect factor while a club has bigger effect factor than a rubber bullet. The Golden Hour concept imported from the PMFserv injury model is an important concept for the proposed model.

Repast Simphony is a useful agent based simulation toolkit to develop innovative project solutions. It provides 2D and 3D layouts in addition to graphical representation of the results to improve the understandings of the projects.

7.2 Future Works

As a result of the intervention of the control forces, many demonstrators may suffer injuries at different scales or even deaths. For example, in Northern Africa, many countries having trouble with the protests against the regime. The proposed model can be used to reduce the number of casualties in advance. However, the proposed model must be tested in the real world, by comparing the results of actual events which occurred, for example, in Egypt or Libya. Details of the events, such as the number of control forces, number of activists, weapon types used by control forces, profiles of the activists and the features of the area may be obtained from the news or from the statistics on the internet.

Domain expert knowledge is the most important part of a fuzzy logic design to define the rule base of the inference system. For a crowd behavior simulation project, it is necessary to work together with military security or police officers. Their experience in riot activities reflects the quality of rules used in an inference system. The sensitivity and the reliability of the proposed method may be improved by adding new rules and changing the effect factors of the present rules.

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APPENDIX A: FUZZY LOGIC INJURY MODEL RULES

RULE 1: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 2: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 3: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 4: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 5: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS head AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 6: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS head AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 7: IF weaponType IS club AND distance IS moderate THEN motiveCapacity IS limpingBadly.

RULE 8: IF weaponType IS club AND distance IS far THEN motiveCapacity IS slowedAndDazed.

RULE 9: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 10: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 11: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND effort IS mild AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 12: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND effort IS mild AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 13: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 14: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 15: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND effort IS moderate AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 16: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 17: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND effort IS mild AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 18: IF weaponType IS club AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND effort IS mild AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 19: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND effort IS moderate AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 20: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND effort IS mild AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 21: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 22: IF weaponType IS club AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND effort IS mild AND vulnerability IS unfirm THEN motiveCapacity IS healthy.

RULE 23: IF weaponType IS club AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 24: IF weaponType IS club AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 25: IF weaponType IS club AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 26: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND effort IS moderate AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 27: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND effort IS mild AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 28: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 39: IF weaponType İs club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND effort IS mild AND vulnerability IS unfirm THEN motiveCapacity IS healthy.

RULE 30: IF weaponType IS club AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 31: IF weaponType IS club AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 32: IF weaponType IS club AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 33: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 34: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 35: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 36: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 37: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS head AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 38: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS head AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 39: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 40: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 41: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND effort IS mild AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 42: IF weaponType IS club AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND effort IS mild AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 43: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND effort IS full AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 44: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND effort IS full AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 45: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND effort IS moderate AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 46: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND effort IS moderate AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 47: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND effort IS mild AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 48: IF weaponType IS club AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND effort IS mild AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 49: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 50: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 51: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 52: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 53: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 54: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS dead.

RULE 55: IF weaponType IS rubberBullet AND distance IS moderate THEN motiveCapacity IS limpingBadly.

RULE 56: IF weaponType IS rubberBullet AND distance IS close THEN motiveCapacity IS incapacitated.

RULE 57: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 58: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 59: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 60: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 61: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 62: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 63: IF weaponType IS rubberBullet AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 64: IF weaponType IS rubberBullet AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 65: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 66: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 67: IF weaponType IS rubberBullet AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 68: IF weaponType IS rubberBullet AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 69: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 70: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 71: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 72: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 73: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 74: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 75: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 76: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 77: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS healthy.

RULE 78: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 79: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 80: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 81: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 82: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 83: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 84: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS dead.

RULE 85: IF weaponType IS gun AND distance IS moderate THEN motiveCapacity IS dead.

RULE 86: IF weaponType IS gun AND distance IS far THEN motiveCapacity IS limpingBadly.

RULE 87: IF weaponType IS gun AND distance IS close THEN motiveCapacity IS dead.

RULE 88: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 89: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS close AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS dead.

RULE 90: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 91: IF weaponType IS gun AND weaponCapacity IS large AND distance IS close AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 92: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 93: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS close AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 94: IF weaponType IS gun AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 95: IF weaponType IS gun AND weaponCapacity IS small AND distance IS close AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS dead.

RULE 96: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 97: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 98: IF weaponType IS gun AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 99: IF weaponType IS gun AND weaponCapacity IS small AND distance IS moderate AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 100: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 101: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 102: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 103: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS incapacitated.

RULE 104: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS dead.

RULE 105: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS dead.

RULE 106: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 107: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS moderate AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 108: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 109: IF weaponType IS gun AND weaponCapacity IS large AND distance IS moderate AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 110: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS far AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 111: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS far AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 112: IF weaponType IS gun AND weaponCapacity IS small AND distance IS far AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 113: IF weaponType IS gun AND weaponCapacity IS small AND distance IS far AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 114: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 115: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 116: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 117: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 118: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS incapacitated.

RULE 119: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS limpingBadly.

RULE 120: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS far AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 121: IF weaponType IS gun AND weaponCapacity IS medium AND distance IS far AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 122: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 123: IF weaponType IS gun AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 124: IF weaponType IS club AND distance IS close THEN motiveCapacity IS incapacitated.

RULE 125: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS far AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 126: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS far AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 127: IF weaponType IS rubberBullet AND weaponCapacity IS small AND distance IS far AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 128: IF weaponType IS rubberBullet AND weaponCapacity IS small AND distance IS far AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 129: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS limbs AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 130: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS limbs AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 131: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 132: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 133: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS limpingBadly.

RULE 134: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 135: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS far AND partOfBody IS head AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 136: IF weaponType IS rubberBullet AND weaponCapacity IS medium AND distance IS far AND partOfBody IS head AND vulnerability IS healthy THEN motiveCapacity IS slowedAndDazed.

RULE 137: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS unfirm THEN motiveCapacity IS slowedAndDazed.

RULE 138: IF weaponType IS rubberBullet AND weaponCapacity IS large AND distance IS far AND partOfBody IS trunk AND vulnerability IS healthy THEN motiveCapacity IS healthy.

RULE 139: IF weaponType IS rubberBullet AND distance IS far THEN motiveCapacity IS slowedAndDazed.

APPENDIX B: FUZZY LOGIC GOLDEN HOUR RULES

RULE 1: IF weaponType IS rubberBullet AND weaponCapacity IS small THEN GoldenHour IS recover.

RULE 2: IF weaponType IS rubberBullet AND weaponCapacity IS medium THEN GoldenHour IS nochange.

RULE 3: IF weaponType IS rubberBullet AND weaponCapacity IS large THEN GoldenHour IS worsen.

RULE 4: IF weaponType IS club AND weaponCapacity IS small THEN GoldenHour IS recover.

RULE 5: IF weaponType IS club AND weaponCapacity IS medium THEN GoldenHour IS nochange.

RULE 6: IF weaponType IS club AND weaponCapacity IS large THEN GoldenHour IS worsen.

RULE 7: IF weaponType IS gun AND weaponCapacity IS small THEN GoldenHour IS worsen.

RULE 8: IF weaponType IS gun AND weaponCapacity IS medium THEN GoldenHour IS worsen.

RULE 9: If weaponType IS gun AND weaponCapacity IS large THEN GoldenHour IS worsen.

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