Linköping Studies in Science and Technology, No. 1842
Licentiate Thesis

An Operations Research Approach for Daily Emergency Management

Niki Matinrad

LINKÖPING UNIVERSITY

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Department of Science and Technology
Linköping University, SE-601 74 Norrköping, Sweden

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Linköping University
Department of Science and Technology
SE-601 74 Norrköping, Sweden

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Abstract

Emergency services play a vital role in society by providing help to affected people and minimizing damage to public and private assets as well as the environment during emergencies. However, these organizations deal with problems of increasing demand uncertainty and resource shortage over time. These problems lead to the creation of many other problems, such as longer response times, lower survivability of victims and patients, and more severe damage to properties and the environment. Acquiring more information about future emergency demand, such as factors affecting this demand, can contribute to reduction of the effects of increasing demand uncertainty. The introduction of volunteers as a new type of emergency resource, which has gained attention in the past few years, can be a solution to the problem of increasing resource shortage.

The aim of this thesis is to provide operations research-based models and methods that can assist medical emergency services in daily emergency management. The aim is supported by two objectives: 1) to develop a forecasting model and 2) to develop models for the dispatch of volunteers. Three separate studies with a focus on these objectives are conducted, and the results are described in three papers.

In the first paper, a forecasting model for predicting the volume of ambulance calls per hour and geographic location for three counties in Sweden is presented. The model takes into consideration geographical zones with few or no population and very low call frequency. Comparative results based on the real data of ambulance calls show that the proposed model performs better than the model that is currently used in some parts of Sweden for operational and tactical planning of emergency medical services. In addition to performance improvement, the proposed model provides information about the factors affecting ambulance demand.

In the second paper, the use of volunteers in response to out-of-hospital cardiac arrest (OHCA) cases is considered, and a deterministic optimization model for their dispatch is provided. The model benefits from a survival function for determining dispatch decisions. The effect of arrival times of volunteers on the survivability of patients is also considered. The results show that, in terms of achieved survivability of patient based on the applied survival function, the proposed model performs better than simple decision rules used today.

The third paper presents a probabilistic method for the dispatch of volunteers to OHCA cases. This method considers the uncertainties associated with the actions of volunteers once they are assigned a task. The proposed method uses a survival function as the objective of dispatch decisions. The results of the method are compared to the static dispatch method that is currently used in an operational system in Sweden for the utilization of volunteers in OHCA cases. Comparative results based on real data show that, with respect to used survival function, the proposed method contributes to higher survivability of OHCA patients than the static dispatch method.

The models and method in this thesis focus on solving real-world problems and use real data for that purpose when available. Some simplifications were considered in the development process. Nevertheless, these models and method have the potential to be beneficial for medical emergency services in practice and can be used as a base for dynamic resource management systems. Such systems can be helpful for both tactical and operational planning of emergency resources.

Acknowledgments

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List of papers

I. Steins, K., Matinrad, N., and Granberg, T. A. 2019. ‘Forecasting the Demand for Emergency Medical Services’, In *Proceedings of the 52nd Hawaii International Conference on System Sciences (HICSS)*, Hawaii, USA, 8th-11th January 2019, pp. 1855-1864.

II. Matinrad, N., Granberg, T. A., Ennab Vogel, N., and Angelakis, V. 2019. ‘Optimal Dispatch of Volunteers to Out-of-hospital Cardiac Arrest Patients’, In *Proceedings of the 52nd Hawaii International Conference on System Sciences (HICSS)*, Hawaii, USA, 8th-11th January 2019, pp. 4088-4097.

III. Matinrad, N., Granberg, T. A., and Angelakis, V. 2019. ‘Modeling uncertain task compliance in the dispatch of volunteers to out-of-hospital cardiac arrest patients’, *Submitted for publication.*

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1. Introduction

1.1 Motivation

Emergency services play a vital role in society by providing help to affected people and minimizing damage to public and private assets as well as the environment during emergencies. The emergencies that they respond to form a spectrum ranging from infrequent incidents with high magnitude of consequences, i.e. disasters, to incidents that have a lower level of consequences but happen every day. Daily emergencies are defined as events with low magnitude of consequences that occur frequently, such as road accidents and cardiac arrests (Quarantelli, 1995). These emergencies, also referred to as everyday emergencies, can be categorized to events that require the help of emergency medical services (EMS), fire and rescue services (FRS), police, or a collaboration among some or all of them. Daily emergencies generally are not complicated events; there are standard routines for handling them, and available local resources can satisfy the requirements for their management (Quarantelli, 2000). According to WHO (2018), in 2013, road traffic accidents alone resulted in 1.25 million people killed and up to 50 million more people injured globally. Between the years 2012 and 2016, there were, on average, 11000 deaths worldwide due to natural disasters (WHO, 2018). These statistics indicate that the number of people killed annually by daily emergencies worldwide exceeds the number of people killed by disasters. However, the emotional impact of disasters on a society are stronger than daily emergencies (Quarantelli, 1995). Based on a report presented by the Swedish Civil Contingencies Agency (MSB) and the Swedish Association of Local Authorities and Regions (SKL), since 2008, the number of people killed in accidents in Sweden has, on average, increased while the response time, on average, has remained the same (SKL and MSB, 2019). Hence, daily emergency management, especially preparation for and response to these emergencies, requires more attention than before. The need for the increase in attention is to reduce the overall impact and consequences of these emergencies over time.

1.2 The emergency response process

A simple illustration of the emergency response process and the relationships between its four components, i.e. demand, resources, response, and outcome, is shown in Figure 1. As presented in Figure 1, both demand and resources are inputs to the response, and outcome is the output. An emergency response process is initiated by the emergency demand, and the available emergency resources are the means of responding to that demand. How well a response is managed to address demand, with the related available resources, is reflected in the outcome of the emergency event. Emergency services can be considered a critical part of the emergency response process as providers of required resources for performing the response.

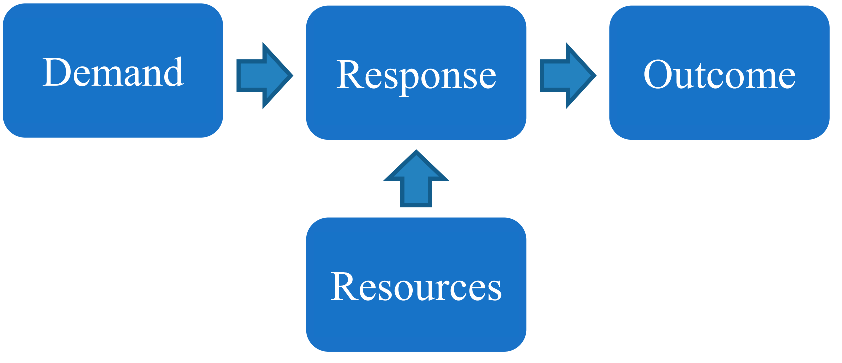

Figure 1. Emergency response process in simple form

Demand for assistance of emergency services can arise as the result of an incident or the presence of such an incident's risk. Building fire, traffic accident, fall, drowning, trauma and cardiac arrest are examples of daily emergencies, and earthquake, forest fire, thunderstorm, and avalanche are examples of disasters. The demand resulting from any of these incidents can be in the form of injured and affected people and damage to private or public properties and the environment. As reported by MSB, the number of rescue efforts in Sweden by FRS between the years 1998 and 2015 has continuously risen (MSB, 2016). This implies an increase in the demand for daily emergency services.

Emergency resources include physical items, vehicles, personnel, and information. These resources are mostly provided by EMS, FRS, Police, and call centers as the main organizations involved in the emergency response process, especially in daily emergency management. The availability of these resources affects the level of service that emergency organizations can provide. This is independent of the emergency type. In accordance with Swedish legislation for fire and rescue services (SFS 2003:778) and for health and medical care (SFS 2017:30), emergency services should be planned so that all people across the country receive an equal level of service and protection against accidents, and the rescue efforts should begin within an acceptable time. These efforts should also be implemented in an efficient manner, which indicates a requirement for maintaining the cost-effectiveness of activities. Thus, there is a need for proper management of emergency resources in order to provide a cost-effective and equal level of service to all people with available limited resources.

The relevant emergency organizations are needed to respond to demand as it arises. At this stage, the response routines of emergency organizations for performing the required actions are initiated, and their relevant available resources are utilized. The call center is responsible for receiving emergency calls and communicating the required information to the relevant emergency organizations, in Sweden these are operated by SOS Alarm Sweden AB (https://www.sosalarm.se/). EMS, as part of the pre-hospital care system, have the tasks of taking care of injured and affected people and transporting patients to medical facilities (Pozner et al., 2004). The primary concern of FRS is the safety of people, properties, and the environment, and therefore, they are responsible for activities such as rescuing people and extinguishing fires (Berlin and Carlström, 2011). Police ensure the security of the public and provide adequate protection, information and other assistance (SFS 1984:387).

Finally, the outcome of an emergency depends on the response, how adequately the resources were managed to meet the demand in a timely manner. There are different indicators for determining how well a response was conducted, such as response time, people's survivability, and the amount of loss and damage. Response time is considered an important factor since it has a direct impact on human lives, properties, and the environment (Swersey, 1994). Other indicators, such as people's survivability and the amount of loss and damage, are affected by response time as well. The later the emergency services arrive at the incident sites, the more severe the damage to people and properties can become, which is evident in cases such as trauma and cardiac arrest (Waalewijn et al., 2001) and fires (Jaldell, 2004).

1.3 Future changes affecting the emergency response process

With time, society experiences demographical and behavioral changes. The former includes, but is not limited to, changes in distributions of people's age, gender, income, and migration. The latter, on the other hand, consists of changes such as alterations in people's mindsets, their preferences for activities on different weekdays, e.g. when and where to dine or go shopping, and whether to travel by private car or use public transportation. Even though the needs of those injured in incidents remain about the same, changes in society may lead to potential changes in how to organize emergency efforts (MSB, 2013). Changes in society may create more complex situations, making it more difficult to predict where and when emergency events will occur. This means that uncertainties regarding emergency demand, including incidents locations, time, and the extent of need for help, can increase. Hence, demographical changes and behavioral changes are two factors that affect demand in the emergency response process. These changes increase demand uncertainty and the problem of how to organize the response to an emergency (see Figure 2).

Emergency services face two major challenges that over time intensify the problem of emergency resource shortages. First, as a result of budget constraints that local authorities have to deal with (Weinholt, 2015), emergency services often experience budget cutbacks (Yousefi Mojir and Pilemalm, 2016). This can negatively affect existing resources that these services utilize for their operations, which are already limited. This leads to the enforcement of more limitations on these resources. Second, there is the issue of long distances to sparsely populated areas (Yousefi Mojir and Pilemalm, 2016), which creates longer response times to emergencies in those regions. This can be the result of the centralization of resources, with increased distances between rural areas and emergency services (Yousefi Mojir, 2016).

Changes in society including a lack of sufficient professional emergency resources as well as behavioral changes, such as alterations in people's mindset regarding providing help to others in times of emergencies, have given rise to the emergence of volunteers, a non-traditional form of resources. Volunteers are one type of resource that has gained a rising interest in the past few years. A noticeable example of the involvement of volunteers in emergencies is disasters where a large number of people spontaneously show up to provide help (Barsky et al., 2007). Willingness of volunteers to provide help as seen in disasters has led to initiatives that utilize volunteers in daily emergencies but in a more organized way (see Ramsell et al. (2017), Ringh et al., (2011), Ringh et al. (2015), Caputo et al. (2017), and http://missingpeople.se/). Volunteers are citizens who are not necessarily affiliated with emergency services yet are willing to provide help in times of emergencies. Compared to professional resources, it may be difficult to fully utilize this type of resource, e.g. due to limited information on the capabilities or the quantities of volunteers. However, they might be able to reach affected people sooner than professionals, and at the same time they induce a lower cost. Their addition to the emergency response process can act as a solution to the increasing resource shortage.

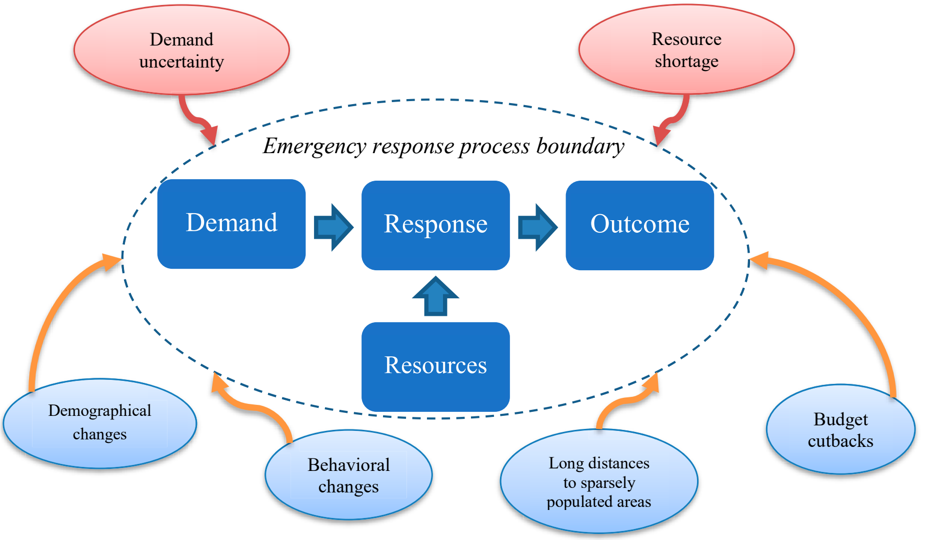

Figure 2. Emergency response process with external affecting factors

Increasing demand uncertainty and resource shortage affect the emergency response process. In order to respond to demand, questions of which resources to utilize, what they can contribute, and how to manage them will be more difficult to answer. This means that the more uncertain emergency demand becomes, and the fewer emergency resources are available, the harder it will be to proactively plan for the management of possible future emergencies. As a result, changes in the outcome of the emergency response process are inevitable. The increase in response time as a result of longer distances between emergency resources and incidents will result in more serious outcomes than today.

Figure 2 illustrates the emergency response process with the external factors affecting it, which can lead to a more complex situation in the future. Four main factors, i.e. demographical changes, behavioral changes, budget cutbacks, and long distances to sparsely populated areas, as discussed affect the emergency response process and raise problems of demand uncertainty and resource shortage. In Figure 2, the four factors are shown as blue ovals, and the two problems as red ovals.

1.4 Scope

With respect to the future changes and developments, this thesis focuses on the management of medical emergencies that occur every day. It considers the Swedish medical emergency response system and addresses the prediction of demand for ambulance services, i.e. EMS, and the utilization of volunteers in out-of-hospital cardiac arrest cases. Forecasting the demand for EMS provides a potential solution to the problem of increasing demand uncertainty as well as the need for more information about possible future demand. Studying the utilization of volunteers in daily medical emergencies provides answers for how to effectively employ this type of resource in response to daily emergencies. The effective use of volunteers can contribute to improve the outcome and lessen the impact of the problem of increasing resource shortage.

1.5 Methodology

This work has adopted Operations Research (OR) to address problems in the area of emergency management. OR as a well-stablished quantitative approach has a decision-oriented nature that, with the use of analytical methods, can provide solutions to complicated decision-making problems. What makes a quantitative approach interesting is the derived models and methods that can be used in the development of management systems. Models produced with the means of OR focus on the improvement of design, management and performance of the systems, and have the potential to help making related decisions (Royston, 2013). In this thesis mathematical programming and forecasting are applied.

1.6 Thesis outline

The remainder of this thesis is organized as follows. Chapter 2 presents the background to emergency management including its life cycle, management of emergency resources, and OR as the methodology in emergency management studies. Chapter 3 provides a detailed description of the aim and contributions. Chapter 4 summarizes the included papers. Finally, in Chapter 5, conclusions of the thesis, and suggestions for future research are provided.

2. Theoretical background

The focus of this thesis is illustrated in Figure 3. Emergency management and, specifically, daily emergency management composes the core of this study. Required activities for proper emergency management can be categorized into four phases: *Mitigation*, *Preparedness*, *Response*, and *Recovery*. Of these four phases, preparedness and response are the focus of this study. One element required to properly coordinate preparedness and response activities is emergency resources. How these resources are handled plays an important part in the management of an emergency event. To manage emergency resources more efficiently, expert systems can function as a catalyst. With the help of these systems, it can be determined which resources are needed and what task(s) they are to perform. Since OR is capable of analyzing and finding solutions to complex problems, it can be utilized as a base for emergency management expert systems.

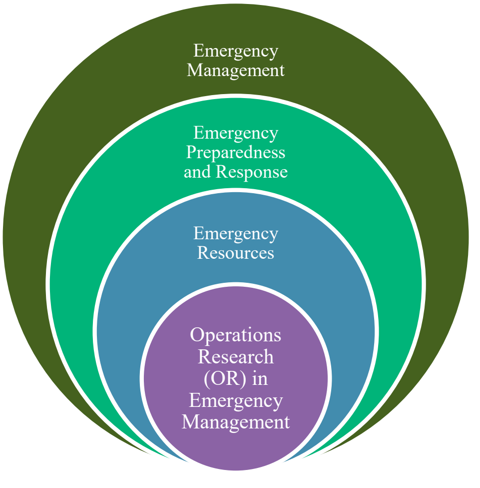

Figure 3. Focus of the thesis

The focus concepts of this thesis are presented in Figure 3 and will be discussed in detail in the remainder of this chapter.

2.1 Emergency management

Emergencies that emergency organizations deal with differ in nature and consequence. They range from low consequence level with high frequency, i.e. daily emergencies, to high level of consequence that rarely occur, i.e. disasters (see Figure 4). Regardless of their consequence and nature, emergencies influence humans, properties, and the environment. Although daily emergencies are events with low level of consequence, considering their high occurrence frequency, over time, the number of people affected and the amount of environmental damage caused by these events are comparable to disasters (Yousefi Mojir, 2016).

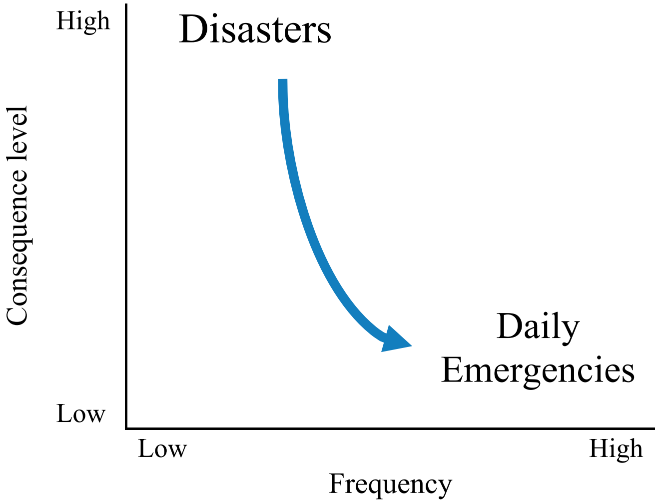

Figure 4. Emergency spectrum

Some emergencies have natural causes and humans do not play an effective role in their occurrence, such as stroke and cardiac arrest. Whereas, humans can play an influential role in the creation of other emergencies, such as traffic accidents and building fires. This fact is not limited to one part of the emergency spectrum and is applicable to all emergency events in this range of events. Regardless of the origin of the emergency, as stated by Taber (2008), under unfortunate circumstances, daily emergencies can evolve into bigger and more complicated events. This means that a daily emergency, such as a small fire combined with inclement weather and other unforeseen factors, can escalate to a bigger emergency involving more people, property, and the environment. According to Bull-Kamanga et al. (2003), parameters such as a society's geographical position, its culture, and the quality of its infrastructures affect the definition of emergencies. This means that a major emergency in one society might be considered a minor one in another society and vice versa. Daily emergencies in Sweden include building fire, traffic accident, fall, drowning, non-building fire, building collapse, person in danger, animal in danger, emission of dangerous substances, and water damage (https://www.msb.se/).

Simply defined, emergency management is “the discipline of dealing with risk and risk avoidance” (Haddow et al., 2013). Thus, to manage emergencies appropriately, it is primarily necessary to determine the potential risks that a society faces. This enables emergency managers to plan accordingly and gives them a better chance to take relevant preventive actions and address those risks. This leads to a reduction in the effects of emergencies, including loss of lives. According to Erickson (2006), to have both proactive and reactive plans for handling emergencies, emergency systems should concentrate on the circumstances of an emergency rather than the event itself. This implies that the degree of damage that an emergency can create is the important factor and should be thought through. For instance, a collision between two vehicles on a highspeed road generates different outcomes than a collision between the same vehicles on an inner-city street.

In daily emergency management, all activities that emergency organizations are responsible for are time-critical. This means that the later these services arrive to the site of the emergency event, the more severe the situation can become, such as in cases of trauma and cardiac arrest (Waalewijn et al., 2001). Delays in the start of emergency response activities can potentially lead to a more complex emergency as the primary emergency might evolve into a bigger and more complicated situation. It should be noted that this characteristic of emergency activities, especially in the response phase, applies to all emergencies across the emergency spectrum and is not limited to daily emergencies.

As Quarantelli (1995, 2000) point out, all emergency organizations have standard routines to manage daily emergencies that are not easily interrupted and are part of their everyday activities. These organizations neither need to utilize a massive number of resources to handle each of these emergencies nor to abruptly form new relationships with other organizations and entities in society. In addition to these, emergency organizations do not lose their relative independence when handling daily emergencies, and their behavioral norms do not change. An example of the latter is speed and the level of emergency service delivery in a hospital that follows the same average throughout time in an everyday setting. Another important point regarding the management of daily emergencies is that these events can be handled with local resources.

Towards the higher end of the emergency spectrum, i.e. disasters, emergency organizations’ characteristics start to change. For example, the standard routines of organizations would not be applicable anymore, behavioral norms would change, and local resources could not cover the risen demand. Consequently, more innovative and agile methods for managing these types of situations would be required.

2.2 Emergency preparedness and response

Emergency management consists of four main phases, referred to as the emergency management life cycle: mitigation, preparedness, response, and recovery, as shown in Figure 5. As Crondstedt (2002) states, these four phases are four elements of emergency/disaster management. This life cycle, however, is seen mostly in disaster management literature (see, e.g. Coppola (2006), Haddow et al. (2013), Haghani and Afshar (2009), and Nikbakhsh and Farahani, (2011)). Nevertheless, these phases are applicable to other emergencies on the emergency spectrum including daily emergencies.

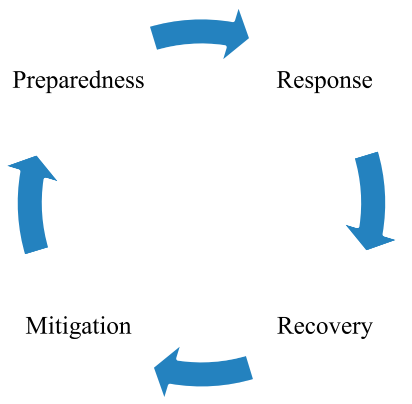

Figure 5. Emergency management life cycle

These four phases can be classified into two main categories of "before" and "after" in relation to the time of an emergency occurrence. "Before" consists of mitigation and preparedness, which include activities that are done prior to the occurrence of an emergency. Whereas response and recovery are phases that start after an emergency situation has occurred and form the "after" category. A short description of each of these phases follows:

- *Mitigation* includes activities that are intended to reduce the effect of a potential emergency by applying preventive measures. It should be noted that, due to the nature of this phase and the required preventive measures, it might require more investment than the other phases (Haddow et al., 2013). The installation of smoke detectors in buildings for identifying fires in the early stages is an example of a measure that can contribute to the prevention of an emergency.

- *Preparedness* consists of all activities that are done prior to an emergency, so that emergency organizations are ready for its occurrence (Rottkemper et al., 2011). As Haddow et al. (2013) point out, all organizations involved in emergency management need a strong preparedness capability, which is achieved through planning, training, and exercising. Periodical practice drills performed by emergency organizations to maintain personnel's required preparedness level is an example of preparedness activities.
- *Response* activities start as soon as an emergency happens and help is required. In this phase, immediate actions, such as dispatching resources including manpower, necessary items for people in need, and equipment for dispatched manpower, should be done (Nikbakhsh and Farahani, 2011). Resources are used to save lives and property and preserve the environment (Berkoune et al., 2012). Examples of what emergency organizations do in this phase include rescuing and taking care of injured individuals, firefighting, securing and policing the area, and restoring order (Haddow et al., 2013).
- *Recovery* is not as easy to classify as the other phases. Exactly when it starts is hard to pin down (Haddow et al., 2013). However, recovery includes handling the secondary needs of the people affected by the emergency after the primary needs have been treated during the response phase (Nikbakhsh and Farahani, 2011). Examples of recovery activities can consist of taking care of patients' needs in hospitals or rehabilitation centers, and rebuilding and restoring homes, facilities, or infrastructures that have been damaged by the fire.

2.3 Emergency resources

Emergency resources consist of physical items, vehicles, manpower, and information. Traditionally, these resources, especially for daily emergencies, are provided by four main organizations: EMS, FRS, police, and call centers. Each of these four organizations have predefined activities and responsibilities. The EMS is the body responsible for providing pre-hospital medical treatment to people in need, and the transportation of these people to a medical facility (Nicoletta et al., 2017). The FRS perform tasks that ensure the safety of people and the environment through activities such as fire prevention or extinguishing (Berlin and Carlström, 2011). The purpose of the police is to promote justice and security by maintaining public order and security and ensuring public protection and other assistance (SFS 1984:387). A call center is responsible for managing emergency lines and alerting the related emergency services to the right location (https://www.sosalarm.se).

In recent years, other non-traditional types of resources, such as volunteers, are being progressively used in the preparation for and response to emergencies. Volunteers might be able to reach affected people sooner than professionals, and at the same time, they entail a lower cost. Depending on their integration within the emergency response process, it is possible to roughly divide volunteers into three different groups: “Established”, “Emergent”, and “Spontaneous”. The *established* group consists of volunteers such as the Red cross/Red crescent and firefighter volunteers that might be well trained, equipped, and experienced, with registered capabilities and existing communication channels. The *emergent* group is composed of more recently developed semi-organized forms of volunteering, where people are registered and possibly receive some training, but they do not have any formal responsibilities. The *spontaneous* group consists of spontaneous volunteers and bystanders who are usually closer to the emergency sites than professionals and the two other groups of volunteers.

There are studies on volunteers as a new form of the emergency response resource from different perspectives such as their attraction and motivation, training, integration into operations, evaluation, use of IT-based tools as a means of communication, the effect of bystander and spontaneous volunteers on emergency outcomes, and task assignment. The following are some example studies regarding these aspects.

Cowlishaw et al. (2008), Choudhury (2010), and Timmons and Vernon-Evans (2013) have studied volunteer attraction and motivation. Cowlishaw et al. (2008) have argued that family issues had a direct impact on the decrease in the number of rural emergency volunteers. Choudhury (2010) has studied the role of local government agencies in attracting volunteers and managing them, and the relationship this role has with volunteering for daily emergency events. Timmons and Vernon-Evans (2013) have investigated reasons that people might have to volunteer and continue their volunteer work, which can be helpful for attracting and motivating future volunteers. Sun and Wallis (2012) have focused on training volunteers and have provided a first-aid responder system model for response to daily emergencies. Hanssen (2015) has described a position tracking system that is being used by volunteer organizations in Norway for rescue and response operations. Pilemalm et al. (2013) have investigated the utilization of new resources, such as volunteers, in the emergency response system and have provided some suggestions for improved integration of these resources into the already existing system. Earl et al. (2003, 2005) have studied the knowledge and skills of volunteers at outdoor music festivals. Groh et al. (2007) have evaluated the characteristics of volunteers that have responded to emergencies, and those authors concluded that previously trained volunteers have a higher tendency to participate in response to medical emergencies. Nord (2017) has investigated the effect of capabilities of bystanders on the survival of OHCA patients.

Majority of the studies regarding volunteers focus on the context of high magnitude-consequence and low-frequency emergencies, i.e. disasters. In recent years, the involvement of volunteers in daily emergencies has been studied and evaluated more than before. Yonekawa et al. (2014), Ringh et al. (2015), Capucci et al. (2016), and Claesson et al. (2017) are some examples of these studies, which largely focus on the effect of the dispatch of volunteers to OHCA cases. Majority of the works that examine the use of volunteers in daily emergencies mainly focus on the evaluation of the effects of their involvement based on different measures, e.g. response time and survivability of patient.

Many studies investigate factors that affect victims of medical emergencies, such as the survivability of OHCA patients. Works of De Maio et al. (2003), Waalewijn et al. (2001) and Valenzuela et al. (1997) are examples of such studies that presented their findings in the form of survival functions. Nevertheless, not many studies have used a form of survival function in conjunction with other operational aspects of daily emergency management, e.g. location-relocation of resources and dispatch of resources. Erkut et al. (2008) have used such aspects. They have presented location models for EMS stations, and in these models, they have considered existing covering models and used a survival function as the objective.

Among volunteer management studies in disasters or daily emergencies, the work of Falasca and Zobel (2012) is one of the few studies that uses OR. They have presented a multi-criteria optimization model for task allocation to both individual volunteers and volunteer groups during disasters. Their bi-objective optimization model aims to minimize the total cost of task shortages and the total number of undesired task assignments.

2.4 Operations research (OR)

Ramamurthy (2007) considers OR as a branch of mathematics for providing a scientific basis for decision making. Eiselt and Sandblom (2012) consider OR as a discipline that is primarily “concerned with quantitative models and their solution”. As Sharma (2008) writes, due to the broadness of OR, it is not an easy task to reach a brief definition of OR. However, different definitions made by various OR organizations and researchers state that OR is the use of scientific methods, techniques, and tools for making a well-defined decision. One of the definitions of OR is presented by the Operations Research Society of America as:

"Operations research is concerned with scientifically deciding how to best design and operate man-machine systems usually under conditions requiring the allocation of scarce resources."

According to Larson (2005) OR is an empirical science that uses mathematics to develop a model of reality, to test, refine, and computer-implement it, although it should be noted that OR might not use mathematics in all cases.

Thus, OR takes efficient steps to aid decision making on the strategic and tactical levels and to automate the operational level's decision making (Eiselt and Sandblom, 2012). It also aims at making improvements in the system, which is often complex, that involves all types of resources, i.e. physical items, people, and information (Royston, 2013).

Major steps in the development of an OR model, from which this thesis benefits, is illustrated in Figure 6. This figure is based on the processes considered by Eiselt and Sandblom (2012) and Ulander (2015).

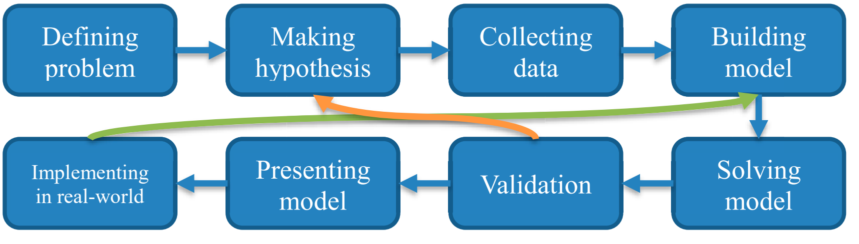

Figure 6. OR modeling process

The process starts by recognizing a problem and properly defining it. For this step, good observation of the system under study is necessary to obtain sufficient information and become familiar with the system. In the next step, hypotheses are constructed based on what was done in the first step. Complex systems are usually simplified in this step. This lays the foundation to aim for the right data and modeling technique in the next steps. Subsequently, based on the constructed hypotheses, data is gathered, and a model is developed. In the next step, a relevant solution technique is chosen, and the model is solved with the help of this technique and the gathered data. In order to determine if the model is a proper representation of the real-world problem, with consideration of the hypotheses, the obtained results in the previous step should be analyzed, i.e. validation. If the results are sound, and also problem owners exist, then the model is presented to them. Eventually, the final model can be implemented in the real world.

This process benefits from two feedback loops. The first feedback loop is when the results are analyzed. If the obtained results are not practical, the hypotheses should be re-evaluated and adjustments made, as shown by the orange feedback arrow in Figure 6. On the other hand, if the model does not reflect reality for any reason during the implementation step, one main reason could be a change in reality, the model must be revised. This forms the second feedback loop, i.e. the green arrow in Figure 6.

2.5 Operations research in emergency management

This section presents a brief overview of some of the works that have used OR as their methodology for daily emergency management. Each of these works focus on different components of the emergency response process: demand, resources, response, and outcome. It should be noted that the summarized studies that follow, are only a few examples of the works that have applied OR in the field of daily emergency management. They, nevertheless, can be considered as representatives of main focus of the studies in the field. In addition, a few review studies relevant to some of components of the emergency response process are included among the presented studies.

2.5.1 Demand

One important aspect regarding the demand for emergency services is the presence of adequate information about future demand. To provide such information, numerous works have used different forecasting methods to predict the number of emergency calls. Based on the utilized method, these works can generally be categorized to “regression” models, “time series” models, and models that consider “time and location simultaneously” or “spatial-temporal” models. Some of the forecasting studies in the context of daily emergencies are briefly presented in the following.

Aldrich et al. (1971) have presented a least square regression forecasting model that takes into account the socioeconomic characteristics of the census tract, the type of public service, and the availability of alternative sources of care as the model’s independent variables. The results of this research show that aged people and single men contribute to a higher rate of ambulance calls than the rest of the population. Siler (1975) has developed a non-linear model for the prediction of community ambulance demand in Los Angeles county, USA. Kvålseth and Deems (1979), similar to Aldrich et al. (1971) and Siler (1975), have used socioeconomic and demographic characteristics of the city of Atlanta's census tracks to predict the ambulance demand of the census tracks. Kamenetzky et al. (1982) have used four independent variables, i.e. population, employment, the logarithm of the percentage of white and married population, and the square of employment to population ratio, together with an independent variable of the total number of emergency calls by geographic units to forecast ambulance demand. They used first-order and second-order regression models to develop their prediction model. Baker and Fitzpatrick (1986), with the use of Winter's exponential smoothing model, have produced a forecasting model that predicts the number of ambulance calls. The aim of the study was to develop a model that can predict both emergency and non-emergency ambulance calls. For this purpose, first a multistep approach for determining the optimal parameters of the exponential smoothing model was used. Then, goal programming was utilized to combine results of both types of calls.

Svenson (2000) has developed a Poisson regression model with the use of the emergency records of Kentucky counties, USA. In this model, location (both rural and urban), level of availability of prehospital care, access to a 24-hour emergency department in the county, availability of 911 service, poverty (per capita income, percentage of households with no wage earner, and percentage of residents below the poverty level), education (percentage of those with less than a ninth-grade education), and the availability of a telephone in the household are considered as independent variables. The results of the study show that age and poverty have the most significant correlation with the level of use of emergency services. Channouf et al. (2007) have utilized emergency calls of Calgary, Canada, to propose two time series approaches for forecasting the number of daily emergency calls: autoregressive models of data without trend and doubly-seasonal autoregressive integrated moving average (ARIMA) models with special-day effects. Results of their study show that times that people work, commute, celebrate, and sleep affects the number of emergency calls. Setzler et al. (2009) have adopted artificial neural networks to forecast the amount of emergency demand for different times of the day and specific geographical regions. Their proposed model accounts for the season of the year, the month of the year, the day of the week, and the time of the day. In two stages, Wong and Lai (2012) have used multiple regression to predict ambulance calls. In the first stage, the relationship between ambulance data and weather variables was studied, and in the second stage, using forward variable selection, a series of regression models based on weather factors were created. In the models, those authors used different cases based on age, triage level, hospital admission status, comprehensive social security assistance recipients, and gender. The results of their study show that weather factors can perform well as a predictor for ambulance demand for older people, patients with more severe conditions, hospital admitted cases, and comprehensive social security assistance recipients.

Lowthian et al. (2011) have used linear regression to predict the demand for ambulances in metropolitan Melbourne, Australia, and used demographical factors, such as age and sex, as independent variables of the model. Their study indicated that older people create more ambulance demand than other age groups. To forecast ambulance calls, Matteson et al. (2011) have combined integer-valued time series models with a dynamic latent factor structure and included all priorities of emergency calls at an hourly level. Cramer et al. (2012) have utilized stepwise regression on ambulance demand data from the Portland, Oregon, Metro Area, USA, and concluded that renters, businesses, jobs, people not in the labor force, and college graduates are independent variables that affect the demand for ambulance service. Based on the determined independent variables, those authors did hotspot analysis to 1) decide which areas have a higher call volume and 2) determine how each variable influences different spatial extent. Vile et al. (2012) have adopted Singular Spectrum Analysis, a non-parametric technique for time series analysis, to forecast emergency demand at a daily level. Wong and Lai (2014) have used 7-day weather forecast data to forecast demand for ambulance services in Hong Kong. Zhou and Matteson (2015) have employed spatial-temporal kernel density estimation to develop a forecasting model for ambulance calls at fine time and location scales. To do this, those authors used ambulance call data of Toronto, Canada. Zhou et al. (2015) have utilized a bivariate Gaussian mixture model on data of ambulance calls in Toronto to predict ambulance calls in a continuous spatial domain and a discretized temporal domain. Nicoletta et al. (2016) have proposed a Bayesian model to predict emergency call volume in the city of Montréal, Canada, which can determine the time and location of future calls. Guo (2017) has studied the relationship between heat and ambulance calls and considered the hourly data of ambulance calls for non-accidental causes, temperature, and air pollutants from Brisbane, Australia, during warm season (November-March). They used a time-stratified case-crossover design and concluded that an hourly temperature of more than 27 Centigrade increases ambulance demand. Habib et al. (2018) have examined the effects of neighborhood characteristics on ambulance demand. For this purpose, they used and compared a Poisson regression model with a Poisson hurdle regression model. They also developed a time-segmented model to consider temporal aspects in their investigations. The results of their study indicate that areas with high population density, a larger proportion of the population older than 40 years, and more heterogenous land use create more ambulance demand. They also found that, in regard to time, residential areas have more demand during morning hours, commercial areas create more ambulance demand during afternoon hours, and people older than 75 years have more demand during morning and midday hours. Huang et al. (2019) have proposed a combined model consisting of two parts for forecasting emergency calls: 1) a Poisson neural network model and 2) a combination of multiple linear regression, autoregressive integrated moving average (ARIMA), and multivariate gray. They have used data from the emergency calls of Ningbo, China. Wong et al. (2019) have investigated the factors that affect the demand for emergency ambulance services in both rural and urban areas of New Taipei City, Taiwan. They found that, for urban areas, only the percentage of people older than 65 was the factor that affected the demand, while in rural areas, population density (Ln-transformed), the percentage of residents with a middle school education and higher, the accessibility of hospitals without an emergency room, and the accessibility of emergency ambulance services were the affecting factors.

2.5.2 Resources and Response

Resources play an important part in how the response to demand will be conducted. The limited available resources need to be used properly, so that all people, as far as possible, receive an equal level of service and protection in a timely manner. "Location of stations" to achieve the best "coverage", "location and relocation of emergency fleets", "deployment/ dispatch of resources", "scheduling of resources", and "cooperation between resources" are main categories of issues regarding resources and response. An overview of some of the works related to daily emergency resources and response are presented in the following.

Carter et al. (1972) have considered the cooperation of two units, such as two fire units or two ambulance units, in response to emergencies in a specific region and have presented a model for their cooperation in response to alarms. The model calculates the average response time and the workload of the units with respect to each units' home location and determines the district boundary that minimizes average response time. Chelst and Barlach (1981) have developed two models, one deterministic and one approximate, to estimate standard performance measures, such as unit workload and travel times, when two identical units are dispatched to a single call. They considered an example from the police and compared the two models based on this example. Iskander (1989) has presented a simulation model for planning EMS in a wide decision-making spectrum ranging from operational, i.e. day to day, to strategic, i.e. long term, activities. These include planning decisions related to equipment, personnel, and processes, e.g. the number of ambulances to be purchased or personnel to be hired and trained, and decisions on ambulance location allocation. Trudeau et al. (1989) have used OR to develop models for planning and operating EMS. They started by presenting a demand forecast, then used the results of the forecasting model to determine resource requirement and, subsequently, developed an optimization model for units and personnel scheduling. They developed another optimization model for the determination of the location of waiting sites for ambulances, and their dispatching rules and relocation. Eventually, they presented a simulation tool that is capable of evaluating any EMS operation strategy. Batta and Mannur (1990) have identified a criterion for determining the location of fire trucks or ambulances where multiples of them might be needed. Their proposed model can be viewed as a general form of backup coverage, which is also applicable to the dispatch of ambulances in an urban setting with a high demand rate that leads to unit unavailability. Goldberg et al. (1990) have studied ambulance base location problem and provided a nonlinear integer programming model to determine the optimal location for these vehicles. The model was developed for EMS that have low vehicle utilization, and the results are compared with the actual emergency medical system of Tucson, Arizona, USA, to evaluate the model's predictivity. Swersey (1994) has presented a review of the deployment of police, fire and rescue services, and emergency medical units in which several aspects related to them are studied: 1) the relationship between effectiveness measures and a system's performance, 2) the number of units that are needed in each region, 3) location models (both deterministic and probabilistic) for determining the location of units, 4) staffing and scheduling for determining the number of staff and level of training each unit needs, and 5) service and political implications of merging several emergency service bases as a result of budgetary constraints. Zaki et al. (1997) have presented a simulation model for resource allocation and the management of resources so that equipment and personnel are allocated properly to existing emergency facilities. The model was evaluated through the allocation of police patrol vehicles in the city of Richmond, Virginia, USA, where there were non-homogenous zones with varying demand patterns.

Brotcorne et al. (2003) have presented a review of ambulance location and relocation models over a time span of 30 years. Their review categorizes the models as deterministic, probabilistic, and dynamic. Goldberg (2004) have also presented a review, but their work focuses on dispatch and planning models for EMS and FRS, and those authors have considered both analytical work and application. Henderson and Mason (2005) have developed a discrete event simulation model for evaluating decisions concerning EMS operations. The model was used for determining which ambulance should be dispatched to a call, and the time and locations that the ambulances should be allocated. They also used GIS to visualize the results of the simulation model. Andersson and Värbrand (2007) have provided algorithms for ambulance dispatch as well as dynamic ambulance relocation. The algorithms benefit from a preparedness measure, which shows the ability that current and future emergency calls, in any part of an area, can be responded to. Erkut et al. (2008) have presented a model for the location of EMS stations. Their model considers a survival function in the existing covering models. They used data from the EMS system of Edmonton, Canada, to evaluate survival-maximizing location models and empirically showed the superiority of these models over the usual covering models. Ingolfsson et al. (2008) have developed an optimization model for ambulance location that aims at minimizing the number of ambulances needed to provide a specific service level. The model considers uncertainties related to travel times, and it determines the specific number of ambulances that should be allocated to each station. The model was tested on real data from the Edmonton ambulance services. Simpson and Hancock (2009) have conducted a review of works that have used OR in the emergency response context over a range of 42 years. Silva and Pinto (2010) have integrated discrete event simulation with optimization to conduct an analysis of a medical emergency system to improve the search for an optimal situation for the system. They tested their methodology on emergency medical system of the city of Belo Horizonte in Brazil.

McCormack and Coates (2015) have developed an optimization model for EMS base station locations and the allocation of ambulances. They used a genetic algorithm with an integrated EMS simulation model. They also considered patient survivability and showed that optimization of the existing resource plan could lead to a noticeable increase in patient survivability. Schneeberger et al. (2016) have proposed an optimization model for the location and relocation of ambulances that considers under-covered areas and has the objective of minimizing the relocation time. Zhang et al. (2017) have considered the uncertainties that emergency service facilities might encounter, and with use of uncertainty theory, they have developed an uncertain location set covering model and an uncertain maximal covering model. Akdoğan et al. (2018) have studied the location of ambulance vehicles on a fully connected network and used queueing theory to obtain the performance metrics of the system. They propose an approximate queuing model along with a mathematical model aimed at minimizing the mean response time of ambulances based on the approximate queuing model. In their model, several vehicles can be located at the same point; this specification led to an improvement in the objective function value. Chu et al. (2018) have investigated the problem of ambulance location and considered partial demand information. They propose a distribution-free chance constraint model and developed two mixed integer programming (MIP) formulations to solve it. The two MIP formulations can determine both base locations and the employment of ambulances, ensuring a high service level in short time. Hansson and Weinholt (2018) have considered FRS in Sweden and studied two cross-sector collaborations: 1) collaboration between FRS and homecare nurses and 2) collaboration between FRS and private security firms. Their study aimed at understanding actor roles and obstacles and possibilities for cross-sector collaboration. Janosikova and Jankovic (2018) have developed a mathematical programming model for determining a better location for the standby site for emergency vehicles while maintaining the current number of vehicles. Kvet and Janáček (2018) have presented a design for a fair emergency system under uncertainty while minimizing the disutility perceived by the worst situated user. The problem under study in that paper can be considered a special class of location problems. Tsai et al. (2018) have presented a multi-objective ambulance allocation model that benefits from demand forecasting, and those authors used historical data from New Taipei City, Taiwan. van Barneveld et al. (2018) have investigated how ambulances should be distributed and redistributed and considered the influence of ambulance crew workload and differentiating between rural and urban areas. For this purpose, they used trace-driven simulation on a real database from the Netherlands. van Buuren et al. (2018) have described and evaluated two dynamic relocation policies implemented in a software tool for real-time decision making by an ambulance provider in the Netherlands. They found that using a dynamic relocation policy leads to an improvement in effectiveness, in terms of response time, compared to no use of a relocation algorithm. Enayati et al. (2019) have introduced a multicriteria optimization model for joint location and distribution decisions while considering different levels of emergency medical call priorities. They aimed at providing good solutions while considering several equity and efficiency measures together. Hammami and Jebali (2019) have investigated the design of an EMS system and considered advanced information on ambulance trip and ambulance busy fraction in this design. For this purpose, they provided two mixed integer linear programming models for the location-allocation of EMS. Jánošíková et al. (2019) have suggested three median-type location models for the optimal relocation of existing emergency medical stations. The proposed models were evaluated using a computer-based simulation model. The results indicate that a simple p-median model can significantly improve the accessibility of ambulances to patients.

2.5.3 Outcome

How the emergency organizations respond to an emergency might influence the outcome of the emergency response process. How fast the resources of these organizations arrive on the scene of events and whether they collaborate with each other and other parties, such as civilians and volunteers, or not are examples of indicators that show how a response has been conducted. The following are some of studies focused on the outcome of the emergency response process. Majority of them have used cost-benefit analysis to evaluate such effects on outcome.

Mattsson and Juås (1997) have studied the benefits and costs of fire and rescue services arrival time delays on society in Sweden. Based on empirical data, they have measured the costs and benefits for three cases of building fires, road transport accidents, and drowning events, as these cases accounted for 38% of alarms at the time of their study. The output of their study indicates that a 5- or 10-minute delay on arrival time is of significance in terms of damage in these three cases, while it is marginal for other types of alarms.

Ali et al. (2006) have investigated the benefits of a public-private partnership in Islamabad, Pakistan. As an innovative EMS collaboration, police and the private sector cooperate with each other to improve the response to emergencies, especially medical emergency calls. They also take part in response to fires, major power and gas breakdowns, crimes, and other emergencies. This initiative was formed due to resource scarcity in the city, which resulted in long response times to emergencies. Examination of the data from this collaboration shows positive results for institutional setup, public-private partnership, client satisfaction, and sustainability. Berlin and Carlström (2011) have investigated the reasons for decreasing collaboration among police, FRS, and EMS. For this purpose, they used data from observation and semi-structured interviews. They conclude that these emergency organizations avoid excellent forms of collaboration at an accident site as collaboration can create uncertainty and asymmetry in their work, and they lack sufficient incentives for it as well. Since time to defibrillation is an important factor in out-of-hospital cardiac arrest (OHCA) patient survivability, Sund et al. (2012) have performed a cost-benefit analysis to investigate the effect of dual dispatch defibrillation by EMS and FRS in the county of Stockholm, Sweden. Their analysis shows this effort to be economically efficient, and the health benefit amounts to 36 times the invested amount. Weinholt and Andersson Granberg (2015) have evaluated the effects of new collaboration forms, i.e. using security guards and home care nurses in response to daily emergencies, with a cost-benefit analysis. They show that such collaborations are cost-efficient, and one of their important benefits is the reduced response time. Kiyohara et al. (2016) have investigated the effect of the availability and use of public-access automated external defibrillator (AED) pads to OHCA patients and find its utilization favorable for outcomes. They mention that the overall survival rate of an OHCA patient depends on the location and availability of AEDs, and thus, strategic deployment of AEDs to the emergency site as well as public training in basic life support are important factors in this regard. Following the shift in attention from each part of the health care system to the entire chain of health care system, Aringhieri et al. (2017) have presented a literature review of emergency care pathways, and based on their analysis, emerging challenges are also identified. This change in focus is to increase patient safety and satisfaction and to ensure that resources are used optimally. Jaldell (2017) has used non-linear regression techniques and data from the FRS in Sweden to analyze the relationship between response time and fatalities in residential homes. The objective of that study was to measure how many lives could be saved with a shorter response time. The results of that study show a positive relationship between longer response time and more fatalities; however, the relationship was found to be non-linear. Sund and Jaldell (2018) have investigated the possible benefits from a potential agreement between the FRS of a Swedish municipality and a private security officer firm. They used cost-benefit analysis, and the result of their study shows that this collaboration results in a faster response time in residential fires and positive economic effects in terms of saved lives and property damage. Karlsson et al. (2019) have studied the relationship between AED accessibility at the time of an OHCA, bystander defibrillation, and 30-day survival. The results of the study indicate that, when the nearest AED to an OHCA was accessible, the chance of a bystander defibrillation tripled, and 30-day survival nearly doubled.

2.6 Research opportunities

With respect to the previous studies briefly presented in Sections 2.3 and 2.5, the following research opportunities can be emphasized:

- When presenting a forecasting model for the emergency demand, not many studies consider both time (day of week and hour) and the geographical location of daily emergencies simultaneously, especially with the use of a regression model. An emergency demand prediction that can provide information about either time or the location of emergencies is useful. However, a forecasting model that can produce a comprehensive prediction containing both the time and location of future emergencies can help emergency managers better in their resource planning and management.
- In the real world there are geographic areas that are locations for vacations or contain roads that cross through them. Hence, they might have no or very few historical calls and no permanent residents. However, these areas pose a positive risk for the creation of future emergency demand. Consequently, in the development of forecasting models that can predict the location of future

emergency calls, these areas need to be considered. To accurately forecast the location of future demand, geographical locations need to be mapped to fine-scale zones. As a result of this modeling necessity, the geographical locations with very low call frequency and no population would be represented as many small zones with very low call frequency and no population. The consideration of these geographical zones can result in the presence of large numbers of zeros in a dataset. There are regression models for demand prediction that can handle count data and large numbers of zeros in the outcome variables. However, to the best of knowledge of the author of this thesis, none of the existing studies about EMS have dealt with large numbers of zeros in their regression forecasting models.

- While there has been a considerable amount of studies on the volunteer management area, few studies use quantitative techniques, such as OR. Among the existing quantitative studies, time, which is one of the critical factors in response to emergencies, is not considered. For instance, time is not included in the work of Falasca and Zobel (2012), which focuses on task allocation decisions. Exclusion of time might not create a noticeable negative effect in models related to the response to disasters. However, in daily emergencies, such as OHCA, fire, and trauma, a delay in response can result in devastating outcomes; this indicates the importance of the consideration of time. So, models for volunteer management in daily emergencies that consider time, such as dispatching models, are the missing pieces of the existing studies.
- Related studies have increased in recent years through the introduction of practical projects in countries such as Sweden, Italy, Switzerland and the Netherlands, for the use of volunteers in daily emergencies, especially OHCA cases. Despite this positive trend, there have not been any studies that use OR and mathematical modeling for volunteer management processes, such as the dispatch of volunteers. The incorporation of a patient survival function into the models for volunteer management processes can result in positive outcomes and is another under-covered area in existing studies.

3. Aim and contributions

3.1 Aim and objectives

The outcome of an emergency depends on how efficiently the resources were used in response to the demand, i.e. how well an emergency response process has been managed. This process faces the challenges of increased demand uncertainty and resource shortage as well as opportunities for new types of resources (see Figure 2). With respect to these challenges and the focus of the thesis, the overall aim of this thesis is as follows:

To provide operations research-based models and methods that can assist medical emergency services in daily emergency management

This overall aim rests on two objectives. These objectives are as follows:

Obj1: To develop a forecasting model for the prediction of future medical emergency demand

Obj2: To provide models for the dispatch of volunteers to out-of-hospital cardiac arrest (OHCA) cases

Figure 7 illustrates the relation between each of the two objectives and the emergency response process, and the affecting external factors as presented in Figure 2.

Obj1 includes the identification of factors that affect the number and pattern of medical emergency calls. This objective focuses on the demand of the emergency response process, and output of this objective provides the base for proactive planning of available resources.

In Obj2 analysis of the impact of arrival times of volunteers on the outcome of the emergency, and the uncertainties associated with task compliance of volunteers are considered. This objective focuses on the resources and outcome of the emergency response process, and its output enables emergency medical services to utilize volunteers effectively.

In general, the two objectives seek to identify: 1) possible solutions to the problem of increasing demand uncertainty, and 2) how to effectively employ non-traditional resources as one way to handle the problem of increasing resource shortage.

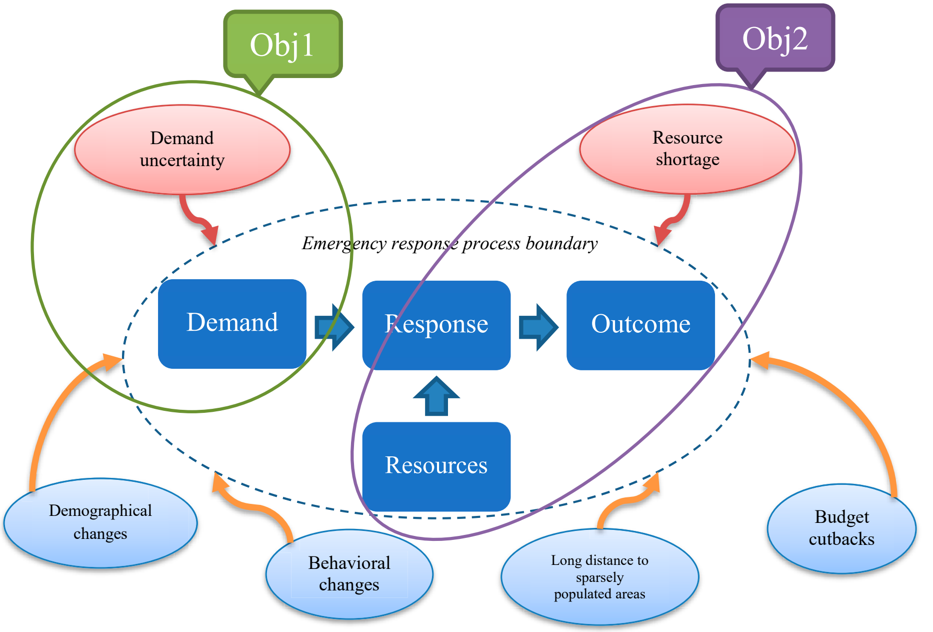

Figure 7. Position of thesis objectives in relation to the emergency response process and its affecting factors

3.2 Contributions

In overall, this thesis contributes to the field of daily medical emergencies. The two objectives considered herein are supported with three papers that resulted in several contributions. These contributions are summarized and briefly discussed below.

In order to have the potential to properly plan emergency resources and respond to medical emergency demand, access to appropriate information about the possible demand for service is a necessity. This need is essentially what motivates Obj1, and in this regard, the thesis makes the following contributions:

- A forecasting model for the prediction of demand for emergency medical services based on demographical and behavioral factors and on a fine-scale level of time and geographical zones (Paper I)
- Identification of factors affecting medical emergency demand that require the dispatch of an ambulance; this information can be useful for proactive

planning of preventive actions by emergency managers and policy makers (Paper I)

Since the emergence of volunteers and the increase in their numbers over the past few years, there has been a lack of models and methods that help to effectively use these emergency resources in the emergency response process, especially in daily emergencies. This leads to Obj2, from which this thesis makes the following contributions:

- An optimization model for the dispatch of volunteers to OHCA cases that utilizes the patient survivability function in determining the dispatch decision (Paper II)
- An investigation of the relationship between the arrival time of volunteers to the site of OHCA case and patient survivability (Paper II)
- A probabilistic method for the dispatch of volunteers to OHCA patients that considers the uncertainties related to the task compliance of volunteers (Paper III)

4. Summary of papers

This chapter includes a summary of the three included papers: Paper I models emergency demand by utilizing forecasting methods; Paper II focuses on the outcome of an emergency and uses deterministic mathematical programming; Paper III considers the importance of resources in emergencies and uses a probabilistic, dynamic method to model the utilization of resources. Table 1 provides an overview of the three papers.

Table 1. Overview of presented papers

	Paper I	**Paper II**	**Paper III**
Title	Forecasting the demand for emergency medical services	Optimal dispatch of volunteers to out-of-hospital cardiac arrest patients	Modeling uncertain task compliance in the dispatch of volunteers to out-of-hospital cardiac arrest patients
Aim	To develop a forecasting model for the prediction of ambulance demand	To provide a mathematical model for the dispatch of volunteers	To develop a dynamic, probabilistic method for the dispatch of volunteers
Methodology	Zero-inflated Poisson regression (ZIP)	Deterministic Mixed Integer Linear Programming (MILP)	Sequential Probabilistic Task Assignment and Dispatch (SePTAD)
Data	Historical data on ambulance calls in three Swedish counties for two years	Experimental data on the dispatch of semi-professionals to out-of-hospital cardiac arrest patients for two months	Historical data on the dispatch of volunteers to out-of-hospital cardiac arrest patients for five months
Focused component	Demand	Outcome and Resource	Resource and Outcome

4.1 Paper I: Forecasting the demand for emergency medical services

Quick and efficient emergency service is possible if the available limited resources of emergency organizations are managed properly. The presence of appropriate information about the expected emergency demand can play an important role in achieving proper resource management. One method to acquire such information is through the reliable forecast of emergencies.

To address this issue, Paper I presents a forecasting model for the prediction of priority 1 and 2 medical emergency calls (acute cases) in three counties in Sweden. The aim of the model was to predict the number of calls for ambulances, per hour and geographical grid zone in each of the counties. To achieve this aim, factors affecting the number of emergency calls were first investigated, and then the forecasting model was developed. This led to two contributions: (1) the development of a predictive model that can be used to better manage existing resources, and (2) the acquisition of information about factors that play an effective role in the creation of emergency calls that can be beneficial in preventive planning.

To develop the forecasting model, as primary data historical data of ambulance calls during years 2013 and 2014 was obtained from SOS Alarm Sweden AB. This organization has the responsibility of managing majority of ambulance resources in Sweden. Since the developed model was to be compared with an operational forecasting model used by SOS Alarm that produces predictions for spatial grid zones, the ambulance call data was also mapped to the same spatial grid zones. Then the data was aggregated with different relevant factors, such as socio-economic ones. Day of week and hour of day as indicators of time were also included in the list of relevant factors.

The variable that was being predicted in this study was count data, i.e. the number of emergency calls, and the final dataset (after all processing steps) contained excessive zeros due to its structure and was not over-dispersed. For these reasons, Zero-Inflated Poisson (ZIP) regression was used to develop the model. Consequently, separate ZIP models with the same set of predictors were developed for each of the three counties. It should be noted that the ZIP model considered both temporal and spatial factors in addition to other factors, such as socio-economic ones. The model could also handle geographical zones that have no population or have a very low call volume, which is difficult with other types of models.

Finally, the three models, one model per each county, were compared with the existing forecasting model that is used by SOS Alarm. Mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE) were used to compare performance of the ZIP model and the existing model. The results show that the model described in this paper performed better than the prediction model currently used by SOS Alarm. In addition to performance improvement, the ZIP model provided information about factors that influence the number of calls that the current model is not capable of. For instance, the results indicate that an older population (65-100) generates more ambulance calls among all age groups. On the other hand, factors such as birth place and employment rate did not have any significant effect on the number of ambulance calls and, thus, were removed from the final model.

Paper I was co-authored with Krisjanis Steins and Tobias Andersson Granberg. The author of this thesis carried out the literature review, the preliminary statistical analysis, and a few interviews, and also participated in data processing, the final statistical analysis, and the writing of the paper.

Paper I is published in

- *Proceedings of the 52nd Hawaii International Conference on System Sciences (HICSS-52)*, Hawaii, USA, 8th-11th January 2019.

Parts of the work were presented by the author of this thesis at

- 43rd annual meeting of EURO Working Group on Operations Research Applied to Health Services (ORAHS), Bath, UK, 30th July – 4th August 2017.
- 2017 Swedish operations research conference (SOAK), Linköping, Sweden, 19th-20th October 2017.

4.2 Paper II: Optimal dispatch of volunteers to out-of-hospital cardiac arrest patients

Volunteers are an emergency response resource that has been the focus of greater interest in the past few years. Many projects utilize semi-organized volunteers for daily emergencies, and the number of these projects is increasing. Among them, SMS lifesavers (https://www.smslivraddare.se/) started in 2010 as a research project in Stockholm, Sweden, and is currently operational in four counties in Sweden. SMS lifesavers are registered volunteers that contribute to out-of-hospital cardiac arrest (OHCA) cases. They receive an alarm on their mobile phone, and if they can, they respond. In this case, tasks that volunteers need to do can be categorized into two main activities: 1) finding an automated external defibrillator (AED) and delivering it to the incident site, or 2) going directly to the patient and performing cardiopulmonary resuscitation (CPR).

This paper proposes a mixed-integer optimization model for the dispatch of volunteers based on the SMS lifesavers project with the main objective of maximizing patient survival. The survival chance is affected by "time to start of defibrillation", "time to start of CPR" and "quality of CPR". The model suggests how many volunteers are needed in total, which volunteers to send directly to an OHCA patient, and who should collect an AED en route to the patient. The quality of CPR is modeled in the form of arrival gaps. This means that the model chooses volunteers so that they arrive in a manner that gives the patient consistent CPR with the required quality until either an AED or an ambulance arrives. The model assumes that all notified volunteers accept the call. All other factors, including the arrival times of the EMS and the travel times of volunteers are not affected by anything throughout the time period and are deterministic. Therefore, the proposed model is developed in the form of a determinist optimization model.

The proposed model was solved using the weighted sum method as it was a multi-objective model. In order to see how the model performs, it was compared with two greedy dispatch approaches that were inspired by the literature. The first greedy approach prioritizes dispatch to the patient all times, while the second one always prioritizes dispatch to pick up an AED. A case study was conducted in the municipality of Norrköping, Sweden, to test and compare the model and the two approaches. In the case study, a set of potential first responders equipped with a smartphone app received alerts that they could accept or decline. The proposed model and the two greedy approaches were tested on a total of 174 cases.

The comparative results indicate that the proposed optimization model performs better than the first greedy and the second greedy approaches, which leads to higher survival rates for the patient in 80% and 7% of the tested cases, respectively. Also, the results indicate that the outcome of the dispatch would be the same regardless of the decision for 13% of the test cases, i.e. the proposed model and both greedy approaches produced the same survival rates. Even though the second greedy approach in 93% of the tested instances produced an optimal solution as the optimization model, having a generalized dispatch decision to always prioritize the delivery of AED might be too simplistic. Since the decision directly affects the patient's life or death, it is not rational to disregard the 7% of cases for which the second greedy approach did not produce an optimal decision. Therefore, an optimization model can take each case's circumstances into account and suggest a dispatch decision that maximizes patient survival.

Paper II was co-authored with Tobias Andersson Granberg, Nicklas Ennab Vogel, and Vangelis Angelakis. The author of this thesis was the paper's main author and carried out the literature review, developed the preliminary model, refined the final model, implemented the model, tested and analyzed the results, and had major involvement in the writing of the paper.

Paper II is published in

- *Proceedings of the 52nd Hawaii International Conference on System Sciences (HICSS-52)*, Hawaii, USA, 8th-11th January 2019.

Parts of the work were presented by the author of this thesis at

- 44th annual meeting of EURO Working Group on Operations Research Applied to Health Services (ORAHS), Oslo, Norway, 29th July – 3rd August 2018.
- Swedish transport research conference 2018, Gothenburg, Sweden, 15th-16th October 2018.

4.3 Paper III: Modeling uncertain task compliance in the dispatch of volunteers to out-of-hospital cardiac arrest patients

Paper III focuses on the same problem as Paper II, i.e. the dispatch of volunteers to OHCA patients. Nonetheless, in Paper III, uncertainties associated with the volunteers' actions once assigned a task are explicitly modeled. This was done by taking into account the probabilities of mission abort, non-complying actions, and full compliance with instructions for each task assignment. This was to have a more realistic approach towards the volunteers' dispatch compared to Paper II.

There is a set of volunteers who could be sent to the patient in the event of an OHCA. However, any volunteer that receives the alarm, with some probability, might accept the call. When the alarm is broadcasted to the volunteers closest to the patient, it is not known which of the volunteers will accept or reject the alarm; therefore, they have an acceptance probability. Also, when volunteers receive a dispatch task, there is a probability that they will assume that doing the alternative task is better; they might decide to discontinue the mission for any reason and, consequently, abort the mission half-way through. In collaboration with the research group in charge of the project SMS lifesavers in Sweden (https://www.smslivraddare.se/), historical data on volunteers' dispatch to OHCA patients for the time between 2018-May-03 and 2018-September-10, consisting of 708 missions, was obtained. Based on the historical data, probabilities associated with volunteers' actions regarding their task assignments were calculated, i.e. complying with task assignment, doing the alternative, or aborting the mission.

After the acceptance signal has been received from each volunteer, the problem is to select which task to assign to the volunteer to maximize patient survival chance, i.e. send them directly to the cardiac arrest patient or first pick up an AED en route to the patient. However, the dispatch decision for each volunteer is affected by previous volunteers' decisions as well as the decision that the current volunteer might make about their task assignments. Consequently, this paper proposes a method in which based on a survivability function and with consideration of all possible outcomes as a result of volunteers' actions, the task assignment at each step (when a new volunteer has accepted the alarm) is decided.

The proposed method was compared with the dispatch approach currently used by the SMS lifesavers project as stated by the project team. Of 708 cases, 37 cases had no mission assignment since no volunteer had accepted the alarm. The comparative results of the remaining 671 cases indicate that, in 90% of the cases, the proposed method performed better than the original dispatch method used by the SMS lifesavers project. In these cases, the largest difference in their achieved survivability is 0.12462. However, in 4% of cases where the original method performed better than the proposed method, the largest difference between their achieved survivability is 0.02447. For the remaining 6% of cases, both methods performed equally well. The sign test for matched pairs was used to investigate whether the difference between achieved survivability based on two methods is statistically significantly different or not. The test result indicates that, with a confidence interval of 95%, the median of the results of the proposed method, 0.18270, is statistically significantly higher than the median of the results of the original method, 0.16218. Based on the mean of the differences between achieved survivability based on two methods, i.e. 0.01747, in the 671 cases, by using the proposed method, about 11 more people, on average, will survive compared to when the original dispatch method is used. As 671 cases are from about four months, use of the proposed method would translate to saving potentially 30 more lives per year in Sweden using a dynamic dispatching method.

Paper III was co-authored with Tobias Andersson Granberg and Vangelis Angelakis. The author of this thesis was the paper's main author and was involved in the modeling and carried out the literature review, did the coding and implementing the method, tested and analyzed the results, and had major involvement in the writing of the paper.

Paper III has been submitted for publication.

Parts of the work will be presented by the author of this thesis at

- 45th annual meeting of EURO Working Group on Operations Research Applied to Health Services (ORAHS), Karlsruhe, Germany, 28th July – 2nd August 2019.

5. Conclusions and future research

5.1 Conclusions

The emergency services are challenged by problems of increasing demand uncertainty and resource shortage over time. Considering these challenges, the aim of this thesis was to provide operations research-based models and methods that can assist medical emergency services in daily emergency management.

To approach the problem of increasing demand uncertainty, OR was adopted to provide a demand forecasting model (Obj1, Section 3.1). The model was developed using Zero-inflated Poisson (ZIP) regression and real data from two years of ambulance calls for acute cases (Priority 1 and 2) in three counties in Sweden. It was found that using an OR method such as ZIP can lead to improvement in forecasting accuracy compared to the existing model. The output of the developed model contributes to both preparedness for and response to daily medical emergencies. The proposed model took into account the first two research opportunities identified in the literature review (see Section 2.6): 1) to simultaneously consider time and geographical location of medical daily emergencies while using a regression model, and 2) to consider geographical zones with few or no population and very low call frequency.

To provide solutions to the problem of increasing resource shortage as well as benefiting from the opportunity of new types of resources, OR-based model and method for the dispatch of volunteers were developed (Obj2, Section 3.1). Experimental and real data were used to test the model and method. Comparison of the results of the model and method developed with the help of OR and benefiting from a specific OHCA survival function with the results of the currently existing models showed higher survivability of OHCA patients for the developed model and method. The outputs of the proposed model and method contribute to the response to daily medical emergencies. In the development of the model and method, the last two research opportunities in Section 2.6 were considered: 1) to use OR for modeling the dispatch of volunteers to OHCA patients while also considering time in the model, and 2) to incorporate the survival function of OHCA patients in the OR model.

The results of these studies provide the medical emergency managers two main opportunities as shortly described below.

1. Acquiring more information about the future demand for the medical services that helps medical emergency managers plan their operational as well as tactical activities. This is achieved with the forecasting model, which provides additional information about future demand and the factors that affect the creation of medical emergency demand. This information provides medical emergency managers with the possibility to plan their available limited resources better and to make proactive decisions in different aspects, such as location-relocation of ambulances, allocation of ambulances to existing stations, and the required number of ambulance staff members and equipment.
2. Obtaining tools that help medical emergency managers effectively utilize volunteers in medical emergency response operations. The number of volunteers and their participation in medical emergency response operations has grown in recent years. However, these positive trends alone will not necessarily lead to achieving the best possible outcomes. Other information required for achieving the best possible outcomes are: 1) good knowledge about how the participation of volunteers affects the outcome of an emergency, and 2) the most efficient way that volunteers should be utilized in response to an emergency. The dispatch model and task assignment method can provide answers to these two questions, which can result in better management of volunteers and better outcomes.

The studies in this thesis show that OR is capable of providing solutions for and information on problems that do not always have trivial answers. These solutions and information can contribute to better decision making. In the context of daily medical emergency management, making better decisions means the possibility of saving more lives and reducing human suffering. Even though much research has used OR in daily emergency management and the emergency response process, including the models and method developed in this thesis, there remain areas for further research in which OR can play a positive part.

5.2 Future research

To further improve management of emergency response processes, especially in the face of increasing demand uncertainty and resource shortage, future research can be carried out in several directions. Based on the two objectives of this thesis, these future research directions can be classified into two main categories of *emergency* *call forecasting* and *volunteer management*. The following future research suggestions are based on the studies conducted within this thesis and previous works, such as that of Wong and Lai (2012, 2014) in *emergency call forecasting* and Falasca and Zobel (2012) in *volunteer management*.

The first category of future research directions, *emergency call forecasting*, mainly focuses on providing more detailed information and factors to the forecasting models. These directions are as follows:

First, *improving the model for the prediction of medical emergency calls with the use of real-time data and making a real-time forecast of the number of medical emergency calls*. This real-time data can include people's movability, weather data, and traffic data. People's movability can be obtained with the use of mobile phone tracking data to estimate the number of people in a zone. This movability data can compensate for the shortcomings of current existing population data. These shortcomings occur because the existing population data is at least one year old when made available, and it does not capture where people actually are in each zone, i.e. it is static. This results in the current model's incapability of capturing temporary population density changes in zones.

Second, *improving the forecasting model for medical emergency calls to consider type and priority of medical emergency*. The proposed model in this thesis only forecasts the number of calls regardless of their type and priority. An improvement can be so that it is also capable of predicting the type of medical emergency, e.g. trauma, drowning, and cardiac arrest, or the emergency's priority, i.e. in the range of 1 to 4 priority, where 1 represents urgent life-threatening emergencies and 4 represents planned patient transportation.

Third, *extending the forecasting model so that it can make predictions for a wider range of emergencies*. The model developed in this thesis is designed to forecast the number of emergency calls that medical services respond to. A more generalized model would have the capability of making predictions for both medical emergencies, as well as fire and rescue calls.

A general direction for future research in *volunteer management* is to include disasters in the area of study, so that the models can be used for any emergency across the emergency spectrum. Furthermore, the following outlines in detail further research directions in *volunteer management* within daily emergencies.

First, *considering volunteers differences when making a dispatch decision*. The models developed in this thesis for the dispatch of volunteers assumed that all volunteers have similar capabilities and behavior. One improvement to these models is the consideration of volunteers' differences. Different capabilities and behavior can lead to different dispatch and task allocation decisions, which can potentially result in different outcomes. The performance of volunteers that responded to prior emergencies, such as OHCA cases, can be measured. These volunteers can be ranked based on their previous performance as well as their capability measures, and future decisions for task allocation and dispatch can be made based on these measures.

Second, *incorporating more stochastic aspects, such as stochastic arrival times, in the models for the dispatch of volunteers*. All times in the current models, i.e. volunteers' travel times both directly to the patient and after collecting an AED, access times to an AED, and the travel time of the EMS, are considered deterministic. To have more realistic models, these times can be treated as stochastic. The model can also be extended to include the stochasticity of a volunteer's primary acceptance or rejection of an alarm.

Third, *extending models for the dispatch of volunteers and the allocation of task to them in the OHCA cases to different types of emergencies*. These emergencies can consist of those covered by fire and rescue services, as well as other types of medical emergencies in terms of daily emergencies. This extension can also include improving the model so that it can be used for all emergencies across the emergency spectrum, specially disasters.

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Linköping Studies in Science and Technology, Thesis No. 1842, 2019
Department of Science and Technology

Linköping University
SE-581 83 Linköping, Sweden

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