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Development of a simulation model to evaluate location strategies for publicly available bleeding control kits

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Abstract

This master thesis aims to evaluate different bleeding control kits locations strategies using a simulation model. The base scenario consists of a pedestrian street in the aftermath of a bomb explosion, where all the inputs of the model remain equal except the bleeding control kits locations.

Based on the information available and following the recommendations of specialized personnel, a model using Arena Simulation Software has been developed. Such a model reads the inputs from an excel file, allowing people who have not been involved during the development to easily vary the inputs and use the model to perform different scenarios.

An important result to highlight is that the number of casualties due to exsanguination after a mass casualty incident can be reduced if bleeding control kits are available. In contrast, the sensitivity analysis shows that it is not only important to have publicly available bleeding control kits, but also skilled people able to apply bleeding control techniques are paramount for providing better outcomes.

Finally, it is important to consider that locations inside buildings should be avoided as fewer bleeding control kits can be picked up, hindering their usage, and more victims die because of exsanguination. Through this thesis, it has been concluded that fewer locations, far from routes used by other people to evacuate, and with a higher number of bleeding control kits per location showed statistically lower number of victims who died because of exsanguination.

Acknowledgement

Without some people, the development of this thesis would not have been possible. I would like to express my gratitude to all of them.

To my tutors Krisjanis and Tobias for allowing and trusting me for the development of this thesis. This research could not have been possible without your support.

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To Javier, who has heard me so many times talk about this project and always gives me unconditional support.

To my closest friends, who are always there whenever I need them.

Tack så mycket! / Thank you!

Linköping in June 2020.

Laura Valdez Vidal

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Abbreviation of terms

ACEP	American College of Emergency Physicians
ACS	American College of Surgeons
AED	Automatic External Defibrillator
ATM	Automated Teller Machine
CoTCCC	Committee on Tactical Combat Casualty Care
EMS	Emergency Medical Services
ERC	European Resuscitation Council
GTI	Global Terrorism Index
KMC	Katastrofmedicinskt Centrum
LiU	Linköping University
LOS	Level of Service
MCI	Mass Casualty Incident
OHCA	Out-of-Hospital Cardiac Arrest
PAD	Public Access Defibrillators
PAHO	Pan American Health Organization
STB	Stop the Bleed
TARMAC	Targeted Automobile Ramming Mass Casualty
US	United States

Chapter 1

Introduction

1.1 Work framework

The final aim of this master thesis is to evaluate different location strategies for publicly available bleeding control kits. For that purpose, a simulation model using Arena Simulation Software has been developed. The need for using a simulation model emerges from the impossibility of testing in the real world due to ethical motives.

Stop the Bleed (STB) is a campaign that strives training bleeding control techniques to bystanders as well as distributing the equipment needed (Stop the Bleed, n.d.; Dhillon, et al., 2019). However, there is a lack of research done in this field so far.

This master thesis has a strong relationship with the research done by Anna-Maria Grönbäck last year (2019) in her project named "*Effekten av tourniquetplaceringar vid en större skadehändelse*" (The effect of tourniquet placements in a mass casualty incident) for the Institutionen för teknik och naturvetenskap (Department of Science and Technology) of Linköping University (LiU). Different bleeding control kits locations were evaluated in a confined space, particularly in an arena. In contrast, this thesis intends to evaluate different location strategies of bleeding control kits in a pedestrian street (open space).

For the development of the thesis, the recommendations of Carl-Oscar Jonson and Erik Prytz, specialized personnel from the Katastrofmedicinskt centrum (Centre for Teaching & Research in Disaster Medicine and Traumatology, KMC) from LiU have been followed.

1.2 Background and motivation

In 2018, more than 9600 incidents were carried out worldwide by terrorist attacks with 22980 deaths and 15690 casualties. The most common types of attacks are bombing/explosion (over 50%) and armed assault (above 25%) (Miller, 2019).

Nowadays, mass casualty incidents (MCIs) are quite common in the Western Countries, examples of that are: Madrid train bombings (2004), Stockholm truck attack (2017), mass shooting and bombing in Paris (2015), etc. Because of the consequences of the Sandy Hook Elementary School shootings in Newtown (United States, US) in December 2012, the STB campaign was launched. The aim is to train bystanders in hemorrhage control techniques to aid injured people before the arrival of emergency responders (Stop the Bleed, n.d.). Furthermore, the STB campaign strives for the distribution of bleeding control kits to individuals and public places (Dhillon, et al., 2019).

Goolsby et al. (2019) determined that intentional vehicle attacks (IVAs) are the ones with a major number of casualties or injuries with 51 victims estimated, followed by blasts with 5-34 victims and shooting with 5-11 victims. Regardless of the population present, the authors estimated that in a mass casualty attack, at least 20 people need hemorrhage control and hence can benefit from tourniquet kits.

Based on what is stated before, there is an emerging need for studying the benefits that publicly available bleeding control kits could offer in such cases.

On the other hand, the need for logistics management in disaster planning is unquestionable. Several benefits can be obtained from the applicability of logistics management in this field like: provision of equipment at the time needed, having available the resources needed, minimize response time and maximize resource capability, handle support teams, etc. (VanVactor, 2011).

Despite the importance of health care logistics for disaster planning, some evidence after previous disasters demonstrated the lack of correctly planning the supply of equipment and communication between organizations (VanVactor, 2011; Holgersson, 2016).

Finally, another motivation for the development of the current master's thesis was the ability to apply the knowledge gained through these last two years to learn and improve the management of bleeding control kits needed in the aftermath of a mass casualty incident. It is important to remark that the results obtained with the development of this thesis might be challenging to generalize and applicate to reality because they are based on a specific simulated scenario.

1.3 Research questions

Firstly, the main research question is introduced:

How can different bleeding control kit location strategies be evaluated using simulation?

For being able to answer the main research question, it was necessary to solve the different sub research questions that arose:

a) What are the key factors and assumptions that should be considered?
b) How should the different key factors and assumptions be implemented in the development of the simulated scenario?
c) Based on the simulation's outcomes, what are the advantages and disadvantages of each location strategy?

In the following subsections, the research questions are discussed.

1.3.1 Main question

How can different bleeding control kit location strategies be evaluated using simulation?

This research question describes the scope of the research that consists of "evaluate different bleeding control kits locations". Nowadays, the location strategies for bleeding control kits are a topic where little is known. In the intent of finding something that could be useful for beginning the study, research about defibrillators has been taken into account. Defibrillator location strategies have been previously studied in more extended than bleeding control kits. But even trying to use previous studies information about defibrillators resulted in limited knowledge but nevertheless useful for this research.

On the other hand, the main question also mentions the word "simulation". The current thesis consists of an experimental research that uses simulation as a quantitative tool for reaching the conclusions.

1.3.2 Subquestion a)

What are the key factors and assumptions that should be considered?

This research question is related to a theoretical framework, focusing on the basic elements and information that is important in order to understand "what happens after a MCI". The information has been studied thoroughly to discard irrelevant elements and the lack of information has been replaced with assumptions or variable parameters.

1.3.3 Subquestion b)

How might the different key factors and assumptions be implemented in the development of the simulated scenario?

This step consists of translating previous research findings into a simulation model. Once more, a literature study has been done to find missing information and then once key factors have been completely identified, in its majorities they have been used as inputs for the model.

1.3.4 Subquestion c)

Based on the simulation's outcomes, what are the advantages and disadvantages of each location strategy?

The last research question has the aim of testing the developed simulation model. The strengths and weaknesses of each location strategy have been analyzed in order to discuss which could be more suitable for the considered scenario.

1.4 Thesis outline

Chapter 1 starts with the introduction of the project outlining the work framework and motivation. The research questions are also stated in this chapter as a guideline for the project.

Chapter 2 follows with the state of the art, which consists of a theoretical study about the background and current situation of the field studied. This chapter starts with the definition of relevant terms, such as MCI and describes how emergency services overcome this type of incident. Later, generalities about tourniquets are described as well as the background of the STB campaign. Finally, the chapter ends with some examples of currently available healthcare equipment to the public.

Chapter 3 deals with the method followed for the development of the thesis. Moreover, the type of research study that is suitable for answering the research questions will be discussed. The reasons why simulation was the chosen tool and which simulation software has been chosen for the project. Chapter 3 ends with the methodology followed to develop the project.

Chapter 4 is a full description of the simulation model which includes the conceptual model. The chapter starts with the scenario description and is followed by the conceptual model, where the outputs and inputs of the model are explained. Finally, the chapter ends with the tests performed with the simulation model.

Chapter 5 shows the results obtained from the simulation model. By doing validation and verification the credibility of the results has been tested. The results obtained by testing the different bleeding control kits locations strategies are included. Ending, a sensitivity analysis is presented in order to evaluate the effect of the variable parameters over the outcomes.

Chapter 6 includes the discussion and conclusions based on the simulation results. Furthermore, the limitations of this thesis have been discussed and possible recommendations for future research are proposed.

Chapter 2

State of the art

2.1 Mass casualty incident

A MCI is defined by The Pan American Health Organization (PAHO) as "[...] any event resulting in a number of victims large enough [at one time] to disrupt the normal course of emergency and health care services" (World Health Organization, 2007).

A hazard is a natural or man-made event that can cause harm or loss (Kluger, Coccolini, Catena, & Ansaloni, 2020).

When a hazard interacts with a community it is called a disaster. The American College of Emergency Physicians (ACEP) defines a disaster as "when the destructive effects of natural or man-made forces overwhelm the ability of a given area or community to meet the demand for health care" (Kluger, Coccolini, Catena, & Ansaloni, 2020).

Two examples of man-made disasters that have the potential to become to MCIs are war and terrorism, due to a large number of casualties and deaths.

2.1.1 Terrorism

Hundreds of definitions of terrorism can be found, however, there is not a unique and internationally accepted definition (Institute for Economics & Peace, 2019). Regardless of the definition, some qualities are common such as a typical focus on civilians, disruption of public order, political or religious project, the danger of public security, among others (Schmid, 2011).

The Global Terrorism Database (2019) reports that in 2018 more than 9600 terrorist attacks were carried out worldwide, with 15690 casualties and 22980 deaths.

According to the seventh edition of the Global Terrorism Index (2019), after the peak in 2014, deaths from terrorism decreased for the fourth consecutive years. Total fatalities from terrorism have decreased since 2014 by 52%. However, the number of countries affected by terrorism is still high.

From 2015 to 2017, Western European countries were affected by attacks conducted by jihadists in Barcelona, Berlin, Brussels, London, Manchester and Nice. The more lethal was in a Christmas market in Strasbourg (France) with 11 injuries and 5 deaths. In Western Europe between 2017 and 2018, terrorist attacks and deaths fell 31 % and 70 %, respectively (Miller, 2019).

In the US, from 2015 to 2016 there was an increase from 38 to 67 terrorist attacks, followed by a stabilization in the two following years. In 2018 in this country, 45 people were killed by terrorist attacks, 54% less compared to 2017 (Miller, 2019).

Islamic State killed more than 500 people per month in more than 100 terrorist attacks between 2014 and 2017. Through the two following years, Iraq underwent the largest decline in terrorist' attacks recording a decrease of 75% fewer deaths compared to 2017 (Institute for Economics & Peace, 2019).

From the data analyzed by the Global Terrorism Database, the most common weapons used for terrorist attacks are explosives/bombs and firearms with 52% and 35%, respectively. On the other hand, Targeted Automobile Ramming Mass Casualty (TARMAC) have arisen in the Western Countries in the last years (Shokoohi, et al., 2018).

2.1.2 Explosive/bombs

In the period from 2014 to 2017, the Global Terrorism Database reports 28593 (50,74%) terrorist attacks where explosives/ bombs were used. This type of event was mainly concentrated in the following regions: Middle-East and North Africa (15124), South Asia (7700), Sub-Sahara Africa (2299), Southeast Asia (1659) and Others (1811).

The effect of an explosive/ bomb attack is strongly associated with the type of bomb. At the same time, the type of bomb depends on several factors such as the chemical used and the amount, the package, whether it has or not embedded bullets, the place where it is located (open-air or confined), among others (Holgersson, 2016). For this reason, it is really hard to generalize the effects of an explosion/ bomb attack in terms of the number of victims, fatalities, injuries, etc.

The type of injuries in bombing incidents have a great deal of different types and it is hard to find a pattern of injuries depending mainly on the scene configuration, people density and explosive settings (Leibovici, et al., 1996). The different injuries have been classified as follows in Table 2.1:

Table 2.1. Blast injuries classification.

Category	Description	Body part affected
Primary	Impact of the over-pressurized blast wave with the body	Lung, ear and bowel
Secondary	Includes penetrating injuries due to flying bomb's fragments	Any body part might be affected
Tertiary	Blast wave pushing the people against surronding objects	Any body part might be affected
Quaternary	Inhalation of smoke and hot gases and exposure to heat, flames and dust	Any body part might be affected

Source: Based on Kluger, Y., Coccolini, F., Catena, F., & Ansaloni, L. (2020). *WSES Handbook of Mass Casualties Incidents Management.* Springer.

Leibovici et al. (1996) studied the influence of blast incidents taking place whether in an open space or not. The results demonstrated that explosions that took place in a confined space (such as a bus) had greater mortality and higher severity of primary injuries, while there are no significant differences in the other categories.

2.2 Health management

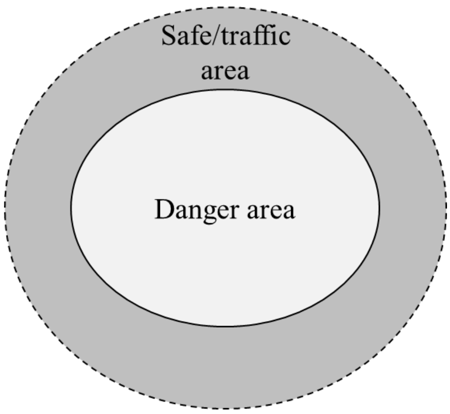
As terrorist attacks cannot be completely stopped, managing the response of bystanders, police, fireman, emergency medical services (EMS) and other emergency services is an important task (Holgersson, 2016). The experience and information provided by previous MCIs are useful to create institutional plans to handle possible future incidents. As seen in the Boston Marathon attack in 2013, preparedness for the possibility of a MCI is an important issue (Biddinger, et al., 2013).

The response as a joint work from different emergency forces is fundamental as it is demonstrated that a victim could die from exsanguination in less than six minutes (Holgersson, 2016; Almogy & Rivkind, 2007).

The role of the bystander is also interesting in this type of incident as they are in the scene even before the arrival of the fastest EMS (Bakke & Wisborg, 2017). However, disparities have been found about if bystanders should or not provide first aid. Some authors said that bystanders' actions have been useless, while others have stated that bystanders have been able to provide aid in hemorrhage control, victims evacuation, triage stations, etc. Despite the benefits that bystanders can provide in such situations, they need to be trained, understand how emergency services work and have access to the required equipment (Holgersson, 2016).

The Israeli force divided the scene after a MCI into two main zones (Holgersson, 2016; Almogy & Rivkind, 2007) where different emergency forces act (Figure 2.1.):

Figure 2.1. Areas after a MCI.



Source: Based on Holgersson, A. (2016, August 29). Review of On-Scene Management of Mass-Casualty Attacks. *Journal of Human Security*, pp. 91–111.

2.2.1 Danger area

The inner zone is restricted to professional forces because it is defined as a danger area not already secured and susceptible to suffer a secondary attack (Holgersson, 2016; Almogy & Rivkind, 2007).

Police

The police are responsible for creating "evacuation corridors" in the scene in order to secure safe access to the EMS. This is due to the necessity of securing responders' safety and providing help to the victims as soon as possible (Holgersson, 2016).

According to Autrey et al. (2014), police are the first force to enter the danger area to stop the threat. While doing this, they can locate and therefore, communicate victims' locations. This allows the following groups of police coupled with EMS to rapidly provide help to the victims (Autrey, Hick, Bramer, Berndt, & Bundt, 2014).

EMS

As said before, once the police noticed that it is secure to enter, the EMS escorted by another group of police enters the danger zone. The goal of the EMS is to rapidly do a first evaluation of the victims and help with hemorrhage control techniques to those more severely injured (Holgersson, 2016; Autrey, Hick, Bramer, Berndt, & Bundt, 2014).

After completing this task, some police and EMS aid in the evacuation of the victims through the "evacuation corridors" (Holgersson, 2016; Autrey, Hick, Bramer, Berndt, & Bundt, 2014).

Rescue services

The rescue services help the police and EMS in tasks like the removal of trapped victims, assessment of the environment, clear the scene, etc. (Holgersson, 2016).

Other

If there are available, other professional forces could enter the danger zone. The bomb squad can search for additional devices, while the forensic team can gather preliminary evidence and information of the scene (Holgersson, 2016).

2.2.2 Safe/traffic area

The majority of emergency personnel are located in the safe area, only a few enter into the danger one (Holgersson, 2016).

Police

The tasks of the police here are: keeping bystanders far from the scene, clearing evacuation routes, cordon off the scene and connecting points, control the access of people to the scene, look for possible secondary devices at the surroundings, collect relevant data, etc. (Holgersson, 2016; Almogy & Rivkind, 2007)

EMS

The main labor of the EMS is to carry out triage and treatment of victims. Triage aims to identify the most injured victims that need immediate assistance while prioritizing the victims for later treatment. Currently, there are multiple triage systems used, although interpretation by the different organizations is the most important issue. Therefore, the easiest triage system consists of classifying victims into "urgent" or "non-urgent" (Holgersson, 2016).

Finally, the victims are going to be evacuated and transported to the pertinent hospitals depending on the hospitals' capability and capacity (Holgersson, 2016).

Rescue services

The rescue services act as additional support to the police and EMS in tasks like creating a cover, helping to develop an entire picture of the scene, clearing corridors, providing equipment and helping the EMS, among others (Holgersson, 2016).

Mental health professionals

The main job of mental health professionals in this type of event consists mainly of restoring the victims' feelings of safety and control. Furthermore, they help the victims to reunite with their families, provide food and treat minor injuries. However, what it is also expected from the mental health professionals is to gather detailed information about the perpetrator and the incident by speaking with the victims (Holgersson, 2016).

2.3 Tourniquet

The most basic definition of a tourniquet is a type of device used for tightening and stopping the blood flow through a limb. It is commonly used for stopping excessive/uncontrolled hemorrhages (Study.com, 2017).

There are two types of tourniquets, the commercial ones and improvised tourniquets. An improvised tourniquet can be easily done by using three materials: band, rigid object to twist and security mechanism. An example of an improvised tourniquet is to use a bandana and a stick. A knot is done to the bandana to have a loop that is big enough to fit over the limb, by inserting the stick inside the loop and twisting, the loop becomes more and more tightened (FirstCareProvider, 2017).

There are pieces of evidence that improvised tourniquets were used in the Boston Marathon Bombing (2013) as a means of prehospital hemorrhage control. However, the data from later studies show that improvised tourniquets are not well applied (King, Larentzakis, Ramly, & The Boston Trauma Collaborative, 2015).

Meanwhile, it is demonstrated in the military context that commercial tourniquets are more effective and therefore, the survival rate is higher when such type is used (Beekley, et al., 2008; Kragh & Dubick, 2016). Since March 2005 all the soldiers from the US Army carry a commercial tourniquet as a means of first aid equipment for early hemorrhage injuries control (Beekley, et al., 2008). Before that implementation, the percentage of deaths on the battlefield due to uncontrolled hemorrhage was 85% higher (Drew, Bennett, & Littlejohn, 2015).

Nowadays, despite all the types of tourniquets developed, only the four shown on Figure 2.2 have been approved by the Committee on Tactical Combat Casualty Care (CoTCCC):

A) Combat Action Tourniquet (CAT).
B) Special Operations Forces Tactical Tourniquet (SOFTT).
C) Special Operations Forces Tactical Tourniquet-Wide (SOFTT Wide).
D) Emergency and Military Tourniquet (EMT).

Figure 2.2. Commercial tourniquets.

Source: Drew, B., Bennett, B. L., & Littlejohn, L. (2015, June). Application of Current Hemorrhage Control Techniques for Backcountry Care: Part One, Tourniquets and Hemorrhage Control Adjuncts. *Wilderness & Environmental Medicine*, pp. 236-245.

Extremity hemorrhage injuries are the leading cause of deaths on the battlefield (Beekley, et al., 2008) and the second cause of deaths in the civilian sector (Sauaia, et al., 1995). Kragh & Dubick (2016) stated that the lessons learned from the use of tourniquets in the military context are:

1. A tourniquet properly applied can reduce the bleeding in extremity hemorrhage injuries and therefore, prevent mortality.
2. Tourniquets are safe as long as the usage does not last an extended time.

Despite the benefits that tourniquets have demonstrated in military settings, their use in civil settings is still a controversial discussion. This results from the complications that could appear when a tourniquet is not properly applied, like unnecessary limb amputations, infections, etc. (Drew, Bennett, & Littlejohn, 2015).

Some studies reveal the willingness of laypersons to help injured people by applying a tourniquet. Schroll et al. (2015) analyzed a total of 197 persons who arrived at a trauma center with a prehospital tourniquet in the period from January 2010 to December 2013. They found that 20.3% of the patients admitted had an improvised tourniquet placed either by themselves or a bystander. Besides that, King et al. (2015) stated that only 37.04% of the improvised tourniquets placed in the Boston Marathon Bombing (2013) were applied by EMS.

As a result, these findings stress the need for training programs to teach laypersons how to correctly apply a commercial tourniquet as well as spread their use in the civilian sector (Schroll, et al., 2015). Commercial tourniquets should be as accessible as defibrillators are in every public gathering area in the US (King, Larentzakis, Ramly, & The Boston Trauma Collaborative, 2015).

2.4 Stop the Bleed

STB is a campaign originated because of the consequences of the Sandy Hook Elementary School shootings in Newtown (United States, US) in December 2012 (Stop the Bleed, n.d.). The perpetrator shot 28 people including children, school staff and his mother (Ray, 2019).

Dr. Lenworth Jacobs, a trauma surgeon and manager of the American College of Surgeons (ACS), and a group of experts decided to form a group named the Hartford Consensus. The group aims to provide knowledge to the immediate responders of a MCI on how to improve the survival rate. In October 2015, the ACS launched the STB campaign which aims to train (one-hour course) bystanders in hemorrhage control techniques to aid injured people before the arrival of emergency responders (Stop the Bleed, n.d.).

The hemorrhage control can be done using bleeding control kits provided with: instructional booklet on bleeding control, tourniquet, bleeding control dressing, marker, protective gloves and a compression bandage (Stop the Bleed, n.d.).

Furthermore, the STB campaign strives for the distribution of bleeding control kits to individuals and public places. Dhillon et al (2019) state that bleeding control kits should be as accessible as automated external defibrillators (AEDs) rather than relying on individuals to purchase them.

The effectiveness of this type of campaign has been demonstrated by different authors. The confidence of the participants when applying bleeding control techniques was increased after the course (Andrade, Hayes, & Punch, 2019).

The increment of laypersons' ability to apply correctly a commercial tourniquet has been also proven. Ross et al. (2018) evaluated the skills of laypersons when applying different types of commercial tourniquets on manikins without previous training. The study showed that less than 17% of laypersons can apply a commercial tourniquet correctly. Goralnick et al. (2018) analyzed the effectiveness of laypersons to place a commercial tourniquet after a one-hour training course, the study concluded that 88% of participants applied them correctly.

2.5 Public healthcare equipment

As defibrillators are more publicly widespread than bleeding control kits are, some research about defibrillators' location strategies has been carried out. Moreover, some examples of publicly available bleeding control kits are presented.

2.5.1 Defibrillators location strategies

Despite the well-known improvement in the survival rate by using automatic external defibrillators (AEDs) before the arrival of EMS, there is a lack of knowledge about which is the best AEDs location strategy (Dahan, et al., 2016). Public access defibrillators (PADs) are used in less than 5% of the out-of-hospital cardiac arrests (OHCA), regardless of hundreds of lives per year that they would save. This is due mainly to three factors: number and location of AEDs, knowledge about the need and willingness to use it, lack of knowledge about the PAD location (Sidebottom, Potter, Newitt, Hodgetts, & Deakin, 2018).

Dahan et al. (2016) evaluated three different AEDs location strategies considering the OHCAs occurred in Paris (France) from 2000 to 2010:

1. Locate AEDs in every location where more than one arrest has occurred in the last five years, following the recommendations from the European Resuscitation Council (ERC).
2. Grid-based strategy, which consists of placing AEDs at fixed distances between each other.
3. Place the AEDs in well-known locations, known as landmarks, such as: bike stations, subway stations, pharmacies, shops, post offices, among others.

As the main outcome of the study, the best location strategy that suits to Paris was placing the AEDs in landmarks, in particular at bike stations or pharmacies. They demonstrated that the average walking time needed from an OHCA to the AEDs placed either at a bike station or a pharmacy was in both cases of three minutes. However, the bikes stations are widely and homogenously spread through the entire city of Paris, while pharmacies are closer to hospitals or commercial areas (Dahan, et al., 2016). Furthermore, an important fact is that bike stations are accessible 24/7, while pharmacies do not.

On the other hand, the main constraint of the first strategy is that it leads to an uncontrollable number of AEDs placed and the time needed to locate them is higher as it is less intuitive to find them (Delhomme, et al., 2019; Dahan, et al., 2016).

Finally, for the grid-based strategy, an expected outcome was that the average walking time needed to reach the AEDs is lesser when the AEDs are placed closer together. For a walking time of three minutes from an OHCA to the AEDs, it is needed the double of AEDs placed than for the landmark strategy (Dahan, et al., 2016).

In conclusion, the landmark strategy has demonstrated to have better outcomes for the city of Paris. Being important the distribution throughout the city of such landmarks and their accessibility (Dahan, et al., 2016).

2.5.2 Bleeding control kits

Three examples of places that already have implemented publicly available bleeding control kits are outlined below:

Cardioprotection tower with bleeding control kit (Pamplona, Spain)

The nurse school has installed the first publicly available cardioprotection tower with a bleeding control kit in Pamplona (Spain). Such a tower is available for everybody 24 hours a day every day of the year (Colegio Oficial de Enfermería de Navarra, 2020).

The tower consists of a semi-automatic defibrillator as well as a bleeding control kit comprised of a commercial tourniquet and compressive bandage. Furthermore, it has a geolocated phone to call 112 to warn the EMS or ask about the usage of the tower (Colegio Oficial de Enfermería de Navarra, 2020).

Finally, the nurse school is going to train different restaurants, pharmacies, shops, schools and neighbours about the usage of the tower (Colegio Oficial de Enfermería de Navarra, 2020).

Cleveland Hopkins Airport (Ohio, US)

Cleveland Hopkins International Airport is the first public space in the city of Cleveland and the eighth airport in the US that implements the STB program. The locations of previous AEDs have been considered as shared points where the bleeding control kits could be located. Moreover, such kits were also located in risky locations where severe injuries could occur (Urie, 2019).

In order to choose which employees should be trained, the areas more likely to suffer an event where several victims with bleeding injuries could be identified were evaluated (Urie, 2019).

Finally, 100 bleeding control kits have been placed at the airport and 2000 employees have been trained in hemorrhage control (Urie, 2019).

American Schools (Texas and Illinois, US)

On the first of January 2019, a new law came out in Texas, requiring bleeding control kits in every school in the state by the first of January 2020 (McCoy, 2020). This is part of the STB movement and each school was responsible for choosing both the locations and the number of bleeding control kits to place. Hospitals helped training school employees and students on bleeding control techniques (Tinsley & Smith, 2019).

During the last scholar year of 2019/2020 more than 7000 STB kits have been distributed by the Terrorism Task Force along the schools of Illinois. Every five trained school employees in bleeding control techniques, the Terrorism Task Force gave five kits (Ready Illinois, 2019).

Chapter 3

Method

3.1 Research study

The choice of the research method, research approach and research strategy/design are going to be affected by the research's character chosen. Therefore, the most basic choice to carry out before developing a research project is the quantitative character or qualitative character of the research (Håkansson, 2013).

It is important to make clear the difference between the research method and the research strategy/design, as both definitions are easily misunderstood. Basically, the research method is the theoretical framework for the research; while the research strategy/design consists of the methodology (or steps) followed to develop the research (Håkansson, 2013).

Finally, the research approach is useful to build conclusions and distinguish between what is true or not (Håkansson, 2013).

3.1.1 Quantitative and qualitative research

The main difference between quantitative and qualitative research relies on either in the usage or not of quantifiable data (Sukamolson, 2007; Håkansson, 2013):

Quantitative research (numerical): Analyses numerical data using mathematically based methods to explain a particular phenomenon. Examples of quantitative research applications are: laboratory experiments, simulations, and field experiments (Wienclaw, 2019).

Qualitative research (non-numerical): Analyses meanings, opinions, and behaviors to explain a phenomenon. Examples of qualitative research applications are field observation, (participatory or not) and survey research (Wienclaw, 2019).

Moreover, it is acceptable to use a mixture of both methods in order to have a complete understanding of the phenomenon, this method is known as *triangulation* (Håkansson, 2013).

For the development of the current master thesis, both quantitative and qualitative methods have been used. The system that has been modeled is both characterized by quantitative and qualitative components, such as people's behavior (qualitative) and numerical components (quantitative) such as: percentage of trained people, bleeding rates, tourniquet application time, and so on. Furthermore, for answering the research questions raised in ***Chapter 1.3. Research questions*** a simulation model has been developed, which consists of a quantitative tool used for experimenting. Finally, another qualitative method has been used, concerning the collection of data for the current project taking advantage of prior studies by other authors.

3.1.2 Research method

As the character of the research project at hand is not entirely qualitative, research methods merely based on qualitative research have been discarded. Therefore, the research methods that could fit the current research project are:

Experimental research (causes and effects): the method studies the relationship between variables by modifying one of them and keeping the others constant. The purpose is to see the effect of one variable over the others and establish causal relations (Ary, Cheser, Sorensen, & Razavieh, 2010; Håkansson, 2013).

Fundamental or Basic research (curiosity-driven): the goal is to analyze empirical data to increase the knowledge of a theory or phenomenon (Ary, Cheser, Sorensen, & Razavieh, 2010). It is used to create principles, theories or innovations to old problems rather than focus on solving a particular problem (Håkansson, 2013).

Applied research (problem-solving): aims to solve specific problems under the conditions that happen in practice. Therefore, it does not provide enforceable knowledge for solving other problems (Ary, Cheser, Sorensen, & Razavieh, 2010). It is also used to develop technologies and applications based on real-world data and previous researches (Håkansson, 2013).

More than one research method can be chosen to build a holistic view of the phenomenon. The necessary criterion is that each research method chosen has to be complementary to the others already chosen (Håkansson, 2013).

A simulation consists of experimental research because it is used to see how the effect of modifying the inputs affect the outputs of the model. However, this thesis is also oriented to solve a specific problem with specific technical data. This means, for example, that the outcomes obtained with a simulation model based on a blast incident, cannot be extrapolated to a shooting incident. In conclusion, both experimental research and applied research have been used as research methods.

3.1.3 Research approach

The most well-known research approaches are deductive and inductive, both explained below:

Deductive approach: a hypothesis is formulated based on known theory (Ary, Cheser, Sorensen, & Razavieh, 2010). Quantitative methods are used for collecting a large amount of data and testing the theory. The outcome is based on the collected data and the relationship between the variables (Håkansson, 2013).

Inductive approach: a hypothesis is formulated based on previous observations (Ary, Cheser, Sorensen, & Razavieh, 2010). Qualitative methods are used for collecting data and later analyze it. The outcome is based on opinions, behaviors and experiences (Håkansson, 2013).

As said before, this project is based on previous studies and researches, which matches with a deductive approach. Moreover, the conclusions of the research are based on the results obtained with the simulation model.

3.1.4 Research strategy/design

The research strategy/design that has been used is known as *Ex post facto research.* The translation of "*Ex post facto*" from Latin means "*after the fact*", which indicates that the variables have been already collected when the research starts. It is recommendable when the variables could not be manipulated due to ethical motives or lack of control over the experiment (Ary, Cheser, Sorensen, & Razavieh, 2010).

Ex post facto research also studies the relationship between variables and test hypotheses as *Experimental research* does. However, the outcomes are less convincing because if it is not possible to manipulate the variables that might affect others, the causal relations are going to be weaker than for Experimental research (Ary, Cheser, Sorensen, & Razavieh, 2010).

3.2 Simulation study

Robinson (2004) defines simulation as:

"Experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for the purpose of better understanding and/or improving that system."

The general definition of simulation is "imitation of something", while the definition of imitation is "to copy something else". But there is a difference whether the simulation evolves through time or not. *Dynamic simulation* imitates a system while it evolves through time; *static simulation*, by contrast, only imitates a system at a specific point in time (Robinson, 2004).

When a simulation model contains random events, it is known as *stochastic*. On the other hand, when all the random events are removed from the model, it is known as *deterministic* (Robinson, 2004; Rossetti, 2016).

The difference between *discrete* and *continuous* simulation relies on when the system is monitored. In discrete event simulation, only the specific points in time when the system suffers any change are gathered; in continuous simulation, by contrast, the system is monitored for every point in time (Rossetti, 2016).

It is desirable to keep a simplified simulation model, since developing a very detailed model would require a big amount of data that would take time to collect (Robinson, 2004). Furthermore, the more detailed a model is, the more complex it becomes.

A simulation is an *experimental approach* as it is used to see how the variation of some variables affects the outcome of the simulated scenario. The goal is to experiment with different alternatives to increase knowledge about the real system or innovate it (Robinson, 2004).

Finally, Wild (2002) defines an *operations system* as "[…] configuration of resources combined for the provision of goods or services".

In conclusion, the type of system that best fits the current research is a stochastic, dynamic and discrete-event. The reasons for using a simulation model are primarily due to ethical motives and the complexity of testing in the real world.

3.2.1 Data collection

The results of the simulation model have a direct relationship with the accuracy of the gathered data used as inputs. The model's inputs concern both quantitative and qualitative data. It is important to assess the data before using it in the simulation model, classifying the data in three main groups depending on the requirements needed (Robinson, 2004):

Preliminary or contextual data: Large amounts of data are not necessary because it is only needed to have a complete understanding of the problem. The development of the conceptual model is done using this type of data.

Model realization data: Large amounts of data are needed in order to develop the computer model. It is an output of the conceptual model.

Model validation data: Data measured directly from the real world that is used to compare, and therefore validate the output of the computer model.

Robinson (2004), states that once all the requirements of the data are known, it is time to collect the data. Again, the data can be categorized in other three groups:

Category A data (available): The data needed for the simulation model has already been collected, maybe for other research projects or purposes.

Category B data (not available but collectable): The data needed for the simulation model is not available but can be collected either by people or electronic machines. A good way of gathering this data is by having interviews with experts on the topic.

Category C data (not available and not collectable): The data needed for the simulation model is neither available nor collectable either because the real world does not exist yet or the time available for collecting it is not enough.

The three types of data categories have been used for the development of the simulation model:

Category A data: The data needed has been gathered from databases, academic journals or books. Examples of data used are: bleeding rates, maximum blood loss, different types of bleeding injuries, reaction time, etc.

Category B data: One of the most important data needed was the tourniquet application time for either trained or laypersons. This data was provided by the KMC from a recent experiment carried out.

Category C data: Some realistic data concerning this research have been limited or impossible to find. To deal with the lack of data, it was necessary to estimate it in order to continue with the research. Examples of estimated data are: person step length, number of patients helped by each ambulance, bomb magnitude, bomb location, among others.

3.2.2 Validation and verification

Validation and verification is a valuable step of a simulation study that should not be overlooked. However, sometimes it is underestimated and does not receive the importance that it should (Robinson, 2004).

Verification consists of making sure that the computer model developed based on the conceptual model is sufficiently accurate (Sargent, 2011; Robinson, 2004). On the other hand, validation consists of checking that the computer model has an acceptable level of accuracy for the intended use (Carson, 1986). The difference between accuracy and validity must be clear: accuracy is measured on a scale from 0 to 100%; while validity is a binary decision based on a “yes” or “no” conclusion (Robinson, 2004).

It is important to remark that validation and verification is a continuous process that has to be done while the simulation study is developed rather than when the simulation model is already completed (Robinson, 2004). Some forms of validation parallel to the development of the simulation study have been discussed by Robinson (2004): conceptual model validation, data validation, white-box validation, black-box validation, experimentation validation and solution validation (only performed when the solution is implemented).

3.3 Arena Simulation Software

Arena is a simulation software based on the SIMAN programming language used to simulate discrete event systems. SIMAN is constituted basically of two objects: blocks and elements. Blocks are operations represented by basic logic constructions like size, delay, and release blocks. On the other side, elements are used to represent facilities such as resources or queues (Altiok & Melamed, 2007).

One remarkable benefit that Arena offers its programming flexibility. The easiest way of programming is using modules, which are predefined constructions formed of SIMAN blocks and elements ready to pick up and drop on the simulation environment for easily programming (Rossetti, 2016). For instance, the module process is constituted by size, delay, and release blocks and a queue element. Meanwhile, for complex algorithms or structures, it is even possible to program in other languages such as C/ C++ (Robinson, 2004). Both methods could be mixed in the same simulation model offering high flexibility to the users.

Connector lines between modules are used to create the flow of entities.

Some interesting components that Arena possesses are explained below:

Firstly, the entities are dynamic objects that move around during the simulation representing things. Entities affect the outcomes of the model but, at the same time, they are affected either by other entities or events (Kelton, Sadowski, & Zupick, 2015; Robinson, 2004).

To characterize entities, attributes are attached to them. An attribute is a characteristic of all entities but has specific values for each entity (Kelton, Sadowski, & Zupick, 2015). For example, an attribute for all entities could be “birth date”, but the birth date is going to be different from one entity to another.

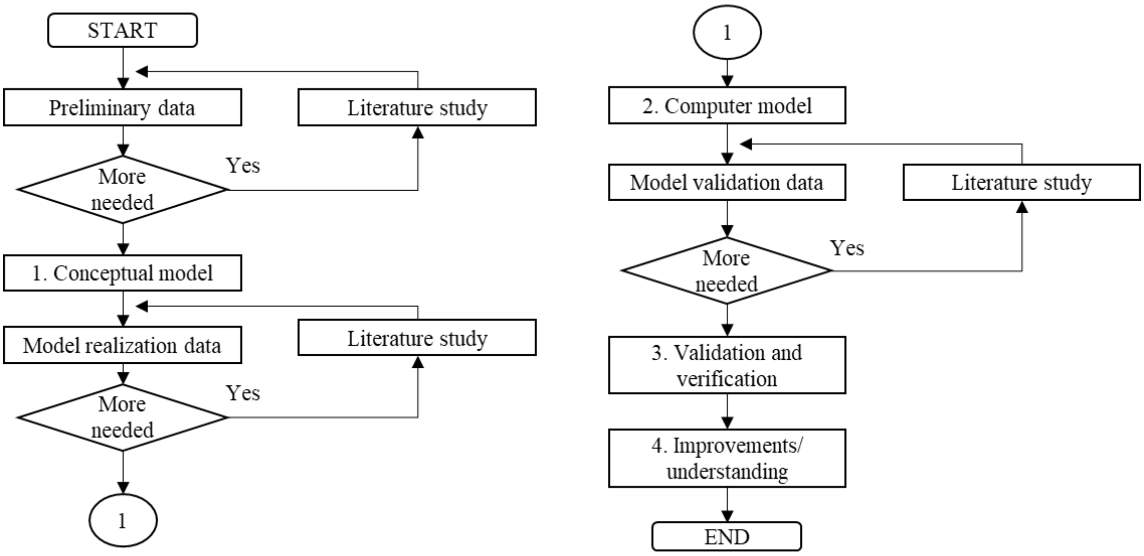
A characteristic of the system can be represented by a variable. Such elements are unique pieces of information that are not linked to a specific entity. However, variables could be modified by any entity (Kelton, Sadowski, & Zupick, 2015).

Resources depict things like employees, machines, space in a warehouse, etc. When a resource is not being used, an entity can seize it and releases it when finished. However, an entity could seize and release several resources at the same time. That is why it is better to think about a resource being assigned to an entity. The waiting places where an entity stays while a resource is being used are known as queues (Kelton, Sadowski, & Zupick, 2015).

3.4 Project methodology

The steps followed for the development of the current thesis, shown in Figure 3.1, were based on the four key stages of a simulation study defined by Landry et al. (1983):

Figure 3.1. Thesis methodology.



Firstly, before the development of the conceptual model, a preliminary study about "what happens in a MCI" was conducted. Such research included: attacks more likely to happen, the use of tourniquets, hemorrhage injuries, people's behavior, and so on.

A conceptual model is essential for describing the content, objectives, inputs, outputs, simplifications and assumptions regarding the simulation model (Robinson, 2004). An analysis of the possible assumptions to include in the model has been done to see either which assumptions should be included and which ones should be assessed or discarded.

Once the conceptual model was developed (***Chapter 4.1 Conceptual model***), it was useful to evaluate the data that was truly necessary for the computer model development. As has been mentioned before the software used for the development of the computer model has been Arena Simulation Software. While modelling, the statements made in the conceptual model have been taken into consideration.

Validation and verification was done (***Chapter 5.1 Validation and verification***) by testing the model with extreme values of the inputs. Some tests performed consisted of: considering 0 tourniquets available in each location, assume that nobody is going to aid the victims with bleeding injuries, etc. The outcomes of this type of tests are easily predictable by the modeler, and therefore, abnormal behaviors are easily detected.

A sensitivity analysis (***Chapter 5.3 Sensitivity analysis***) has been also carried in order to test the model. It consisted of modifying the values of different inputs and study the variations in the outputs. Such analysis was done to make sure that the changes made in the inputs generate a change in the outputs that makes sense. On the other hand, it was useful to see the limitations of the model (***Chapter 6.1.3 Limitations***).

Finally, the last stage defined by Landry et al. (1983) consists of the implementation of the solutions or improvements in the real world. Such a stage is outside the scope of this project because the responsibility of implementing publicly available bleeding control kits is the responsibility of other organizations. Even if publicly available tourniquets were placed, due to ethical motives again, it is not possible to carry out an attack and see the performance of the improvements in a real scenario.

3.4.1 Data collection

The advice and recommendations of experienced people in the field have been included during the entire development of this master thesis. Counseling of both supervisors and specialized personnel from the KMC from LiU.

In relation to material resources, some information used has been gathered from databases such as the Global Terrorism Database and the International Federation of Red Cross and Red Crescent Societies.

The two main topics of this research are disaster planning and logistics. For collecting relevant data about these two fields, sources of information used were academic journals or books through Linköping University Library, Polytechnic University of Valencia Library and Google Scholar.

Data gathered from governmental agencies such as laws, recommendations and regulations have been considered as a reliable source of information. For example, the different reaction times have been based on (Boverket, 2006).

Finally, relevant data has also been provided by the KMC like the tourniquet application time by trained people and laypersons.

The keywords used for finding relevant information, and therefore developing the current master thesis are listed below:

- Stop the Bleed
- Hemorrhage control
- Mass Casualty Incident (MCI)
- Barcelona’s attacks
- Tourniquets
- Defibrillator
- Public bleeding kits
- Discrete-event simulation
- Modeling in Arena
- Building occupancy
- The density of a crowded space
- Bleeding rates
- Pedestrian flow
- Large crowd evacuation
- Terrorism
- Terrorism injuries
- Research methods
- Arena Simulation Software
- Running speed
- Blast injuries
- Publicly available tourniquets
- Publicly available defibrillators
- Defibrillators location strategies

Chapter 4

Implementation

4.1 Conceptual model

The conceptual model consists of an overall description of what the simulation model does. The outputs and inputs of the model are detailed avoiding technical information. The aim is to increase the understanding of how the simulation model works.

The outputs of the model are explained in Table 4.1 shown below:

Table 4.1. Outputs of the model.

Output	Explanation
Total number of people in the street	Number of people present in the street before the incident takes place.
Total number of trained	This output stores the number of trained, which is a percentage of the Total number of people in the street.
Total number of volunteers	This output stores the number of volunteers, which is a percentage of the Total number of people in the street.
Bomb magnitude	Magnitude of the detonated bomb.
Total number of people who directly die	Number of people killed due to the detonation.
Total number of victims	Number of victims (with any kind of injuries) due to the detonation.
Victims with bleeding injuries	Number of victims with bleeding injuries.
Fatality Rate	Defined as: Total number of people who directly die/(Total number of people who directly die+Total number of victims)
Mild bleeding victims	Number of victims with mild bleeding injuries.
Moderate bleeding victims	Number of victims with moderate bleeding injuries.
Severe bleeding vcitims	Number of victims with severe bleeding injuries.
Massive bleeding victims	Number of victims with massive bleeding injuries.
Tourniquets wasted	Number of tourniquets that have been picked up but not applied.
Tourniquets wrongly applied	Number of tourniquets that have been wrong applied.
Tourniquets not used	The sum of Tourniquets wasted and Tourniquets wrongly applied.
Tourniquets that still are inside a store	Number of tourniquets that are inside a store and have not been picked up.
Bleeding control kits not picked up	Total number of tourniquets that have not been picked up, includes tourniquets placed inside buildings or in the street.
Victims with tourniquet	Number of victims with bleeding injuries that have received a tourniquet.
Victims who died because of exsanguination	Number of vicitms with bleeding injuries who have died because of exsanguination.
Victims who left in ambulance	Number of victims with bleeding injuries who have been aided by an ambulance.

In the following subchapters, all the inputs of the model are explained as well as the source from where they have been gathered. Some inputs included are assumptions or simplifications from reality that have not been possible to estimate or are complex to model.

4.2 Scenario description

In a fictitious scenario, simulating a pedestrian street of a commercial area on a regular day, people are walking around. In a specific moment, an explosion of a bomb occurs at a random location of the street, never inside a building. The people affected by the blast radius are going to be injured or dead, the number of people included in each case varies with the bomb magnitude. The victims are going to be inside the boundaries of the street, never inside buildings. Possible collapses or failures in the structures of the buildings inside the blast radius have not been considered, neither the people that could be inside the buildings. Meanwhile, the people out of the bomb radius are not going to be affected. The scenario simulates a MCI such as a terrorist attack characterized by a detonation of a pipe bomb or a bomb located inside a backpack in a public environment without secondary threats.

Different types of people can be distinguished:

1. Trained: A small percentage of bystanders are people who either work in the medical sector or have taken a course on bleeding control techniques. They can apply both pressure or tourniquets.
2. Pressure volunteers: some laypersons that are willing to help by only applying pressure.
3. Tourniquet volunteers: a small group of laypersons that are willing to apply either pressure and tourniquets.
4. Common people: those who are not injured and do not want to help. After realizing that an explosion has just taken place, they try to leave the incident by hiding inside a building or running through another street

Bleeding control kits are placed in different locations of the street, such locations are going to vary in order to evaluate different location strategies. Tourniquet volunteers will try to find such locations with the aim of picking up a tourniquet. It is assumed that nobody knows the locations of the bleeding control kits. In the meantime, trained people and pressure volunteers will move to the explosion zone and provide pressure application to the victims, in order to reduce the bleeding rate, while waiting for the arrival of tourniquets. Once a volunteer picks up a tourniquet, he will go to the explosion zone and look for the most serious victim so far who needs a tourniquet. Three different options might happen at that moment:

- The victim was not receiving pressure before the arrival of the tourniquet. The volunteer carrying the tourniquet is going to apply it.
- The victim was receiving pressure by a trained before the arrival of the tourniquet. The trained is going to apply the tourniquet while the volunteer who brought it applies pressure to the wound.
- The victim was receiving pressure from a volunteer before the arrival of the tourniquet. The volunteer applying pressure keeps doing it while the other volunteer applies the tourniquet.

Moreover, there is a possibility of not correctly apply a tourniquet depending on whether the person applying it is a trained or a volunteer. If someone fails to correctly apply a tourniquet to a victim, the victim is going to start bleeding again and is going to need, once more, pressure application or another tourniquet. The reasons that could lead to failure when applying a tourniquet are out of the scope of this project, and therefore, have not been modelled. Other things that neither have been modelled are the materials included in the real bleeding control kits, such as gloves, compressive bandage, etc. nor the possibility of being the tourniquet broken before using it.

If there are not tourniquets left at the first bleeding control kits location, the volunteer is going to look in the next location closer to him. If there are not tourniquets lefts at the second bleeding control kits location, the volunteer is going to give up and leave the incident. After a volunteer wrongly applies tourniquet, he is going to leave the incident. Regardless of wrongly or correctly applying a tourniquet, a percentage of the trained are going to remain in the incident in order to help other victims.

After some time since the bomb explodes, the first group of ambulances, between one and two, is going to arrive. More groups of ambulances are going to arrive at the incident with an estimated interarrival time between them. To simplify, how emergency responders help the victims have not been modelled, it has been considered that emergency responders need between 5 and 6 minutes to locate the victims, help them and take them to the ambulance.

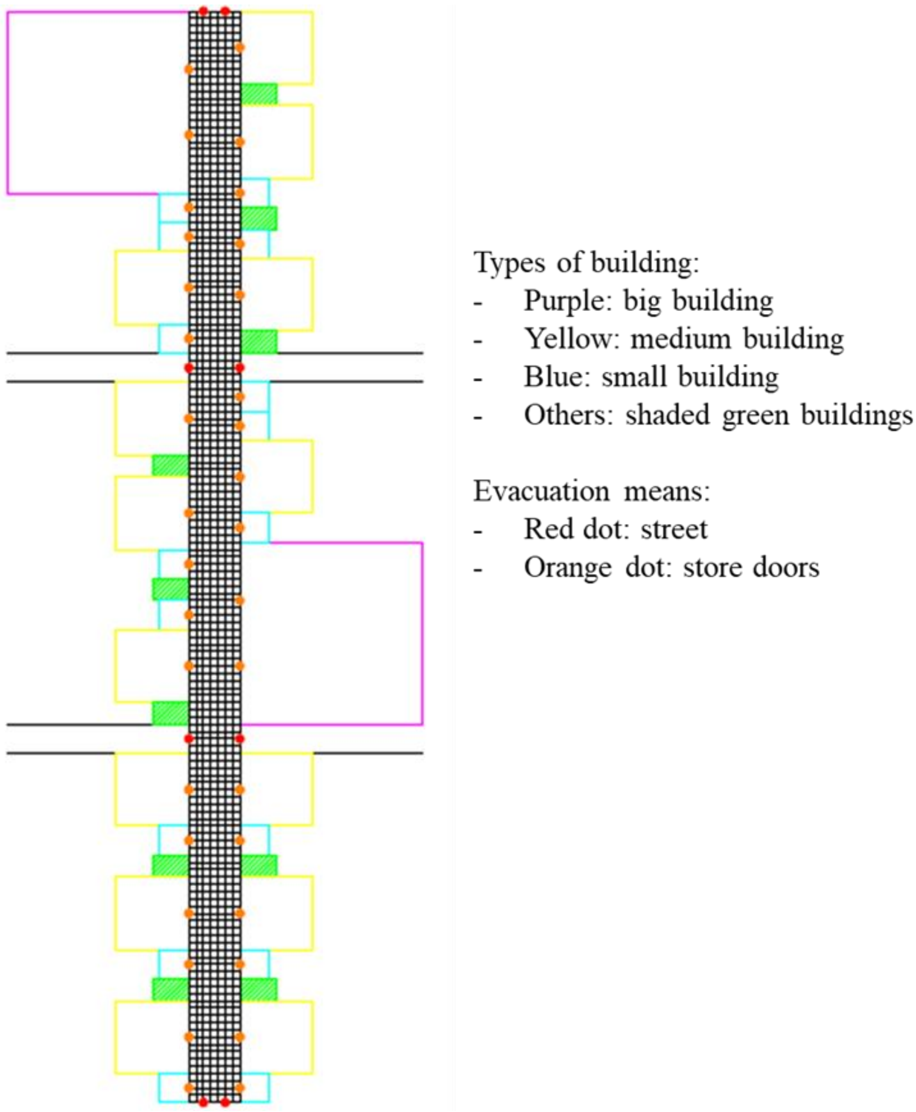
The scenario ends when the last victim, with bleeding injuries, that needs help dies, leaves in an ambulance or receives a tourniquet.

4.2.1 Commercial area features

After evaluating different real pedestrian streets, the features to consider on the simulation model were chosen. The simulated pedestrian street does not represent a specific real street but the most common features found among the different pedestrian streets evaluated. To simplify, those streets with one or more driveways have been discarded because simulating the movements of cars is not relevant in this study.

The street simulated represents a pedestrian street of a commercial area of 14 meters width and 300 meters in length. In addition, two secondary streets of 8 meters width intersect perpendicularly with the main street, see the Figure 4.1 below:

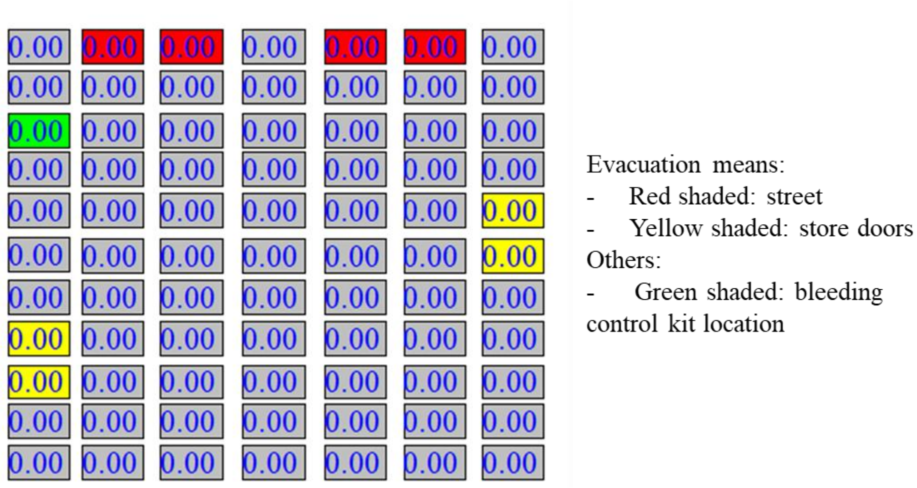
Figure 4.1. Street layout.



There are two ways of evacuating the street, hiding inside stores or running through a secondary street. To simplify, eight different points of evacuation have been defined in the simulation model (red dots). Furthermore, the doors of the stores are represented for each building (orange dots).

Neither the buildings nor the secondary streets that intersect perpendicularly with the main street have been modelled. Instead, the zones in the grid between the mentioned dots have been shaded in different colors (Figure 4.2).

Figure 4.2. Animation of the simulation model.



To know the types of buildings to consider and reasonable distribution of them along the simulated scenario, two known Spanish pedestrian streets located in commercial areas were studied. By using Google Earth, the types of buildings and percentage of them were estimated and classified for the following pedestrian streets: Preciados (Madrid, Spain) and Don Juan de Austria (Valencia, Spain).

Table 4.2 includes a summary of the types of buildings and distribution considered in the simulation model:

Table 4.2. Types of buildings and distribution.

Type of building	Area (m2)	Included buildings	Total	Percentage (%)
Big	≥ 400	Department store	2	4.65
Medium	200	Restaurants and medium retail shops	14	32.56
Small	30	Bars/Cafeterias and small retail shops	17	39.53
Others	-	Residential buildings and offices	10	23.26
		Total	43	100

Furthermore, the number of doors of each building has also been considered. All building types have one door, expect for big buildings that have two doors and the buildings classified as "Others" which are not accessible.

4.2.2 Density, location and movement of people

The number of people considered, the different ways to locate them and how movements are performed in the simulated scenario are explained below:

Density of people

For estimating the density of people that could be in a regular day of a pedestrian street, it was necessary to know the area (m2) of the pedestrian street and the area required per person (m2/pers).

The area required per person (m2/pers) has been based on the pedestrian Level of Service (LOS). The Highway Capacity Manual (2020) defines pedestrian LOS as a qualitative measure that expresses the level of satisfaction perceived by pedestrians in a street depending on the comfort, convenience, safety, security, and economy of the walkway system.

In the following Table 4.3 are the specifications of each LOS:

Table 4.3. Pedestrian Level of Service description.

LOS	Pedestrian space (m2/pers)	Flow rate (pers/m/min)	Description
A	> 5.6	≤ 16	Pedestrians move in desired paths, walking speeds freely selected, unlikely conflicts between pedestrians
B	> 3.7 - 5.6	> 16 - 23	Walking speeds freely selected, posibility of bypass other pedestrians, crossing conflicts are avoidable, pedestrians aware of the presence of others
C	> 2.2 - 3.7	> 23 - 33	Normal walking speeds, bypassing in primarily unidirectional streams, minor conflicts with reverse direction or crossing movements
D	> 1.4 - 2.2	> 33 - 49	Restricted walking speeds and bypassing, high probability of conflict with reverse direction or crossing movements, frequent changes in speed and position, friction and interaction is likely
E	> 0.75 - 1.4	> 49 - 75	Restricted walking speeds, might be possible forward movement, insufficient space for passing pedestrians, extreme difficulties with reverse direction or crossing movements, stoppages and interruptions of flow
F	≤ 0.75	Variable	Severly restricted walking speeds, forward movement by shuffling, unavoidable contact, reverse or crossing movements are impossible, sporadic and unstable flow, queued pedestrians

Source: Transportation Research Board. (2020). *Highway Capacity Manual.* United States of America: National Research Council.

By choosing level D and assuming a uniform distribution, UNIF(1.4, 2.2) m2/pers, all the values between 1.4 and 2.2 have the same probability of occurring.

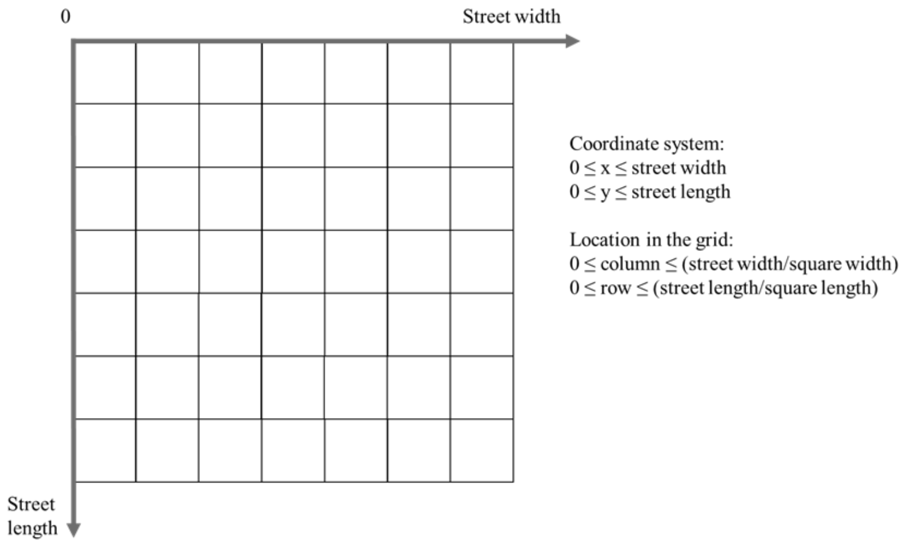
Finally, the following expression has been used for calculating the number of people in the street:

$$People\ in\ the\ street = \frac{Street\ length\ (m) \cdot Street\ width\ (m)}{UNIF(1.4, 2.2)(m2/pers)}$$

Location of the people

There are two ways of locating the people in the simulated pedestrian street, by using both a coordinate system and a location in a grid (Figure 4.3).

Figure 4.3. People's location.



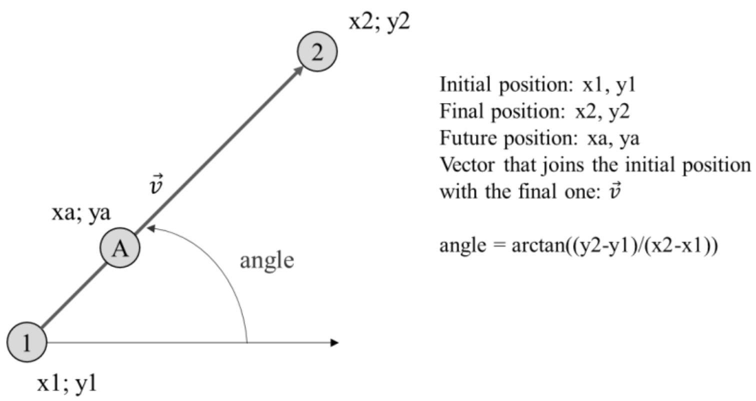
The first one consists of a coordinate system location, each person, represented by an entity, has the x and y values of their current position. The x and y values depend on the street configuration; therefore, the x values can vary between [0, street width] while the y values can vary between [0, street length].

The second way of locating people in the street consists of locating each entity on a grid. Such a grid consists of squares of 4 meters area distributed along the entire street. The number of zones depends on the street configuration; therefore, the column values can vary between [0, street width/zone width] while the row values can vary between [0, street length/zone length].

Movement of people

By knowing the current position and final position in a coordinate system, the movement of people is performed using vectors (Figure 4.4). Once the initial and final position is known, the direction is calculated, which is the angle of the vector with respect to the x-axis.

Figure 4.4. Movement of people.



The future position is calculated by considering a step length of one meter by using the following formulas:

$$x_a = x_1 + Step\ Length \cdot \cos(angle)$$

$$y_a = y_1 + Step\ Length \cdot \sin(angle)$$

The number of steps needed to walk from the initial position to the final position is calculated as the module of the vector divided by the step length. Every time someone takes a step, they need one less step to reach the final position.

The running speed of the people is simulated as a function of the density of the people in the future zone. This means that, before the person moves, the density of the people in the future zone is going to be checked, and depending on it, the person will move at a specific speed. The ranges of density and running speed of Table 4.4 have been based on the research done by Prytz et al. (2019). The running speed has been calculated multiplying by three the values used in the research done by Prytz et al. (2019). This assumption has been done following a study that suggests that a fast running to escape from a hazard event is around 3.85 m/s (Yosritzal, Kemal, Purnawan, & Putra, 2018). Furthermore, Sterken (2003) modelled the different running speeds from people participating in a marathon as a function of age, sex, and distance. The outcome was also that the average running speed of male adults was around 4 m/s (Sterken, 2003) However, in the model is included the time needed to perform the movement, in this case, to take a step. The time needed for taking a step depending on the density of the future zone is also attached below:

Table 4.4. Speed of movement as a function of the density.

Density (pers/m2)	Running speed (m/s)	Time to move (s)
≥ 0 to ≤ 1	TRIA(2.4, 3.9, 4.5)	Step length/TRIA(2.4, 3.9, 4.5)
> 1 to ≤ 2	TRIA(2.1, 2.4, 2.7)	Step length/TRIA(2.1, 2.4, 2.7)
> 2 to ≤ 3	TRIA(1.2, 1.5, 2.1)	Step length/TRIA(1.2, 1.5, 2.1)
> 3 to ≤ 4	TRIA(0.9, 1.2, 1.5)	Step length/TRIA(0.9, 1.2, 1.5)
> 4 to ≤ 5	TRIA(0.6, 0.9, 1.2)	Step length/TRIA(0.6, 0.9, 1.2)
> 5 to ≤ 6	TRIA(0.3, 0.6, 0.9)	Step length/TRIA(0.3, 0.6, 0.9)
> 6 to ≤ 7	TRIA(0.15, 0.3, 0.6)	Step length/TRIA(0.15, 0.3, 0.6)
> 7	TRIA(0.09, 0.15, 0.3)	Step length/TRIA(0.09, 0.15, 0.3)

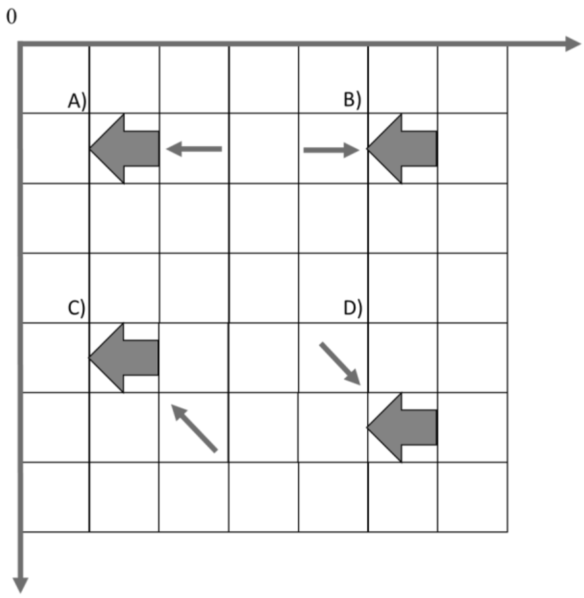
Source: Based on Grönbäck, A.-M. (2019, October 3). Effekten av tourniquetplaceringar vid en större skadehändelse. *Linköping University*.

Another consideration done is an increase in the "time to move" by comparing the direction of movement. The average angle of movement of the people in each zone of the grid is calculated in order to compare it with the direction of another person that is going to move to that zone. There are going to be different time penalties regarding the relationship between directions of movement. Following Figure 4.5 where the big arrow represents the average direction of the people and the small arrow the direction of a person that is going to move to the other zone:

A) The person that is going to move to the other zone and the people already there moves in the same direction. The penalty is equal to 1.
B) The person that is going to move to the other zone and the people already there moves in the opposite direction. The penalty is equal to 1.5.
C) The person that is going to move to the other zone and the people already there moves in the same direction with a deviation on the horizontal axis. The penalty is equal to 1.2.

D) The person that is going to move to the other zone and the people already there move in the opposite direction and with a deviation on the horizontal axis. The penalty is equal to 1.3.

Figure 4.5. Movements direction comparison.



Finally, the time that each person needs to move is calculated as follows:

$$Total\ time\ to\ move\ (s) = time\ to\ move(s) \cdot direction\ penalty$$

Every time a person takes a step, the density of people in the future zone is calculated as well as the total time needed to move. A person knows that he has arrived at the destination when they do not have steps left to take.

4.2.3 Types of people

In the simulation model, the people have been classified into four different groups:

- Common people: people that were walking around the commercial area and are not injured after the bomb explosion. They are not willing to help injured people.
- Volunteers: also known as laypersons, those who are willing to help the injured people but they have knowledge neither in first aid nor bleeding control techniques.
- Trained: either medical staff or someone who has taken a course on bleeding control techniques.
- Injured: people that have been injured because of the bomb explosion.

Estimating the percentage of people to include in each group is one of the most challenging assumptions of the model. Despite there are several studies that aim to estimate the percentage of people that would help after an incident, most of them are based on surveys which are considered as an unreliable tool.

As information gathered from previous incidents is considered more reliable than a survey, some research about the use of tourniquets and AEDs by bystanders has been done. Ashour et al. (2007) found that only 12 (10.7%) victims out of 112 victims analyzed who suffered an OHCA receive first aid or a cardiopulmonary resuscitation from bystanders. Schroll et al. (2015) analyzed a total of 197 persons who arrived at a trauma center with a prehospital tourniquet in the period from January 2010 to December 2013. They found that 20.3% of the patients admitted had an improvised tourniquet placed either by themselves or a bystander. However, considering that the aim is to simulate a MCI, the threatening environment and the extent of the event is different from the cases stated before, most of the people will be scared due to the uncertainty of secondary incidents happening. Therefore, fewer people are going to be willing to help the victims.

Due to what is stated above, the percentage of volunteers is included as a variable parameter (input) which has been tested in the sensitivity analysis. Initially, the value considered was 4.5 % and later, in the sensitivity analysis that value was reduced and increased.

While the information about the percentage of people that would help is not reliable to take it from a survey, the percentage of trained people is useful to get it from that type of source. The Hartford Consensus (2017) carried a survey to 1051 randomly picked individuals. Some interesting results were that 47% of the people took a first aid course at some time, and 72% of those included bleeding control techniques. With that information, the percentage of trained people is 33.84% but only 13% of them took the course in the last two years. Because it is demonstrated that the ability to apply bleeding control techniques after a one-hour course decreases after a certain time without retaking the course (Goralnick, et al., 2018), only those who took it in the last two years are going to be included. By rounding up, it ends to 5% of trained people in bleeding control techniques in the last two years.

Attending to the difficult nature of the hazard event involved and the difficulty to be managed, the percentage of trained people considered has been reduced to 1.5%. Such value is also included as a variable parameter (input) which is going to be tested in the sensitivity analysis.

Finally, the percentage of common people is calculated using the following formula:

$$Common\ (\%) = 100 - trained(\%) - volunteer(\%)$$

The percentage of injured people depends on the bomb features, which is explained in the next subchapter.

4.2.4 Bomb explosion

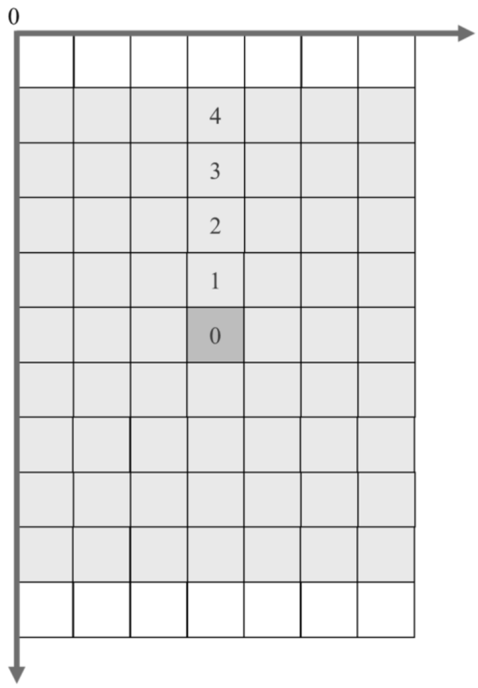
The scenario simulated consists of a bomb detonation, possible secondary detonations have not been modelled in order to simplify. The bomb can be placed in the center of any of the zones of the grid, all of them have the same probability. Because of that, a uniform distribution has been used to place randomly the bomb in a location defined by a column and a row, UNIF(1, street width/zone width) and UNIF(1, street length/zone length) respectively.

Modelling the effects of a bomb is a difficult issue because as said before, they depend on the bomb features and location. In order to reduce the variability of the model, it has been assumed that the effects of the bomb simulated could correspond to small bombs like a bomb located in a backpack, briefcase or pipe bomb (Lamar University, n.d.). In order to consider the possible effects of different bombs, the simulation generates bombs of four different magnitudes, in Figure 4.6 is an example of bomb magnitude 4:

A) Bomb magnitude 4 (9 m radius): central zone (zone 0) and four adjacent zones to it affected.
B) Bomb magnitude 5 (11 m radius): central zone (zone 0) and five adjacent zones to it affected.
C) Bomb magnitude 6 (13 m radius): central zone (zone 0) and six adjacent zones to it affected.
D) Bomb magnitude 7 (15 m radius): central zone (zone 0) and seven adjacent zones to it affected.

It is important to remark that in the model it is assumed that the buildings are not affected by the detonation.

Figure 4.6. Bomb magnitude 4 example.



If the position of someone is the same as where the bomb is located (zone 0), the person automatically dies. The further the people are from zone 0, less amount of people are going to die but they are going to be injured whether they are inside the bomb radius. Meanwhile, in the outer zones affected by the explosion (zone 4 in Figure 4.6), nobody is going to die, all the people will be injured.

The percentage of death people and injured people per zone affected is calculated as follows:

$$Death(\%) = \frac{\left(\frac{100}{Bomb\ Magnitude}\right) \cdot i}{2}; \quad i = 1, 2, \ldots (Bomb\ Magnitude - 1)$$

$$Injured(\%) = 100 - Death(\%)$$

Where “i” represents each zone affected by the bomb explosion.

It has been assumed that all bomb magnitudes have the same probability of occurring.

Detection time

The detection time is the time elapsed since the event starts until someone realizes that something has happened (Boverket, 2006). It is difficult to estimate it because several facts can influence the reaction time of each person, for example: the sound of an alarm, people screaming or running, etc.

The detection time for the blast incident has been calculated by estimating the time that the sound needs to travel from the bomb location to the location of a person. For that reason, the formula used calculates the module of the vector that joints the bomb coordinates with the person coordinates and divide it by the speed of the sound:

$$Detection\ time(s) = \frac{module\ of\ the\ vector\ (m)}{340\ m/s}$$

Reaction time

The reaction time is the time elapsed since someone realizes that something is happening and knows what is truly happening, for example, understands that there is a fire, a shooting, an accident, etc. (Boverket, 2006).

Boverket (2006) shows different reaction times to fires regarding the situation considered. The reaction time for a person who sees the fire in a public environment is 1 minute. Considering the nature of the event simulated and that there could be differences that might affect the reaction time, for example, not being able to see the explosion. A triangular distribution has been considered TRIA(0.5,1,1.5) minutes for common people and volunteers. The same distribution has been considered for trained but with lower values, TRIA(0.25,0.5,1) minutes.

Location time

The location time is defined for this particular project as the time needed for each person to identify where the tourniquet cabinet is located in the street. Despite the type of person, it is assumed that nobody truly knows where the cabinets are located in the street. The distribution chosen is based on the values used in the previous research: TRIA(1,1.25,1.5) minutes (Grönbäck, 2019).

Triage time

The triage time is defined for this project as the time needed for each person to identify which is the most serious victim so far that needs aid. This time has been assumed to be equal to the location time TRIA(1,1.25,1.5) minutes for trained and slightly higher for volunteers, TRIA(1.25,1.5,1.75) minutes.

4.2.5 Bleeding injuries

Assuming that the total weight of an adult is around 70 kilograms and that the estimated blood volume is 7% out of the total weight, an adult has a total of 5 liters of blood. A life-threatening bleeding starts when the blood loss is over 40% (Parra M, 2011). Without life-saving measures and a blood loss of over 50%, people are likely to die (Holland, 2018). Therefore, in the simulation model when a person bleeds out more than 2.5 liters of blood it is considered as death.

On the other hand, there are different bleeding stages defined with regard to the blood loss (Holland, 2018; Riddez, 2017) while based on other studies it was possible to estimate the bleeding rates for those stages (Tjardes & Luecking, 2018; Grönbäck, 2019). The information mentioned before is summarized in Table 4.5:

Table 4.5. Bleeding stages.

Stage	Bleeding loss (%)	Bleeding rate (ml/min)
1. Mild	10 to 15	20
2. Moderate	15 to 30	80
3. Severe	30 to 40	200
4. Massive	> 40	400

Source: Based on Holland, 2018; Riddez 2017; Tjardes & Luecking, 2018.

The percentage of injured people included in each stage is a complex assumption to do as there is not a generalized pattern of injuries, and the information of victims from previous incidents is not publicly available. The assumed values are attached in Table 4.6:

Table 4.6. Bleeding injuries percentages.

Stage	Injured percentage (%)
1. Mild	25
2. Moderate	30
3. Severe	30
4. Massive	15

Goolsby et al. (2019) by reviewing different databases and publications, estimated that approximately 40% of the people injured in a MCI could benefit from tourniquet application. As tourniquets are not needed for mild injuries (SAMUR, 2017; Doyle & Taillac, 2008), Goolsby et al. (2019) did not include them in that 40%.

Estimating the total percentage of victims with bleeding injuries needs to be recalculated including mild injuries. Using the values in Table 4.6, the percentage of victims with bleeding injuries is:

$$Bleeding\ injuries(\%) = \frac{40 \cdot 100}{30 + 30 + 15} = 53.333\%$$

4.2.6 People response to the incident

There are several options about how people act in a MCI. However, the ones considered are explained below:

Tourniquet and pressure application

It is demonstrated that not all the volunteers are willing to apply a tourniquet. The Hartford Consensus (2017) after doing the survey explained before, stated that 62% of the volunteers are not willing to apply a tourniquet, and therefore only would apply pressure to reduce the bleeding. In the simulation model is considered that 62% of the volunteers will only apply pressure, while the others are able to apply either a tourniquet or pressure.

A triage time has been considered, as the time spent by the volunteer or trained to find the most injured victim that needs pressure application. The application of pressure to a victim has been modelled considering that the first who arrives at the victim (either a pressure volunteer or a trained) is the one who helps the victim.

It might happen that when a trained arrives to help a victim, the victim is already being helped by a pressure volunteer. In such cases, the trained is going to swap with the pressure volunteer that is helping the worst bleeding victim so far and continue helping the victim himself.

Not every time that either a volunteer or a trained applies pressure or a tourniquet is going to successfully do it. A study carried by Prytz & Jonson (2018) about the ability of trained people to correctly apply a tourniquet, shown that 90% of them successfully applied it. Besides that, another research done by Goralnick et al. (2018) had similar outcomes, demonstrating that 87.7% of the trained people tested correctly applied a tourniquet. Ross et al. (2018) evaluated 195 laypersons' ability to apply tourniquets without previous training, the outcome was that 16.9% successfully applied it. Therefore, in the simulation model is considered that 90% of the trained people apply correctly a tourniquet while for volunteers the percentage is only 16.9%.

The latest experiment done by Prytz & Jonson (2019-2020) consisted of measuring the tourniquet application time needed by both laypersons and trained personnel under calm classroom environments and stressful situations. A triangular distribution has been used in the simulation model based on the statistics provided, tourniquet application time for laypersons TRIA(44.52,67.23,89.94) seconds, and trained TRIA(34.95,45.42,55.89) seconds. Once the tourniquet is applied and the bleeding stopped, there is a time needed to finish the application of the tourniquet. Such time needed to finish the tourniquet application is for laypersons TRIA(11.97,14.71,17.44) seconds and trained TRIA(12.04,13.73,15.41) seconds.

Goolsby et at. (2019) evaluated the ability and willingness of laypersons applying hemostatic dressing, where the application of pressure is essential. Based on the results obtained, only 44% of laypersons are able to apply correct pressure. On the other hand, it seems reasonable to assume that trained people always correctly apply pressure.

When either a trained or volunteer correctly applies pressure, the reduction of the bleeding rate is 40% (Tjardes & Luecking, 2018). Otherwise, when they fail, the reduction of the bleeding rate is assumed to be only 10%.

Locate bleeding control kits

As stated before, not every volunteer that is going to help a victim is willing to apply a tourniquet. Therefore, it has been assumed that only the volunteers that are able and willing to apply a tourniquet are going to be the ones that look for them. It does not seem reasonable to search, pick up a tourniquet, bring it to the explosion zone, and do not want to apply it.

Another assumption done is that all trained people will go directly to the explosion zone to help the victims with pressure application while waiting for the arrival of the tourniquets. It is a waste of time for the trained people to go to search for tourniquets instead of helping the victims.

Firstly, the volunteer that is going to look for tourniquets is going to have a delay time to locate the bleeding control kits cabinet, as explained before “location time”. Each volunteer is going to move to the closest bleeding control kit location, as they still do not know whether there are or not kits left.

Once they arrive at the bleeding control kit location, and if there are bleeding control kits left, it takes 15 seconds to the volunteer to open the cabinet and pick up the kit. However, when there are no kits left, it takes between 2 and 4 seconds to realize that there are not any tourniquet in that location, UNIF(2,4) seconds (Grönbäck, 2019).

When there are no bleeding control kits left in the first location checked, the volunteer is going to check the next closest location. If once again there are no kits left, the volunteer is going to give up and leave the incident.

Finally, when a volunteer picks up a tourniquet, they will bring it to the explosion zone. The volunteer prioritizes among all the victims and the one bleeding the most so far will receive the tourniquet. The tourniquet can be applied to the victim either by a trained, who was applying pressure to him before or by the volunteer who was carrying a tourniquet because the person that was applying pressure before was a pressure volunteer.

Evacuation behavior

The first ones that are going to leave the scene of the incident are the common people that have not been injured by the bomb explosion. There are two ways of leaving the street, the first one consists of hiding inside a store before the store closes the doors or running through a street. It is assumed that 40% of the common people will try to hide inside a store, while the other percentage will leave through a street. The main reason for assuming this percentage is because of the lack of information available. The percentage has been evaluated by increasing and decreasing it showing no significant changes in the outputs. This could be because of the number of people considered in the street. If the street was more crowded, more differences would be noticed in the outputs.

It is also hard to estimate the time elapsed between the bomb explosion and the doors of the stores close due to the lack of information. In order to move on with the research and to simplify it has been assumed that all the doors close at the same time, which is 145 seconds after the bomb detonation. Lower and higher values have been tested before assuming such a value, it was possible to see that the variations affected mainly to the number of bleeding control kits picked up when they were placed in inside buildings.

A person that wants to hide inside a store is going to run to the closest door. However, it is possible that when the person arrives the door is closed. In such a case, the person is going to leave through a street.

On the other hand, when there are not victims left who need help, it is assumed that 50% of the trained people are going to remain in the scene to help in other tasks such as triage, evacuation of the victims, etc. (Grönbäck, 2019). Moreover, they could help a victim to which a tourniquet was previously wrong applied by applying pressure or even another tourniquet again.

It is assumed that every time a volunteer wrongly applies a tourniquet is going to leave the scene through a street.

4.2.7 Emergency medical services

The emergency medical services have been modelled as ambulances that arrive at the scene and provide help to those bleeding victims who have not been helped yet and lost more blood so far. It is assumed that each ambulance can help 2 victims.

To simplify, instead of implementing the mechanisms used to help the victims, each medical responder needs a fixed time to find the victim, provide help and take it to the ambulance. Autrey et al. (2014) analyzed the response of EMS in a mass shooting in Minneapolis (US), in September 2012. By subtracting the departure time and arrival time of the EMS since 911 was called, there was a range between 5 and 6 minutes. Therefore a uniform distribution between 5 and 6 minutes has been considered UNIF(5,6) minutes.

Every time a medical responder helps a victim, the victim is going to survive, the possibility of dying while been helped by them has not been modelled.

The first group of ambulances is going to arrive between 7.2 and 8.2 minutes after the bomb detonation (Andrade, Hayes, & Punch, 2019). It has been assumed that between 1 and 2 ambulances are going to arrive each time. Ambulances will keep arriving at the scene until the last bleeding victim is aided. Such an assumption is based on that in reality, more ambulances than needed arrive at the scene (Erik Auf der Heide, 2006).

Finally, the last assumption done consists of the interarrival time between ambulances which has been assumed as a uniform distribution UNIF(2,3) minutes. The reason for assuming such value comes from the huge variability regarding previous incidents studied by other authors.

The variables explained above have been tested in the sensitivity analysis, as there was a lack of information to estimate them.

The arrival time could be delayed to see the effects of applying tourniquets.

4.3 Number of replications

The method used to determine the number of replications needed to obtain accurate results is known as the "Confidence Interval method". The interval becomes narrower the more replications are made until at some point it meets the needs of the model user (Robinson, 2004).

Based on the results obtained by running the model, the confidence intervals are calculated as follows:

$$CI = \bar{X} + t_{n-1,\alpha/2} \cdot \frac{S}{\sqrt{n}}$$

Where:

$\bar{X} = cumulative\ mean\ calculated\ with\ the\ results\ of\ the\ replications$
$S = Standard\ deviation\ calculated\ with\ the\ results\ of\ the\ replications$
$n = number\ of\ replications$
$t_{n-1,\frac{\alpha}{2}} = value\ from\ Student's\ t - distribution$

To calculate the number of replications based on the formula above, a simply rearrangement is needed:

$$n = \left(\frac{100 \cdot S \cdot t_{n-1,\alpha/2}}{d \cdot \bar{X}}\right)^2$$

Where:

$\mathrm{d} = \text{deviation (\%) of the confidence interval about the cumulative mean}$

The output chosen from the simulation model in order to calculate the number of replications is "Victims who died because of exsanguination". In order to choose the more suitable output that determined the number of replications, the five more important outputs of the model have been selected. Table 4.7 shows the chosen outputs and the deviation calculated between the limits of the confidence intervals to the average:

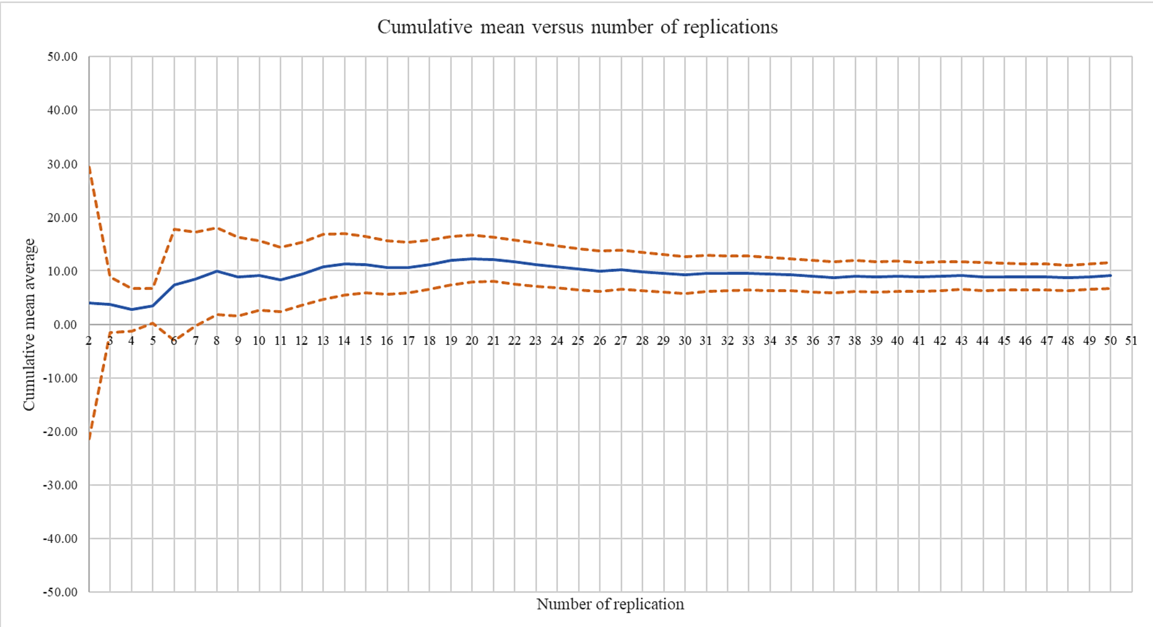
Table 4.7. Deviation of the confidence intervals about the mean.

Output	Average	Half width	Lower interval	Upper interval	Deviation (%)
Victims with bleeding injuries	86.04	6.4	79.64	92.44	7.438
Total number of people who directly die	34.98	3.31	31.67	38.29	9.463
Victims who died because of exsanguination	9.12	2.39	6.73	11.51	26.206
Total number of victims	157.6	11.66	145.94	169.26	7.398
Victims with tourniquet	19.54	0.71	18.83	20.25	3.634

As can be seen above, the output with higher deviation and therefore, variability is the number of victims who died because of exsanguination. For such a reason, this output has been used to calculate the number of replications.

In ***Appendix 1: Confidence interval method*** the values of "victims who died because of exsanguination" for 50 replications are attached as well as the cumulative mean and confidence intervals calculated. The significance level chosen is 5%, which means that there is a 95% probability that the mean is inside the confidence interval. Figure 4.7 beneath depicts the cumulative means and confidence intervals calculated for each replication:

Figure 4.7. Plot of cumulative mean and confidence intervals.



As it can be seen in Figure 4.6, the cumulative mean (solid line) becomes flattered as the number of replications increases. Moreover, the deviation of the confidence intervals (dashed lines) from the cumulative mean (solid line) becomes narrower as the number of replications increases. However, a deviation of 26.04% obtained with the replication 50 (see ***Appendix 1: Confidence interval method***), is not satisfactory to meet the requirements.

Therefore, to calculate the number of replications based on the confidence interval, a simply rearrangement is needed:

$$n = \left(\frac{100 \cdot S \cdot t_{n-1,\alpha/2}}{d \cdot \bar{X}}\right)^2$$

Where:

$\text{d} = \text{deviation (\%) of the confidence interval from the cumulative mean}$

The desired deviation is 10% and with the values obtained with replication 50, the number of replications needed is:

$$n = \left(\frac{100 \cdot S \cdot t_{n-1,\alpha/2}}{d \cdot \bar{X}}\right)^2 = \left(\frac{100 \cdot 8.356 \cdot 2.0096}{10 \cdot 9.12}\right)^2 = 339.02 \approx 340\ replications$$

Obviously, the accuracy of this method depends on the accuracy of calculating the standard deviation and the cumulative mean for the replications performed as well as, indirectly, the number of replications done (Robinson, 2004).

4.4 Bleeding control kits locations

Despite of the population present, Goolsby et al. (2019) estimated that in a mass casualty attack, at least 20 people need hemorrhage control and hence can benefit from tourniquet kits.

In order to evaluate and compare the different bleeding control kits locations, the same number of bleeding control kits have been considered for each scenario, which was 24.

Landmark strategy

Because this strategy seems to be suitable for the location of AEDs in the city of Paris, it is reasonable to test it for this particular scenario. Three different tests have been performed to evaluate different landmarks locations:

- Inside the malls: In reality, some AEDs are placed inside pharmacies, post offices, stores, etc. As the location of malls normally is well known, the effect of placing the bleeding control kits inside them it is interesting to study. Four locations with six bleeding control kits per location have been simulated.
- Outside the malls: In a MCI after a certain time, all buildings will try to close their doors and will not allow people to get inside anymore. For that reason, this scenario has been tested in order to compare it with the one explained before. The same four locations with six bleeding control kits per location have been simulated but were accessible 24/7.
- Well known locations: Such as bike stations, public transport stops and Automated Teller Machines (ATMs). For this experiment, four well-known locations have been tested assuming that three of them are accessible 24/7 while the other one is a pharmacy. A certain time after the bomb detonation, the pharmacy closes its doors and is no longer accessible.

Grid-based strategy

Consists of placing the bleeding control kits with a fixed separation between them. Three different separations have been tested and the same number of tourniquets are going to be considered per location, as can be seen in Table 4.8. It has been assumed that for every fixed distance, there is one cabinet with bleeding control kits:

Table 4.8. Grid-based strategy.

Scenario	Distance between cabinets (m)	Number of locations	Tourniquets per location
GB 50 m	50	6	4
GB 150 m	150	3	8
GB 300 m	300	2	12

Effects of placing bleeding control kits in evacuation routes

To finish the evaluation of different bleeding control kits locations, another four different placements have been also tested.

The first scenario (Two locations) consisted of placing all bleeding control kits in two locations far from the streets used by other people to evacuate the scene. This leads to 12 bleeding control kits per location. The second scenario (Two locations (evacuation routes)) also had two locations but in two evacuation routes, this test aimed to see the effects of picking up bleeding control kits from crowded placements.

The last two scenarios One location and One location (evacuation route) were almost the same as the ones explained above but only one location per test was considered. That leads to 24 bleeding control kits placed in one single location.

To see the coordinates values considered for each scenario see ***Appendix 2: Bleeding control kits coordinates***.

Chapter 5

Results

5.1 Tests performed

The three different tests done with the developed model consisted of: validation and verification, evaluate different bleeding control kits locations and finally, a sensitivity analysis.

It is important to highlight that for validation and verification the bomb magnitude considered was from one to four (the initial values in the model). For such a reason there are so few victims with bleeding injuries and victims who died because of exsanguination. It was possible to perform this test with those values as a statistical comparison was not needed.

However, it was not possible to compare the different bleeding control kits locations using the output of victims who died because of exsanguination with such low value (around 1). For such a reason it was necessary to calibrate the model by increasing the bomb magnitude to values from 4 to 7 (the current values considered) and therefore, the number of victims with bleeding injuries and victims who died because of exsanguination increased.

Finally, the tests done in validation and verification have not been repeated as the model would behave the same but with higher outputs.

5.2 Validation and verification

Due to the complexity and variability of previous real incidents, it is really hard to validate the simulation model with outputs from a real scenario. Therefore, the method used in order to validate the model consists of performing tests where obvious outcomes can be predicted.

First of all, it is necessary to define a "base scenario" for comparing the outputs of the tested scenarios with regards to the ones obtained with the base scenario.

It is important to highlight that this test has been performed with a bomb magnitude varying from one to four. For such a reason there are so few victims with bleeding injuries and victims who died because of exsanguination.

5.2.1 Base scenario 1)

The first chosen scenario for validating the simulation model is based on the Grid-based location strategy. All bleeding control kits are placed in the street, outside the buildings, every 150 meters between one another starting at the beginning of the street. This leads to 6 locations and 4 bleeding control kits per location because, as said before, at least 20 tourniquets are needed (Goolsby, et al., 2019). The values of the inputs for this scenario are the ones defined in ***Chapter 4.1. Conceptual model.***

The outputs of interest to compare with the tests are in Table 5.1 as well as the results obtained for 10 replications:

Table 5.1. Outputs of base scenario 1.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	1.1	1.14	0	5
Victims with tourniquet	14.3	4.78	2	22
Victims who left in an ambulance	19.8	14.15	1	48
Victims who died because of exsanguination	0.9	0.79	0	3

5.2.1.1 Number of bleeding control kits

It is easy to check the effects on the outputs by modifying the number of bleeding control kits in the model. As the number of victims with tourniquets applied should vary depending on the number of bleeding control kits available as well as the number of bleeding control kits not picked up by volunteers.

Four different tests have been performed regarding the number of bleeding control kits over the same locations:

50% more bleeding control kits considered: It is assumed an increase in the number of bleeding control kits available in each location, compared with the base scenario. The initial number of bleeding control kits considered was 24 and in this test is 36 bleeding control kits. An expected outcome would be that more victims receive tourniquets compared to the base scenario.

In Table 5.2 are the results obtained by increasing the number of bleeding control kits available with 50% compared to the base scenario:

Table 5.2. Scenario with many bleeding control kits available.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	4.6	2.81	0	11
Victims with tourniquet	17.6	7.97	2	35
Victims who left in an ambulance	17.3	11.33	1	41
Victims who died because of exsanguination	0.1	0.23	0	1

Comparing with the base scenario, it is possible to see that in this case, the maximum value of victims with tourniquet is 35 whereas in the base scenario was 22. Also, the average number of bleeding control kits not picked up is greater in this case and fewer victims die because of exsanguination, which makes sense as more bleeding control kits than needed are available.

50% fewer bleeding control kits considered: A decrease in the number of bleeding control kits available is assumed in each location, compared with the base scenario. The initial number of bleeding control kits considered was 24 and in this test is 12 bleeding control kits. An expected outcome would be that fewer people receive tourniquets compared to the base scenario.

In Table 5.3 there are the results obtained by decreasing 50% the number of bleeding control kits available compared to the base scenario:

Table 5.3. Scenario with few bleeding control kits available.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	0	0	0	0
Victims with tourniquet	9.7	2.21	2	12
Victims who left in an ambulance	22.3	14.88	1	51
Victims who died because of exsanguination	3	3.37	0	13

In the base scenario the average number of victims with tourniquet is 14.3 and by decreasing 50% the number of bleeding control kits available, the average decreases to 9.7. Obviously, those people who now do not receive a tourniquet leave in an ambulance, therefore the average of such output has increased. Another expected result is that all bleeding control kits are picked up.

Many bleeding control kits available: It is considered an excess of bleeding control kits available in location, which is 15 bleeding control kits per location and 90 bleeding control kits in total. The outcomes of this test should be that the number of bleeding control kits not picked up is greater than in the base model.

In Table 5.4 there are the results obtained by considering 90 bleeding control kits available:

Table 5.4. Scenario with a lot of bleeding control kits available.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	40.2	6.35	20	50
Victims with tourniquet	19.2	8.92	2	36
Victims who left in an ambulance	15.8	10.69	1	40
Victims who died because of exsanguination	0	0	0	0

As was predicted, the average number of bleeding control kits not picked up is much higher than in the base scenario, 40.2 against 1.1. Another expected outcome is that on average more victims receive a tourniquet and therefore, fewer victims die because of exsanguination.

No bleeding control kits available: When no-bleeding control kits are considered in each location, the number of injured people who leave in an ambulance should be higher as well as the number of people who die because of exsanguination.

In Table 5.5 there are the results obtained by considering 0 bleeding control kits available at each location:

Table 5.5. Scenario without bleeding control kits available.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	0	0	0	0
Victims with tourniquet	0	0	0	0
Victims who left in an ambulance	27	13.14	3	51
Victims who died because of exsanguination	8	6.26	0	22

When no-bleeding control kits are available, the average of victims who left in ambulance increases significantly as the only help that victims are receiving is pressure application. All the victims with bleeding injuries either leave in an ambulance or dies because of exsanguination.

5.2.1.2 Bleeding people do not receive help

The effects of considering that nobody is going to aid the victims with bleeding injuries have been tested. Clearly, all the victims die because of exsanguination as they do not receive any help at all. On the other side, nobody is going to look for bleeding control kits, and therefore, are not going to be picked up, which is a total amount of 24 bleeding control kits.

In Table 5.6 are the results obtained by considering that nobody aids the victims with bleeding injuries:

Table 5.6. Scenario where nobody aids.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	0	0	0	0
Total number of volunteers	0	0	0	0
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	24	0	24	24
Victims with tourniquet	0	0	0	0
Victims who left in an ambulance	0	0	0	0
Victims who died because of exsanguination	35	18.89	3	72

As expected, all the victims who had bleeding injuries die because of exsanguination as neither volunteers/trained nor ambulances are considered in this scenario.

5.2.1.3 Nobody has bleeding injuries

When a scenario of people injured but nobody of them has bleeding injuries that could be treated with tourniquet application, the expected results are that the bleeding control kits are going to be picked up but nobody will receive them. Furthermore, nobody is going to leave in an ambulance as the ambulance only loads the victims who have bleeding injuries.

In Table 5.7 there are the results obtained by considering that nobody of the injured victims has bleeding injuries:

Table 5.7. Scenario where nobody has bleeding injuries.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	0	0	0	0
Bleeding control kits not picked up	1.9	1.19	0	5
Victims with tourniquet	0	0	0	0
Victims who left in an ambulance	0	0	0	0
Victims who died because of exsanguination	0	0	0	0

The volunteers that go to look for bleeding control kits do not know the number of victims who need a tourniquet until they arrive at the explosion zone with the bleeding control kit. Therefore, some bleeding control kits are picked up but none of them are applied to victims.

The average number of bleeding control kits not picked up is higher than in the base scenario because when a volunteer picks them up and correctly applies it to a victim, he goes to look for another bleeding control kit. However, when the volunteer does not correctly apply it or nobody needs the bleeding control kit picked up, the volunteer leaves the scene without looking for more.

As expected, the outputs of victims who left in an ambulance and victims who died because of exsanguination are 0.

5.2.1.4 Movement of people

After the bomb explosion, the people that have not been injured and are not going to aid can either leave the scene through the closest street or hide inside the closest building. Both options have been modelled following the same logic and therefore, only one of them has been checked below.

One random entity of the model has been picked up and the coordinates of the current position were given by Arena: x= 4.95906 and y= 29.1739. The behavior of that entity or person is to hide inside the closest building.

The doors coordinates are a fixed and known variable of the model. It is easy to find the distance to every door by calculating the module of the vector that joints the position of the entity with the location of each door. The distance of the entity to each door calculated using an excel sheet is attached beneath in Table 5.8:

Table 5.8. Minimum distance to each door.

Minimum door index	Doors coordinates		Distance to doors (m)	Minimum door index	Doors coordinates		Distance to doors (m)
	x	y			x	y	
1	14	10	21.198	18	0	152	122.926
2	0	16	14.076	19	14	162	133.133
3	0	34	6.920	20	0	166	136.916
4	14	36	11.328	21	0	180	150.908
5	14	50	22.704	22	14	180	151.097
6	0	54	25.317	23	0	214	184.893
7	0	62	33.199	24	14	214	185.047
8	14	64	35.981	25	0	228	198.888
9	0	76	47.088	26	14	228	199.032
10	14	78	49.656	27	0	248	218.882
11	0	90	61.028	28	14	248	219.013
12	14	106	77.356	29	0	262	232.879
13	0	112	82.974	30	14	262	233.002
14	14	114	85.307	31	0	282	252.875
15	14	128	99.239	32	14	282	252.988
16	0	138	108.939	33	0	296	266.872
17	14	142	113.188	34	14	296	266.979

As indicated in the table above, the closest door to the entity is at a distance of 6.920 meters.

By following ***Chapter 4.2.2. Density, location and movement of people***, the angle of the vector, the steps needed and the future position of the entity can be calculated. Table 5.9 shows the results obtained by calculating with Excel and Arena, all decimal digits have been included in order to see that the results obtained in both methods are almost the same:

Table 5.9. Future position calculation.

Tool	Minimum distance (m)	Corrected angle (rad)	Steps needed	x future	y future
Excel	6.919806	2.369779	6.919806	4.242410	29.871312
Arena	6.919806	2.369786	6.919806	4.242405	29.871307

The running speed of the entity has also been validated. The attributes needed have been gathered from Arena and are attached in Table 5.10:

Table 5.10. Time needed to reach the future position using Arena.

Entity's attributes	
Time to move (h)	0.000136
Angle (rad)	2.3698
Density future zone	1.5
Angle future zone (rad)	0.394964

By knowing the density of people in the future position of the entity, the time needed to take a step can be calculated as follows:

$$1 < Density\ future\ zone \leq 2 \rightarrow\ Step\ Length/TRIA(2.1, 2.4, 2.7)$$

However, as explained in ***4.2.2 Density, location and movement of people***, there is also a time penalty which considers the direction of the movement flow of people in the future zone:

$$Direction = Abs(0.394964 - 2.3698) = 1.975\ rad = 113.149\ degrees$$

When the difference of the angles is between 90 and 165 degrees or between 195 and 270 degrees is considered a time penalty of 1.3. Such value corresponds with a perpendicular opposite flow (see ***4.2.2 Density, location and movement of people***, case D))

The time needed to take a step as well as the total time to move, which considers the time penalty, can be seen in Table 5.11:

Table 5.11. Time needed to reach the future position using Excel.

Speed (m/s)	**Time to take a step (s)**	**Total time to move (s)**	**Total time to move (h)**
2.1	0.476190	0.619048	0.000172
2.4	0.416667	0.541667	0.000150
2.7	0.370370	0.481481	0.000134

As seen in Table 5.11 above, the time to move obtained with Arena is between 0.000150 and 0.000134 hours. This means that the value chosen in the triangular distribution by the program is between 2.4 and 2.7 m/s.

Finally, the last test performed to validate the movement of people consisted of just observe the variation on the animation included in the model. At the beginning of the simulation, all entities are placed randomly along the street. After the bomb detonation, as the simulation progresses the animations indicating the number of people in each location vary. It is possible to appreciate that in locations which are neither a door location nor street for evacuating, the numbers decrease until they reach zero. However, the numbers increase for those locations which represent doors or streets for evacuation.

5.2.2 Base scenario 2)

The second chosen scenario is based on the Landmarks location strategy. All bleeding control kits have been located inside the malls. This leads to 4 placements and 6 bleeding control kits per location. It is assumed that the doors of the malls close 145 seconds after the bomb detonation. This means that after that time, no more bleeding control kits can be picked up from inside the malls. Once again, the outputs for this scenario are the ones defined in ***Chapter 4.1. Conceptual model.***

The outputs of interest to compare with the tests are in Table 5.12 as well as the results obtained for 10 replications:

Table 5.12. Outputs of base scenario 2.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	12.6	1.69	9	16
Victims with tourniquet	8.7	2.63	2	14
Victims who left in an ambulance	23.4	14.83	1	53
Victims who died because of exsanguination	2.9	3.15	0	12

5.2.2.1 Doors closed since the beginning

If the doors of the malls are closed since the bomb explosion, a predictable outcome is that no-bleeding control kits would be picked up. Therefore, any victim with bleeding injuries is going to receive a tourniquet and the number of people who die because exsanguination will increase. Finally, the number of people who leave in an ambulance will also be greater.

In Table 5.13 there are the results obtained by closing since time zero the doors of the malls:

Table 5.13. Doors closed since bomb detonation.

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	35.1	5.02	24	44
Total number of volunteers	98.6	11.13	77	115
Total number of victims	62.2	31.57	8	123
Victims with bleeding injuries	35	18.89	3	72
Bleeding control kits not picked up	24	0	24	24
Victims with tourniquet	0	0	0	0
Victims who left in an ambulance	27.6	13.71	3	55
Victims who died because of exsanguination	7.4	5.93	0	22

As was stated before, any victim receives tourniquet application which makes the average of victims leaving in an ambulance grater, from 23.4 to 27.6. Another expected outcome is that the average number of victims who died because of exsanguination increases from 2.9 to 7.4.

5.3 Bleeding control kits location strategies

As explained in ***Chapter 4.3.1. Number of replications***, the output object of interest to determine the number of replications is "Victims who died because of exsanguination" because it is the output with the highest variability. Such output has been also used to evaluate the different locations strategies to find which bleeding control kits location reduces more the number of victims because of exsanguination. Furthermore, this output is directly linked with the number of victims who received a tourniquet because the more tourniquets are applied, the fewer victims die because of exsanguination.

In ***Appendix 3: Bleeding control kits location strategies outcomes*** are shown all the important outputs of the model. In Table 5.14 below are the values of victims who died because of exsanguination for each tested scenario:

Table 5.14. Victims who died because of exsanguination among the different scenarios.

Scenario	Average	Half width	Minimum value	Maximum value
GB 50 m	10.538	1.06	0	51
GB 150 m	10.366	1.04	0	45
GB 300 m	9.954	1.02	0	43
Inside malls	18.105	1.28	0	55
Outside malls	10.631	1.04	0	43
Two locations	9.892	1.04	0	42
Two locations (evacuation routes)	10.224	1.04	0	47
One location	10.119	1.02	0	51
One location (evacuation route)	10.267	1.03	0	47
Well known	11.259	1.11	0	53

At first sight, it seems that the scenario with the lowest number of victims who died because of exsanguination is Two locations. However, a statistical analysis is needed to establish solid conclusions.

5.3.1 Statistical comparison

A suitable statistic approach to establish if a significant difference exists or not over the number of "Victims who died because of exsanguination" obtained among two different scenarios is the paired-t approach (Robinson, 2004). To calculate the confidence interval, it is necessary to use the following formula:

$$CI = \overline{D} \pm t_{n-1,\frac{\alpha}{2}} \cdot \frac{S_D}{\sqrt{n}}$$

Where:

$\overline{D}$ = mean difference between scenarios
S_D = Standard deviation of the difference
n = number of replications (needs to be the same for both scenarios)
$\mathrm{t}_{\mathrm{n}-1,\alpha/2}$ = value from Student's t − distribution

Three different conclusions can be obtained for the chosen level of confidence (Robinson, 2004):

1) If zero is included in the confidence interval, there is no significant difference between the two scenarios (represented by 0 in Figure 5.16).
2) If the limits of the confidence interval are lower than zero, the number of victims of scenario 1 is significantly lower than in scenario 2 (represented by < symbol in Figure 5.16).
3) If the limits of the confidence interval are higher than zero, the number of victims of scenario 1 is significantly higher than in scenario 2 (represented by > symbol in Figure 5.16).

For calculating the confidence intervals between scenarios, the Arena's tool "Output Analyzer" has been used. The confidence intervals obtained between scenarios using a level of confidence of 95% are shown in Table 5.15. Furthermore, Table 5.16 depicts the results from this analysis, where zero represents that there is no statistical difference between the two scenarios compared.

Table 5.15. Paired-t confidence intervals for evaluating location strategies.

Scenario	GB 150 m	GB 300 m	Inside malls	Outside malls	Two locations	Two locations (evacuation routes)	One location	One location (evacuation route)	Well known
GB 50 m	(-0.175,0.519)	(0.262,0.907)	(-8.28,-6.73)	(-0.449,0.263)	(0.288,1)	(-0.0602,0.688)	(0.0455,0.792)	(-0.0602,0.688)	(-1.11,-0.333)
GB 150 m		(0.0869,0.739)	(-8.6,-7.01)	(-0.601,0.0724)	(0.161,0.787)	(-0.197,0.482)	(-0.0899,0.584)	(-0.247,0.445)	(-1.24,-0.541)
GB 300 m			(-9.01,-7.37)	(-1.04,-0.313)	(-0.255,0.377)	(-0.608,0.0676)	(-0.484,0.153)	(-0.631,0.00301)	(-1.66,-0.95)
Inside malls				(6.55,8.17)	(7.29,8.94)	(7.23,8.81)	(7.19,8.86)	(6.88,8.55)	(5.93,7.5)
Outside malls					(0.37,1.11)	(0.076,0.738)	(0.157,0.867)	(-0.00566,0.732)	(-1.02,-0.24)
Two locations						(-0.674,0.0177)	(-0.557,0.104)	(-0.723,-0.0273)	(-1.73,-1)
Two locations (evacuation routes)							(-0.232,0.442)	(-0.408,0.321)	(-1.4,-0.667)
One location								(-0.494,0.198)	(-1.51,-0.771)
One location (evacuation route)									(-1.35,-0.636)

Table 5.16. Results obtained with the paired-t approach.

Scenario	GB 150 m	GB 300 m	Inside malls	Outside malls	Two locations	Two locations (evacuation routes)	One location	One location (evacuation route)	Well known
GB 50 m	0	GB50 > GB300	GB50 < IM	0	GB50 > TWO	0	GB50 > ONE	0	GB50 < WK
GB 150 m		GB150 > GB300	GB150 < IM	0	GB150 > TWO	0	0	0	GB150 < WK
GB 300 m			GB300 < IM	GB300 < OM	0	0	0	0	GB300 < WK
Inside malls				IM > OM	IM > TWO	IM > TWO (ER)	IM > ONE	IM > ONE (ER)	IM > WK
Outside malls					OM > TWO	OM > TWO (ER)	OM > ONE	0	OM < WK
Two locations						0	0	TWO a) < ONE (ER)	TWO < WK
Two locations (evacuation routes)							0	0	TWO (ER) < WK
One location								0	ONE < WK
One location (evacuation route)									ONE (ER) < WK

By statistically comparing pairs of scenarios in Tables 5.15 and 5.16 is possible to see that the worst scenarios are the ones that consider bleeding control kits inside any building. The average number of victims who died because of exsanguination for those scenarios is always statistically higher than in the other scenarios.

On the other side, for the grid-based locations, there are no statistical differences between placing the bleeding control kits every 50 or 150 meters. But the number of victims who die because of exsanguination is statistically higher for the scenarios with locations every 50 and 150 meters than for the scenario that considers placements every 300 meters.

Despite no statistical differences are found when placing the bleeding control kits are placed either in two locations or two locations in evacuation routes (Table 5.16), in Table 5.14 is possible to see that the number of victims who died because of exsanguination is slightly lower when the evacuation routes are avoided. It is possible to see the same behavior in the scenarios where a single bleeding control kit location was considered.

These results have been thoroughly discussed in ***Chapter 6.1.1 Bleeding control kits locations***.

5.4 Sensitivity analysis

The sensitivity analysis is performed in order to evaluate how variations on the model inputs might affect the outputs. This has been done by varying the most uncertain inputs included, those which have been assumed due to the lack of information available (Robinson, 2004).

As there are a lot of model inputs and performing the analysis with 340 replications over all of them would be time-consuming, the sensitivity analysis has been performed with 150 replications. The paired-t approach has been used once again to determine whether there are or not statistical differences between scenarios. When a statistical difference is found for 150 replications, it is ensured that for 340 replications there would also be. However, when no statistical difference is found for 150 replications, it might be due that the confidence interval is not narrow enough. Therefore, the analysis has to be performed once again but with 340 replications before stating that there are no statistical differences.

5.4.1 Base scenario

The whole sensitivity analysis has been performed over the same bleeding control kits location strategy without changing the locations of the cabinets. The base scenario chosen is the one which consists of placing the cabinets in two locations far from the streets used by some people to evacuate. This results in the fact that this scenario is the one with fewer victims who died because of exsanguination.

However, this analysis could have been also performed in the Grid-based strategy and placing the bleeding control kits every 300 meters. This leads to a similar configuration as also two placements are considered and no statistical differences are found between both scenarios.

As the output object of interest to evaluate the different bleeding control kits location strategies was the number of victims who died because of exsanguination, such output has been also used to compare the different variations over the inputs in the sensitivity analysis.

5.4.2 Time to take a step

The time to take a step depends on the density of people in the future zone but at the same time, the lesser time required to take a step, the lesser time a person will be in the future zone. The running speeds for each range of density, have been based on different studies which observed the running speed of people in hazard events or marathons.

Because of that, the sensitivity analysis has been performed by increasing and decreasing the running speed by 60% compared with the base scenario:

Table 5.17. Sensitivity analysis: running speed variation.

Scenario	Average	Half width	Minimum value	Maximum value
Running speed -60%	13.593	1.61	0	43
Base scenario	10.227	1.49	0	33
Running speed +60%	9.533	1.47	0	34

In Table 5.18, the confidence intervals calculated between each pair of scenarios are shown:

Table 5.18. Confidence interval for running speed variation.

Scenario	Running speed -60%	Running speed +60%
Base scenario	(-4.03,-2.7)	(0.215,1.17)
Running speed -60%		(3.36,4.756)

Table 5.18 above shows that the number of victims who died because of exsanguination is sensitive to variations in the running speed of the people. In the scenario with lower speeds, more victims died because of exsanguination because volunteers need more time to move to the bleeding control kits locations as well as for arriving at the explosion zone with them. Furthermore, the time needed for volunteers and trained to arrive at the victims to apply them pressure is higher, and the victims will have lost more blood when they arrive compared with the base scenario.

5.4.3 Maximum blood loss

In the model, someone is considered dead when it losses a total amount of blood greater than 2.5 liters. However, such a value is not realistic because it depends on several factors such as gender, age, physical condition, among others.

The sensitivity analysis has been performed by increasing and decreasing the maximum blood loss by 25% compared with the base scenario:

Table 5.19. Sensitivity analysis: maximum blood loss variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Max blood loss -25%	17.633	1.95	0	49
Base scenario	10.227	1.49	0	33
Max blood loss +25%	10.273	1.5	0	37

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.20. Confidence interval for maximum blood loss variation.

Scenario	Max blood loss -25%	Max blood loss +25%
Base scenario	(-8.17,-6.64)	(-0.393,0.3)
Max blood loss -25%		(6.57,8.15)

As can be seen in Table 5.20, the model is sensitive to small decreases in the total amount of blood that someone can lose before dying. This is because the people bleed at the same rates as in the base scenario, die because of exsanguination faster as they need to lose less amount of blood before dying.

5.4.4 Percentage of trained and volunteers

The number of trained and volunteers are two of the most challenging inputs of the model as it is hard to estimate the number of people that would aid in this kind of incident. The percentage of volunteers is based on researches on previous real incidents, although such value might greatly vary among incidents. While the percentage of trained is based on surveys carried by the Hartford Consensus (2017), which is not very realistic as the hazard environment of the incident is not depicted in a survey.

The percentage of trained considered in the base model was varied ± 50% and the results are included beneath:

Table 5.21. Sensitivity analysis: number of trained variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Trained percentage -50%	15.280	1.53	0	38
Base scenario	10.227	1.49	0	33
Trained percentage +50%	8.760	1.35	0	31

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.22. Confidence intervals for number of trained variation.

Scenario	Trained percentage -50%	Trained percentage +50%
Base scenario	(-5.79,-4.32)	(0.975,1.96)
Trained percentage -50%		(5.74,7.3)

Changes in the percentage of trained considered in the model affect greatly the number of victims who died because of exsanguination. This might be due that the number of victims with bleeding injuries is higher than the number of trained estimated in the base scenario.

The percentage of volunteers considered in the base model was also varied ± 50% (Table 5.23):

Table 5.23. Sensitivity analysis: number of volunteers variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Volunteer percentage -50%	11.813	1.56	0	39
Base scenario	10.227	1.49	0	33
Volunteer percentage +50%	9.713	1.39	0	35

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.24. Confidence interval for number of volunteers variation.

Scenario	Volunteer percentage -50%	Volunteer percentage +50%
Base scenario	(-2.23,-0.948)	(0.0238,1)
Volunteer percentage -50%		(1.47,2.73)

A variation on the number of volunteers makes a significant difference as can be seen in Table 5.24. The reason could be that the number of bleeding control kits picked up depends on the number of volunteers considered. The fewer volunteers are considered in the model, the fewer bleeding control kits are picked up. Therefore, fewer victims have received a tourniquet or even pressure, as a percentage of volunteers also apply pressure.

Other facts that play an important role in this comparison are the success rate. When more trained are considered in the model, more bleeding victims receive tourniquets as the success rate of trained is 90%. If the percentage of trained is reduced, and therefore, more volunteers have to apply tourniquets, fewer victims receive tourniquets because volunteers only have 16.9% of succeeding.

5.4.5 Volunteers who only apply pressure

The percentage of pressure volunteers and the percentage of tourniquet volunteers are linked. The percentage of pressure volunteers is also based on the same survey carried by the Hartford Consensus (2017). While the percentage of tourniquet volunteers is assumed on the basis that both percentages have to sum 100%. All these assumptions make both percentages major inputs to do a sensitivity analysis.

Table 5.25 shows the results of the number of victims who died because exsanguination varying 30% the number of volunteers who apply pressure:

Table 5.25. Sensitivity analysis: volunteers who apply pressure variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Volunteers who apply pressure -30%	10.060	1.48	0	38
Base scenario	10.227	1.49	0	33
Volunteers who apply pressure +30%	11.433	1.57	0	39

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.26. Confidence interval for volunteers applying pressure variation.

Scenario	Volunteers who apply pressure -30%	Volunteers who apply pressure +30%
Base scenario	(-0.362,0.695)	(-1.79,-0.619)
Volunteers who apply pressure -30%		(-2.03,-0.713)

The model is sensitive to increments in the number of pressure volunteers whereas there is not a statistical difference when such input is decreased. Increasing the number of pressure volunteers means a decrease in the number of tourniquet volunteers that are going to pick up bleeding control kits. If fewer bleeding control kits are picked up, fewer bleeding victims receive a tourniquet and therefore, more die because of exsanguination.

On the other hand, the model is not sensitive to decreases on the number of volunteers who apply pressure because there are more people applying pressure (trained and pressure volunteers), while waiting for the bleeding control kits, than bleeding victims.

5.4.6 Reduction of bleeding with pressure application

It has been assumed that when someone correctly applies pressure the reduction on the bleeding rate is 40% whereas when is wrongly applied the reduction is only 10%. These are generalized values gathered from different previous studies. However, it is really hard to estimate this because it depends on the ability of the person applying pressure (e.g. the ability of medical staff is not the same as the ability of a layperson), the type of injury, the amount of blood that the victim is losing, etc.

The change made consisted of increasing and decreasing the bleeding reduction with pressure application a 50% (Table 5.27):

Table 5.27. Sensitivity analysis: bleeding reduction with pressure application variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Bleeding reduction -50%	16.107	1.94	0	49
Base scenario	10.227	1.49	0	33
Bleeding reduction +50%	4.653	0.81	0	20

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.28. Confidence intervals for bleeding reduction with pressure application variation.

Scenario	Bleeding reduction -50%	Bleeding reduction +50%
Base scenario	(-6.57,-5.19)	(4.65,6.5)
Bleeding reduction -50%		(10.1,12.8)

Variations on the bleeding reductions when applying pressure affect significantly the number of victims who died because of exsanguination. This could be because it has been modelled that when a victim receives pressure application and someone arrives with a bleeding control kit, the victims can receive at the same time pressure application and a tourniquet. Such behavior is probably affecting significantly the number of victims who died because exsanguination because the greater is the bleeding reduction, the less probability have the victims to die. At the same time, when someone wrongly applies pressure and the bleeding reduction is 50% decreased, the bleeding reduction is only 5% which is almost nothing.

5.4.7 Bleeding control kits location and triage time

The time needed to find the locations of the cabinets in the street and triage time to prioritize the victims were hard to estimate. The location time is based on previous studies while the triage time is completely assumed. For those reasons, both parameters are really uncertain and susceptible to perform a sensitivity analysis.

The changes made consisted of increasing and decreasing both location and triage time a 50%, and the outcome of victims who died because of exsanguination are in Table 5.29:

Table 5.29. Sensitivity analysis: Bleeding control kits location and triage time variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Location and triage time - 50%	10.153	1.5	0	38
Base scenario	10.227	1.49	0	33
Location and triage time + 50%	10.420	1.46	0	36

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.30. Confidence intervals for bleeding control kits location and triage time variation.

Scenario	Location and triage time - 50%	Location and triage time + 50%
Base scenario	(-0.433,0.58)	(-0.701,0.314)
Location and triage time - 50%		(-0.797,0.264)

As seen in Table 5.29, the average number of victims who died because exsanguination varies slightly when the location time and triage time changes. However, as shown in Table 5.30, there is no statistical difference between scenarios for 150 replications. A sensitivity analysis was performed once again with 340 replications, showing no differences between scenarios.

5.4.8 Success rates

The success rates both for pressure and tourniquet application are based on previous researches carried by different authors. However, in reality, these depend on several factors that have not been considered such as different abilities between medical staff and people who received only one-hour course, success rates depending on the type of bleeding injury, stressful situation, etc.

A variation of ± 25% over the success rates considered in the base scenario for both pressure and tourniquet application has been performed (Table 5.31):

Table 5.31. Sensitivity analysis: success rates variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Success rates - 25%	14.333	1.57	0	42
Base scenario	10.227	1.49	0	33
Success rates + 25%	8.153	1.36	0	32

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.32. Confidence intervals for success rates variation.

Scenario	Success rates - 25%	Success rates + 25%
Base scenario	(-4.7,-3.51)	(1.61,2.54)
Success rates - 25%		(5.58,6.78)

As seen in both Tables 5.31 and 5.32 above, the model is really sensitive to variations on the success rates, especially to decreases. This is because a decrease of 25% means that only 67.5% of trained and 12.68% of volunteers are going to correctly apply a tourniquet. Furthermore, more people are going to wrongly apply pressure too, and therefore, victims bleed faster. This results in an increment of victims who died because of exsanguination.

5.4.9 Ambulances

It is important to not forget that it has been modeled that when a victim is aided by personnel from an ambulance, the victim is going to survive. For this reason, the effects of varying the inputs linked with the ambulances influence greatly to the outcomes of the model.

Arrival and interarrival time

The arrival time of the first group of ambulances and the interarrival time between groups of ambulances have been based on researches done before the development of this project. However, such variables might vary in reality depending on factors such as geographical distance from the incident to the hospitals, time elapsed since the bomb detonation until 911 is called, the possibility of secondary attacks, etc. Because of these reasons, both inputs are susceptible to influence the outputs of the model.

A variation of ± 50% over the arrival and interarrival time considered for the group of ambulances in the base scenario has been done (Table 5.33):

Table 5.33. Sensitivity analysis: arrival and interarrival time variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Arrival and interarrival - 50%	2.973	0.52	0	16
Base scenario	10.227	1.49	0	33
Arrival and interarrival + 50%	17.173	2.02	0	51

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.34. Confidence interval for arrival and interarrival time variation.

Scenario	Arrival and interarrival - 50%	Arrival and interarrival + 50%
Base scenario	(6.06,8.45)	(-7.76,-6.13)
Arrival and interarrival - 50%		(-15.9,-12.5)

As seen above in Table 5.34, variations on the arrival and interarrival time between groups of ambulances generate statistical differences between scenarios. The fewer is the time elapsed between the arrival of groups of ambulances, the more victims are going to be aided in lesser time.

Ambulance per arrival

In reality, the number of ambulances per arrival varies greatly. Comparing previous real incidents, it is observed that normally, more ambulances than needed arrive at the scene. However, it is difficult to generalize how many ambulances could arrive at the same time. For that reason, variations on this input have been tested in order to see the effects on the number of victims who died because of exsanguination.

Table 5.35 shows the number of ambulances considered for each scenario as well as the results of the victims who died because of exsanguination:

Table 5.35. Sensitivity analysis: ambulances per arrival variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Ambulance per arrival 0-1	25.413	2.68	0	61
Base scenario	10.227	1.49	0	33
Ambulance per arrival 2-3	6.293	1.08	0	26

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.36. Confidence intervals for ambulances per arrival variation.

Scenario	Ambulance per arrival 0-1	Ambulance per arrival 2-3
Base scenario	(-16.7,-13.7)	(3.34,4.53)
Ambulance per arrival 0-1		(17,21)

The number of victims who died because of exsanguination is really sensitive to variations on the number of ambulances per arrival. The more ambulances arrive, the more bleeding victims are helped earlier and therefore, fewer victims die because of exsanguination.

Patients helped per ambulance

One of the major assumptions in the model is the number of people that each ambulance aids. Due to the lack of information available, it has been assumed that each ambulance can help two bleeding victims. This input represents a huge uncertainty of the model and is susceptible to perform a sensitivity analysis:

The conditions considered for each scenario and the number of victims who died because exsanguination are attached in Table 5.37:

Table 5.37. Sensitivity analysis: patients helped per ambulance variation.

Scenarios	Average	Half width	Minimum value	Maximum value
One patient per ambulance	19.287	2.3	0	56
Base scenario	10.227	1.49	0	33
Three patients per ambulance	7.027	1.18	0	27

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.38. Confidence intervals for patients helped per ambulance variation.

Scenario	One patient per ambulance	Three patients per ambulance
Base scenario	(-10.2,-7.94)	(2.67,3.73)
One patient per ambulance		(10.8,13.7)

As seen in both Tables 5.37 and 5.38, the number of victims who died because exsanguination is sensitive to variations of the number of patients that each ambulance can aid. This results from the fact that in a few minutes a victim can bleed out and die. The more victims are treated by each ambulance, the fewer victims die.

Time it takes to cure a victim

The time it takes to cure a victim aided by medical personnel from the ambulances has been estimated based on a previous study by Autrey et al. (2014). However, this input is of interest to perform a sensitivity analysis because the time needed to help a victim cannot be generalized based only in one study. This time might vary from event to event and depends on the accessibility to the victims, the degree of the injuries, among others.

A variation of increasing and decreasing 75% the time needed by the EMS to aid the victims has been done and the outcomes are attached below (Table 5.39):

Table 5.39. Sensitivity analysis: time it takes to cure a victim variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Time to cure victim -75%	7.287	1.3	0	36
Base scenario	10.227	1.49	0	33
Time to cure victim +75%	14.753	1.68	0	43

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.40. Confidence intervals for time it takes to cure a victim variation.

Scenario	Time to cure victim -75%	Time to cure victim +75%
Base scenario	(2.43,3.45)	(-4.92,-4.13)
Time to cure victim -75%		(-8.17,-6.77)

As it also happened with the other inputs related to the ambulances, a variation over the time it takes to cure a victim statistically affects the number of victims who died because of exsanguination. Fewer victims die when lesser time is required to cure them as more victims can be helped in a lesser period.

5.4.10 Number of bleeding control kits

The number of tourniquets and therefore, bleeding control kits is the last input analyzed in the sensitivity analysis. Despite using the same number of bleeding control kits while testing different location strategies, it is also interesting to evaluate the effects of changing this input.

Table 5.41 shows the results of the number of victims who died because exsanguination making a change of 20% the number of bleeding control kits available in each cabinet:

Table 5.41. Sensitivity analysis: number of bleeding control kits variation.

Scenarios	Average	Half width	Minimum value	Maximum value
Number of tourniquets -20%	12.507	1.63	0	37
Base scenario	10.227	1.49	0	33
Number of tourniquets +20%	8.540	1.25	0	32

The confidence intervals calculated between each pair of scenarios are shown below:

Table 5.42. Confidence intervals for number of bleeding control kits variation.

Scenario	Number of tourniquets -20%	Number of tourniquets +20%
Base scenario	(-2.86,-1.7)	(1.12,2.25)
Number of tourniquets -20%		(3.29,4.64)

Finally, the number of bleeding control kits available in each cabinet is also an input that statistically influences the number of victims who died because of exsanguination. The number of victims who died because exsanguination is indirectly linked with the number of bleeding control kits available in the scene. The fewer bleeding control kits available, the fewer victims are going to be treated by tourniquet application and therefore, more victims die because of exsanguination.

Chapter 6

Discussion and conclusion

6.1 Discussion

The discussion of the results obtained has been divided into the following four main subchapters:

- Bleeding control kits locations
- Sensitivity analysis
- Limitations
- Future research

Each of them is discussed below.

6.1.1 Bleeding control kits locations

The location strategies are evaluated based on the output that stores the number of victims who died because of exsanguination. The only difference between all the location strategies tested is the placement of the bleeding control kits in each scenario, the other inputs of the model remain equal. Because of that, the following outputs are the same for all scenarios tested: total number of trained, total number of volunteers, total number of victims and victims with bleeding injuries (see ***Appendix 3: Bleeding control kits location strategies outcomes***).

The worst location for placing bleeding control kits is, without any doubt, inside the malls with an average of 18.105 victims who died because of exsanguination. This happens because a certain time after the bomb explodes, the doors of the malls close, and no more bleeding control kits can be picked up. As can be seen in Table 5.16, there is a statistical difference in the number of victims who died because of exsanguination between the scenarios when considering the bleeding control kits inside or outside the malls. The comparison shows that the number of victims is significantly higher when the kits are placed inside the malls. For the other bleeding control kits placements, the differences in the number of victims who died because of exsanguination is not very appreciable, it varies on average from 9.892 to 11.259.

Another important fact to mention is that the second-worst scenario is the one which considers well-known locations. This is due that one of the landmark locations considered is a pharmacy, and a certain time after the bomb detonation, no more volunteers are going to be able to access inside to pick up bleeding control kits, as also happened with the scenario of the kits being inside the malls.

Despite that no statistical differences are shown between placing the bleeding control kits in the streets used by people to evacuate and locations far away from there (Table 5.16), it is possible to see in Table 5.15 that there are slightly fewer victims when the bleeding control kits are not placed in the streets used to evacuate. This behavior would have been more accentuated if it has been considered a higher density of people in the street.

For the Grid-based locations, there is a tendency that more victims die the closer the bleeding control kits are located to each other. As the same number of bleeding control kits are considered for all scenarios, the closer the locations are, the more cabinets are needed and fewer bleeding control kits are placed in each location. When more locations are considered, and less bleeding control kits are located in each one, the possibility of volunteers being close to a cabinet is higher. As bleeding control kits are picked up and the cabinets start to be empty, the harder it is for the volunteers to find more bleeding control kits available as they have to reach the cabinet to know if there is any bleeding control kit left. Furthermore, it has been taken into account in the model that when the volunteers try two different bleeding control kits location without finding kits available, they leave the scene. This has been assumed considering that in a real situation, nobody is going to be eternally looking in every single location considered until a bleeding control kit is found.

The scenarios with fewer victims who died because of exsanguinations left are: grid-based locations with kits every 300 meters, outside the malls, two locations and one location (both far from the streets used by people to evacuate). Among these selected scenarios of minor bleeding victims who died because of exsanguination, the one with a statistically higher number of victims is the scenario where the kits are placed outside the malls.

Finally, it is hard to be absolutely sure about which is the best bleeding control kits location. There are no statistical differences about placing the bleeding control kits based on a grid-based strategy every 300 meters (which leads to two locations), two locations far from the streets and one location. However, the number of victims is slightly lower for the scenario where two locations are considered.

6.1.2 Sensitivity analysis

The sensitivity analysis done shows that the model is rather sensitive to changes in the inputs. Such behavior is probably due to the huge amount of inputs that have been assumed because of the lack of information available.

An important result obtained with the sensitivity analysis is that the number of victims who died because exsanguination is statistically affected by the number of trained and volunteers present in the incident. When more people are skilled in bleeding control techniques and therefore, in tourniquet application, the number of victims who died because exsanguination is significantly reduced.

On the other hand, increasing trained and volunteer's ability to apply both tourniquets and pressure is also important. The lower are the success rates considered in the model, the more people die because of exsanguination.

The time needed to locate the cabinets where bleeding control kits are located as well as the time needed to prioritize among the victims did not show statistical differences when were varied. This means that either the location of the cabinets is known or not, that would not make a great difference in the number of victims that could die because of exsanguination. However, the time needed to locate the cabinets should be a determinant issue. One study shows that a good way of reducing the time needed to find AEDs is place them at visible locations and signal them (Sidebottom, Potter, Newitt, Hodgetts, & Deakin, 2018). Probably the extent of the street simulated is not long enough to test and see a great difference when the location time and triage time are varied.

Despite that changes made in the inputs related to the ambulances generate important variations on the model outputs, a deep analysis is out of this study. This thesis aims to evaluate the effect of including bleeding control kits in public venues and how different locations might affect the outcomes.

Finally, the total number of bleeding control kits considered in the simulation has been based on the study done by Goolsby et al. (2019) which estimates that around 20 tourniquets are needed in a MCI. The sensitivity analysis showed statistical differences when the number of bleeding control kits was varied. This means that the number of bleeding control kits and therefore, tourniquets considered in the model has not been overestimated.

6.1.3 Limitations

The simulation model developed could be classified as a "Throwaway model". The reasons that lead to this classification are mainly that it is a really complex model and highly focused on a specific purpose (Robinson, 2004), which is to evaluate the different bleeding control kits locations strategies. Because of that, it is extremely hard for someone who has not been involved during the development of the model to understand and follow it or even reuse it. Mentioned reasons could be considered as first set of limitations to take into account.

The only way to validate the model was by testing extreme situations were obvious outputs could be predicted, this could be other limitation. It is not possible to validate a model were several inputs have been estimated or even assumed with the results obtained in a previous real MCI. Due to ethical motives, it is not possible to simulate in real life the features considered in the simulation model, observe and compare the results.

On the other hand, some implementations that could be done in the future are:

- Consider a greater extent of the street, currently only 300 meters have been simulated. By increasing the large of the street, it would make more sense to evaluate the effects of higher bomb magnitudes. Furthermore, it would even allow to test in a better way the effects of variating the location time and triage time.
- Currently, the people that evacuate the street either by hiding inside a building or running through another street are not able to change the path they follow based on the density of people in the future zones.
- The problems that could emerge due to a wrongly applied tourniquet have not been modelled.
- Try to consider in some way that people know where the locations are by increasing the running speed or reducing the location time.

The sensitivity analysis done in the most uncertain inputs of the model, shown that the model outputs are quite sensitive to changes in the inputs. The main reason for this could be again that several inputs have been assumed due to the lack of information available. Another reason also could have been that an attempt to develop a model as complete as possible finally lead to a model not as robust as expected. If more time would have been available, some simplifications could have been implemented and fewer inputs assumed, which would have improved the model.

6.1.4 Future research

In addition to the implementations mentioned in the previous chapter, it would be interesting to develop a simulation model where different MCIs could be tested, such as shootings, bombs detonations and vehicle ramming. In a future research, that type of model would be useful to evaluate in which situations are more suitable for the use of bleeding control kits.

Apart from studying the benefits that tourniquets can offer in the civilian context, it would also be interesting to do further research about the disadvantages too. For example, what happens when a bystander wrongly applies a tourniquet and the victim suffers more pain.

Finally, another interesting issue to study is how the application of tourniquets by bystanders in an early first aid before the arrival of the EMS could affect the trauma chain of survival. An important consideration is that extensive use of a tourniquet for more than two hours could lead to other lesions (Doyle & Taillac, 2008).

6.2 Conclusion

This master's thesis has demonstrated that it is possible to evaluate different bleeding control kits location strategies using a simulation model. The developed model in Arena reads the inputs from an excel file, this allows all model users to be able to modify the inputs without knowing exactly how the model has been programmed. After running the model, it is possible to visualize in the screen all the outputs for the specified inputs.

It has been demonstrated that the availability of bleeding control kits in a public venue, in this case a pedestrian street, could reduce the number of casualties due to exsanguination after a MCI.

The number of bleeding victims after a bomb detonation depends on a great number of factors and therefore, the variability from one incident to another is high. In the intent of reducing the variability in the model and simplifying, it has been assumed that the bomb range considered (maximum 30 meters) corresponds to a bomb that could be located inside a backpack or briefcase. Higher magnitudes could be considered by simply changing the input on the excel file.

Furthermore, something important to highlight about the sensitivity analysis is that the presence of people with knowledge about bleeding control techniques is essential to reduce the number of victims.

Finally, for the simulated scenario, fewer locations with a higher number of bleeding control kits per location seem to be more suitable to reduce the number of casualties because of exsanguination. Furthermore, locations susceptible to be used as evacuations routes should be avoided due to the congestion that might be formed.

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Appendix 1: Confidence interval method

The table beneath shows the cumulative means and confidence intervals for each replication performed with the base simulation model. The results correspond with the output named "Bleeding people number output" and a significance level of 10%:

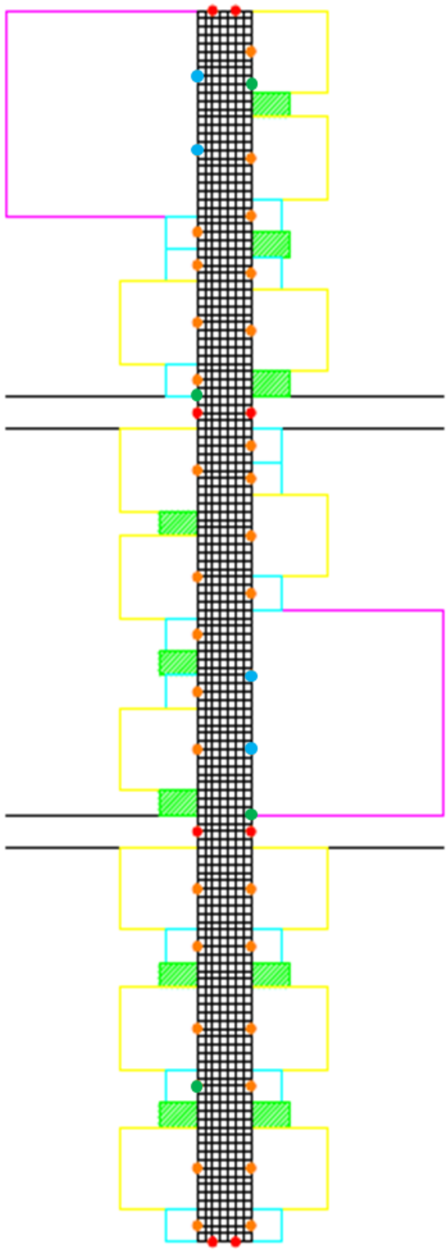
Replication	Result	Cumulative mean	Standard deviation	Confidence interval		Deviation (%)
				Lower interval	Upper interval	
1	2	2.000	n/a	n/a	n/a	n/a
2	6	4.00	2.83	-21.41	29.41	635.31
3	3	3.67	2.08	-1.50	8.84	141.03
4	0	2.75	2.50	-1.23	6.73	144.66
5	6	3.40	2.61	0.16	6.64	95.23
6	27	7.33	9.91	-3.07	17.74	141.86
7	15	8.43	9.50	-0.36	17.22	104.26
8	20	9.88	9.70	1.76	17.99	82.14
9	1	8.89	9.55	1.55	16.23	82.54
10	11	9.10	9.02	2.64	15.56	70.94
11	1	8.36	8.90	2.38	14.34	71.51
12	21	9.42	9.24	3.55	15.29	62.34
13	27	10.77	10.10	4.67	16.87	56.68
14	17	11.21	9.85	5.53	16.90	50.70
15	10	11.13	9.49	5.88	16.39	47.22
16	3	10.63	9.39	5.62	15.63	47.11
17	10	10.59	9.10	5.91	15.27	44.17
18	21	11.17	9.16	6.61	15.72	40.79
19	25	11.89	9.45	7.34	16.45	38.30
20	19	12.25	9.34	7.88	16.62	35.67
21	10	12.14	9.11	8.00	16.29	34.16
22	1	11.64	9.20	7.56	15.72	35.07
23	0	11.13	9.31	7.10	15.16	36.19
24	1	10.71	9.34	6.76	14.65	36.84
25	1	10.32	9.35	6.46	14.18	37.39
26	1	9.96	9.34	6.19	13.73	37.87
27	15	10.15	9.21	6.50	13.79	35.90
28	1	9.82	9.20	6.25	13.39	36.33
29	0	9.48	9.22	5.98	12.99	36.98
30	1	9.20	9.19	5.77	12.63	37.30
31	19	9.52	9.20	6.14	12.89	35.48
32	11	9.56	9.06	6.30	12.83	34.15
33	9	9.55	8.92	6.38	12.71	33.12
34	5	9.41	8.81	6.34	12.49	32.68
35	4	9.26	8.73	6.26	12.26	32.40
36	0	9.00	8.74	6.04	11.96	32.87
37	0	8.76	8.75	5.84	11.67	33.31
38	19	9.03	8.79	6.14	11.91	32.00
39	1	8.82	8.77	5.98	11.66	32.21
40	15	8.98	8.71	6.19	11.76	31.03
41	5	8.88	8.62	6.16	11.60	30.65
42	13	8.98	8.54	6.32	11.64	29.64
43	15	9.12	8.49	6.50	11.73	28.65
44	0	8.91	8.50	6.33	11.49	29.00
45	9	8.91	8.40	6.39	11.44	28.32
46	5	8.83	8.33	6.35	11.30	28.02
47	8	8.81	8.24	6.39	11.23	27.46
48	2	8.67	8.21	6.28	11.05	27.50
49	18	8.86	8.23	6.49	11.22	26.69
50	22	9.12	8.36	6.75	11.49	26.04

Appendix 2: Bleeding control kits coordinates

In the Table shown below are the coordinates of the bleeding control kits location consider for each scenario, while in the Figures each location is marked with a dot:

Bleeding control kits locations	Coordinates	
	x	y
Inside/Outside malls	0	16
	0	34
	14	162
	14	180
Well known	14	18
	0	94
	14	196
	0	262
GB 50 m	0	0
	14	50
	0	94
	14	150
	0	196
	14	250
GB 150 m	0	0
	14	150
	0	300
GB 300 m	0	0
	14	300
Two locations	0	170
	14	120
Two locations (evacuation route)	13	96
	1	202
One location	0	150
One location (evacuation route)	13	96

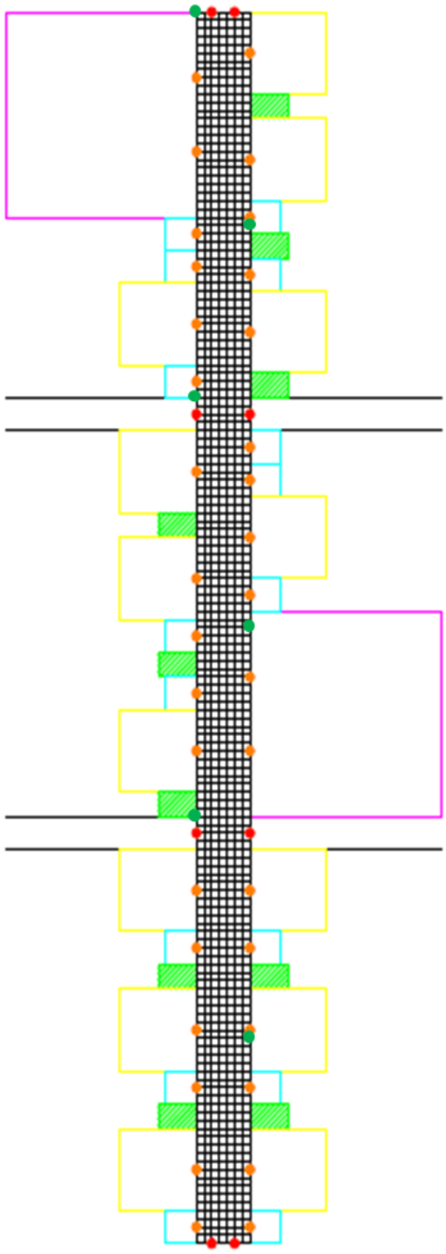
Landmark strategy:



Bleeding control kits locations:

- Blue dots: inside/outside malls
- Green dots: well known

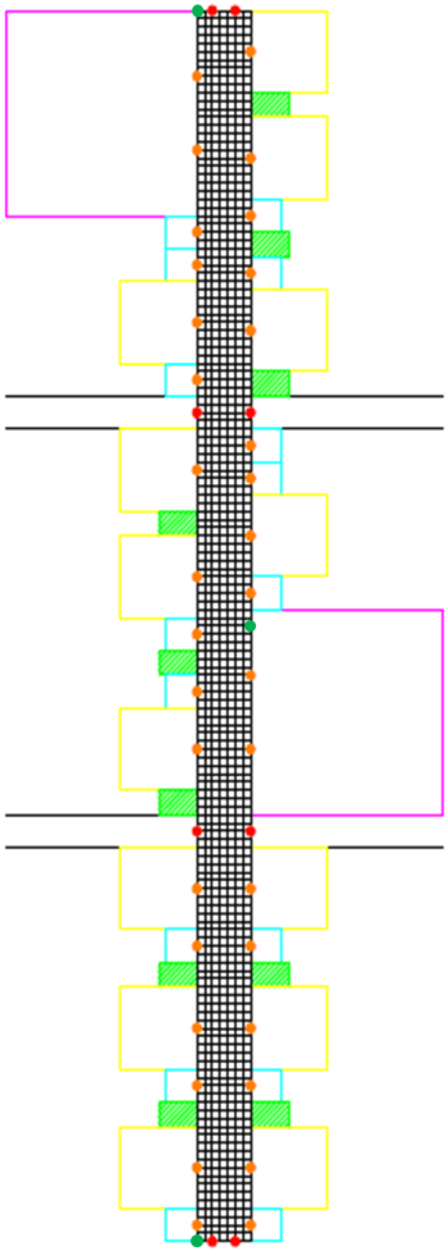
Grid based every 50 meters:



Bleeding control kits locations:

- Green dots: GB 50 m

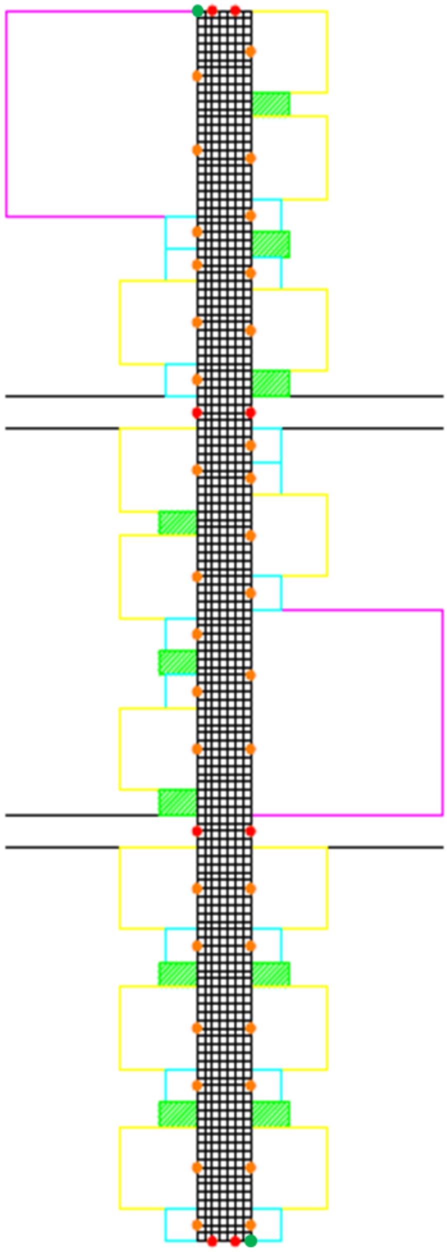
Grid based every 150 meters:



Bleeding control kits locations:

- Green dots: GB 150 m

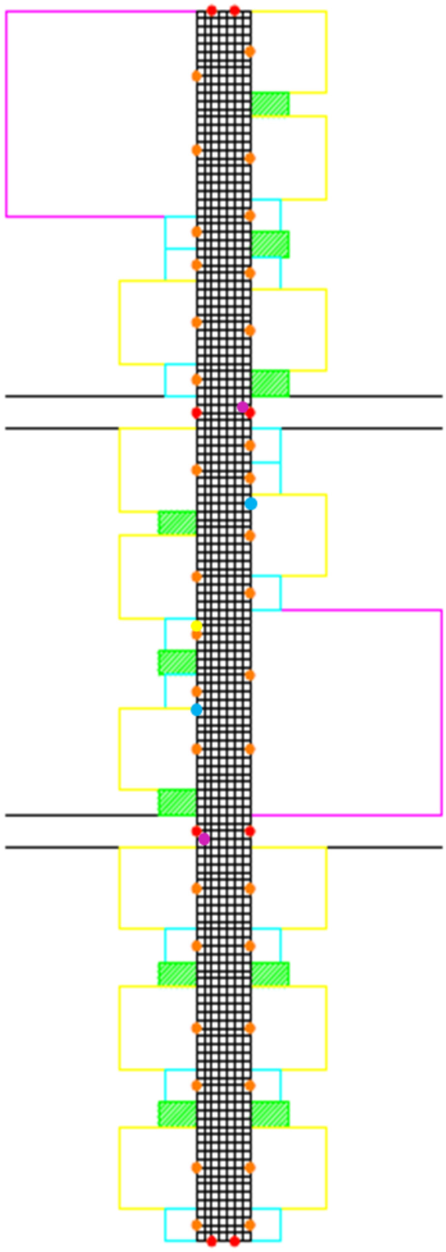
Grid based every 300 meters:



Bleeding control kits locations:

- Green dots: GB 300 m

Effects of placing bleeding control kits in evacuation routes



Bleeding control kits locations:

- Blue dots: Two locations
- Purple dots: Two locations (evacuation routes)
- Yellow dot: One location
- Upper purple dot: One location (evacuation route)

Appendix 3: Bleeding control kits location strategies outcomes

This appendix has the most important outcomes of each scenario simulated to evaluate the different bleeding control kits locations:

Grid-based locations every 50 meters:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	1.137	0.14	0	7
Victims with tourniquet	19.195	0.26	8	24
Victims who left in ambulance	50.067	1.66	9	87
Victims who died because of exsanguination	10.538	1.06	0	51

Grid-based locations every 150 meters:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.093	0.05	0	3
Victims with tourniquet	19.817	0.24	11	24
Victims who left in ambulance	49.616	1.67	8	88
Victims who died because of exsanguination	10.366	1.04	0	45

Grid-based locations every 300 meters:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.000	0	0	0
Victims with tourniquet	20.154	0.23	13	24
Victims who left in ambulance	49.692	1.67	8	88
Victims who died because of exsanguination	9.954	1.02	0	43

Locations inside the malls:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	12.148	0.32	3	20
Victims with tourniquet	10.035	0.31	0	20
Victims who left in ambulance	51.660	1.42	18	85
Victims who died because of exsanguination	18.105	1.28	0	55

Locations outside the malls:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.951	0.17	0	7
Victims with tourniquet	19.349	0.27	9	24
Victims who left in ambulance	49.820	1.64	9	88
Victims who died because of exsanguination	10.631	1.04	0	43

Two locations far from the streets used to evacuate:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.000	0	0	0
Victims with tourniquet	20.145	0.24	11	24
Victims who left in ambulance	49.762	1.7	7	88
Victims who died because of exsanguination	9.892	1.04	0	42

Two locations in the streets used to evacuate:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.000	0	0	0
Victims with tourniquet	20.055	0.24	12	24
Victims who left in ambulance	49.520	1.65	8	89
Victims who died because of exsanguination	10.224	1.04	0	47

One location far from the streets used to evacuate:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.000	0	0	0
Victims with tourniquet	20.291	0.21	13	24
Victims who left in ambulance	49.390	1.68	8	87
Victims who died because of exsanguination	10.119	1.02	0	51

One location in a street used to evacuate:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	0.000	0	0	0
Victims with tourniquet	19.980	0.23	12	24
Victims who left in ambulance	49.552	1.67	8	89
Victims who died because of exsanguination	10.267	1.03	0	47

Well known locations:

Output	Average	Half width	Minimum value	Maximum value
Total number of trained	33.015	0.71	14	57
Total number of volunteers	98.773	1.82	57	145
Total number of victims	148.590	4.25	62	256
Victims with bleeding injuries	79.799	2.44	29	142
Bleeding control kits not picked up	2.029	0.18	0	6
Victims with tourniquet	18.314	0.26	11	24
Victims who left in ambulance	50.227	1.61	9	87
Victims who died because of exsanguination	11.259	1.11	0	53