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A Simulation study of logistics for disaster relief operations

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Abstract

Natural events, climate change and urbanization are pushing the pressure on disaster relief operations. Decision science and ICT technologies can be effectively used to face humanitarian logistics issues. This concerns both man-made threats (accidents) and natural hazards such as e.g. floods, storms, earthquakes and volcanic eruptions. The purpose of this paper is to analyse the operation strategies for rescue in emergency situations deployed by specialized rescue teams. Usually standard procedures are applied for rescue operations. These procedures can fail in disaster relief situations where an abnormal number of rescue operations are to be fulfilled. It is important to study mechanisms able to give more flexibility to these procedures and to study the effectiveness of the procedures in planning phase. At this aim we used discrete event simulation as decision support for planning different strategies of action to apply in emergency and risk situations. In particular several scenarios have been developed as simulation models combining different initial hypothesis with the aim to build a generalized and flexible procedure to apply in different scenarios. As a result, the simulation is able to allocate efficiently different resources under emergency situations (multiple scenarios for specific events). Tests and sensitivity analysis have been performed using instances related to a GIS of the Italian Sicily region and a typical set of facilities and rescue team. The simulation system works considering the different typologies of vehicles and staff to choose the best solution available in that specific time. The work is part of a national research project aimed to develop cloud-based systems and sensor networks for multi-risk management. The developed simulation system can provide crucial help to the rescuers in order to planning the best relief strategy for mitigate the effects of natural and industrial disasters.

1. Introduction

Natural events, climate change and urbanization are pushing the pressure on disaster relief operations. This growing trends is confirmed from almost recent studies on global warming. Expected average annual flood losses in the EU, estimated at €4.9 billion/year for the period 2000-2012, were projected to potentially increase to €23.5 billion by 2050 [1]. The topic of this article is the logistics as it covers the most important element in any disaster relief effort, and the most expensive part because it accounts for about 80% of the total costs in disaster relief [2]. Emergency or humanitarian logistics can be defined as the application of the methods and practices of the logistics science to emergency and relief operations for the mitigation of the effects of anthropic or natural disasters. The aim of this paper is to analyse the operation strategies for rescue in emergency situations deployed by specialized rescue teams. The research context is an IT based project aimed at integrating heterogeneous networks in a cloud platform for emergency events management. Decision science and ICT technologies can be effectively used to face humanitarian logistics issues. This concerns both man-made threats (accidents) and natural hazards such as e.g.
floods, storms, earthquakes and volcanic eruptions. Often the problem is that risks events are associated to different sources and treated in a different and disaggregated manner. The scope of the project addressed in this work is to study the integration of multi-risk events. Different risk events can be related (e.g. earthquakes and landslides) and must treated in an aggregated way. Integration has been addressed also regarding resource allocation at strategic, tactical and operational way. Relief facilities must be designed and relief resource allocated often for different risk event. In this research we address the problem of relief operation management and optimization when they must be used for multi-risk event management. Simulation has been used to analyse relief operations and investigate properties. The concrete objective is to analyse the effectiveness of relief strategies when they are applied in a emergency scenario and different risk sources emerge. The implementation of dynamic relief operations able to be interrupted can improve in some situation improve flexibility and relief success rates. The paper is organized as follows. Section 2 reviews research literature on discrete event simulation for emergency logistics. Section 3 describes the addressed problem and the relief procedures to be simulated. Section 4 detail the implemented simulation model. In Section 5 simulation results are discussed while Section 6 contains concluding remarks.

2. Literature review

Logistics in emergency scenarios is strongly affected by uncertainty. Uncertainty is in the relief request (the demand of humanitarian logistics), resources and equipment provided by public and private actors, uncertainty in the conditions of the connecting network. At this aim both optimization and simulation approaches must address uncertainty for emergency logistics [3]. For optimization, fuzzy systems and robust optimization are used to tackle uncertainty [4]. Simulation enable the study of dynamicity of the logistic systems by using what if analysis for strategic tactical and operational development of relief operations. Sheu in [5] apply fuzzy clustering and multicriterial analysis to dynamic relief demand management to address uncertainty in demand caused from imperfect information. Monte Carlo analysis has been approached in [6] in order to improve the effectiveness of emergency logistics models. Simulation exploited through intelligent agents is addressed in [7] with application to military logistics. Military logistics often have many similarities with emergency logistics and the authors show the usefulness of simulation in describing analysing and improving of resource allocation in term of vehicles, equipment and facilities. Applications of what if analysis are exploited in [8] where emergency management simulation models are developed and applied to the settings of natural disasters. The literature search shows potentiality of simulation in emergency logistics and in the following of this paper we describe the proposed usage of simulation through the discrete event simulation.

3. The problem addressed

3.1. The SIGMA project and the aim of the work

The project “Integrated system of sensor in cloud environment for advanced multi-risk management” (SIGMA – Sistema Integrato di sensori In ambiente cloud per la Gestione MultiRischio Avanzata) is composed of a multi-level architecture (Fig. 1) designed to acquire, integrate and process data from various heterogeneous sensor networks (weather, seismic, volcanic, water, rain, traffic, maritime, environmental, video-monitoring, etc...) with the aim of strengthening of control and monitoring systems (both for environmental and industrial production) to provide support to prevention and management of risk situations [9]. The system will allow to send data gathered by sensor networks even in critical situations and in areas where the usual communication infrastructure will not be available.
3.2. Relief procedures

The modelling approach for relief procedures, according with multi-risk management approach, considers two main criteria: the chronological order of events occurrence and their severity. Moreover, flexibility has been considered in term of allowing preemptive execution for relief operations, i.e operations may be stopped. The three procedures modeled and simulated in this work are described as follows:

1: *FIFO* procedure: requests are processed according to their order of arrival (First In First Out). This criterion does not take into account the severity of events but their temporal order of occurrence in different places.

2: *NonPreempt* procedure: The severity of the events is the driver for event sorting: when a dangerous event occurs, it get priority and become the first next event to process. Moreover the rescue operations in progress (also relative to lower priority events) must be completed.

3: *Preempt*: A real-time monitoring of the situation and a re-evaluation of the requests arrived is carried out, in order to give more importance to the events with the highest priority. This logic is also applied to the already started activities, by means of interruption of less critical operations. Moreover, the priority of interrupted interventions is increased, so they could be finished before events of the same type occur. This scenario represents the currency emergency management of the National Fire Service at least as regards the ordinary events management.

| Priority criteria          | Model name  | Flexibility criteria                  |
|----------------------------|-------------|---------------------------------------|
| chronological order        | 1 – FIFO    | started action cannot be interrupted  |
| relevance based criterion  | 2 – NonPreempt | started action can be interrupted    |
|                            | 3 – Preempt |                                        |

4. Simulation model – main components

In the following of this section the implemented simulation model is detailed in its main components which are: road network, rescue facilities, request demand sources, rescue vehicle and equipment, SSS paradigm (source-server-sink).

The simulation model exploit the use of a geographical map loaded on the SIMIO® simulation software; the facility and the road network are geo-localized over the loaded map. Risk events are represented by model entities which are generated following an exponential random distribution. The entities are firstly generated as general risk and after assigned at specific demand node, then characterized as specific type event (fire or flood). Each risk event requires - in order to be mitigated - a set of resources representing, in the analysed case, the needed rescue vehicle (pumper trucks and dewatering systems). The events and resources are logically connected through simulation processes. Once an entity is created, a simulation process is activated and its execution defines the assignment (through the seize simulation step), of vehicles to risk events following the defined rescue procedures. In the simulation run, as shown in Fig. 2, these logic steps cause vehicles to travel the road network for risk mitigation. When the process is completed (or is interrupted), the resources are released and can return to the home node or go to mitigate another risk event.

4.1. The road network

The road network was modelled over data tables mapping the distance (in km) between facility and demand point. Travelling time over the defined road network is given by the predefined velocity parameters of each vehicle of the rescue fleet.
4.2. The rescue facility

The modelled facility identifies Firefighters, Civil Defence and Medical First Aid. It is represented by a node in the road network, located in a predefined point of the map and connected to the road network. The rescue facility as a home for the fleet where.

4.3. Rescue vehicles

Vehicle have been modelled according to information taken with interview with Firefighters teams. To every type of vehicle has been assigned a specific speed and each vehicle represent a rescue team. Speed can be modified programmatically to model road network and viability state.

4.4. Demand nodes

The demand nodes, which identify the places of interest, have been represented by a SSS model (Source- Server-Sink) and by a node on the road network. The source object models the person calling the facility asking for help. Its behaviour is not trivial because it depends by an event generator and different tables which define the type of event and interarrival time for each demand node (place where the disaster occurred). This makes it possible to customize every point of the map with more realistic data. The risk map is parameterized with the localization on the map and can be connected with the historical data of the risk events.

The servers are the core of the simulation. They establish the service rules according to the priority criteria such as chronological order of arrivals or importance of request. The servers, thanks to additional processes and tables, dynamically define which and how many resources are required for each type of intervention as well as the processing time required to solve the emergency. In order to optimize the response time for high priority events, especially for some model scenarios, it has been created an additional process to interrupt low priority requests if enough vehicles are not available. The sinks do not define special operating modes because they simply represent the communication from rescue teams about the emergency resolution.

4.5. Requests

The entities entering the SSS system represent different relief requests arrived to the logistic central facility. To each request a priority is assigned which value depends on the nature of the event. table data store the information about the needed resources and the processing time requested to fulfill the request. For a particular scenario (the preemptive one) has been created a process used to augment the priority of the interrupted requests.

4.6. Events Generator

The events generator object allows, in absence of sufficient historical data, to simulate the occurrence of emergencies however based on real data, living a probabilistic weight to the path that define in which place the event will occur.

5. Simulation scenarios: settings and results

5.1. Experiments settings

Design of experiment has been performed taking into account some common settings: a network with only a rescue facility (Scalaletta Superiore) and three demand nodes (Itala, Giampilieri and Atolia) have been considered; duration of the simulation has been set to 24h; the events has been generated with the aim to simulate different scenarios obtained by changing the mean of interarrival time's exponential distribution (with 5, 10 or 20 minutes); for each simulation run with different interarrival time, 50 replications were made in order to obtain statistically significant data. Moreover, as already said, two different types of event with different probability of occurrence have been considered: for the fire event the probability has been set to 40% while for the flooding event the probability has been set to 60%. However the events have the same chance of occurrence in one of the three demand nodes which customize the events with the territorial target. Processing time of rescue operations is different depending on the type of event. The distribution used is a random Pert. This distribution (also known as the Beta-Pert) is a particular version of the Beta distribution where the shape parameters are computed from the minimum, modal (most likely), and maximum parameters. This is a useful distribution for modelling expert data based on these three parameters and in some case more suitable of the triangular distribution. In fact, unlike the triangular distribution the Beta-Pert distribution provides a smooth curve which can closely approximate the normal or lognormal distributions. The mean of the pert distribution is equal to (minimum + maximum + 4 * mode) / 6. Inside SIMIO®, Beta-Pert is named random.Pert(minimum, modal, maximum). Fire events follow a random.Pert(30,35,40) [minutes] distribution, while flooding events follow a random.Pert(15,20,25) [minutes] distribution. It is very important to consider also the travel time of vehicles which depends on the distance between vehicles and demand nodes and the speed of vehicles. Regarding the availability of vehicles and relief equipment, we have set six pumper trucks and six dewatering systems. In particular fire event needs three pumper trucks and one dewatering system while
flooding event needs one pumper truck and three dewatering systems.

5.2. Results

Comparison has been carried out by aggregating the following data: 1) the percentage of resolved events (fire and flooding); 2) the percentage of vehicle utilization (marking pumper trucks and dewatering systems), detailing both each vehicle utilization and the total usage for each fleet type; 3) the average number of events in queue and their waiting time. Sensitivity analysis has been performed in particular stressing the interarrival time and then the three scenarios have been compared to see how the system reacts to the different logics. In order to calculate the resolution rate we have compared number of events created (an average of the 50 replications performed) with the number of events resolved (event\_resolved / event\_created); this has been done for the different interarrival rated for each of considered models (FIFO, NonPreempt and Preempt).

As depicted in Fig. 3 and Fig. 4, the behaviour of the models change significantly when these parameters are varied; it can be immediately noted how stressing the system (high frequency of event occurrence) the resolution rate is affected by this variation. In particular Fig. 3 and Fig. 4 highlights as the resolution rate is almost 100% if interarrival time is 20 minutes, but if the frequency increases is not possible to fulfil all requests. When the system is stressed, the effect of priority on resolution rate is very clear; indeed in Fig. 3 (fire event, high priority) the preemptive model (Preempt), which encourage the resolution of fire, is the best solution, while in Fig. 4 (flooding event, low priority) this model has the worst performance. Obviously for the flooding event, when the interarrival time is 5 minutes, the best solution is the FIFO procedure model because in this scenario only the chronological order of arrival is important.

Emergency logistics is characterized by uncertainty and strong variations in the rates of relief requests. In particular, at the beginning of a disaster, the relief requests may raise following an exponential profile while, after some time, they may decrease significantly. It is therefore important to check the effectiveness of the proposed relief procedures in different settings, from when the system is under-capacitated, i.e. with high rate of relief requests, to when the system is over-capacitated, i.e. with low rate of relief requests. 3) From the analysis it results that lowering the relief request frequency corresponds in a more than proportional lowering in waiting times. This happen s specially when the frequency change from a mean rate to a low rate and less when the frequency change from a high rate to a mean rate. This is explained by the consideration that when the relief requests frequency is too high, the relief team are not able to keep up with the event occurrences and the systems tend to freeze. Under these conditions complex procedures tend to fail especially when they consider preemption. This is due to the fact that in the Preempt procedure, events interrupted to give precedence to the most urgent events, are put on hold with the other events (although with an increase of the priority). Doing this it will cause to have an increase of the entities in the queue with a consequent increase of the waiting time because time wasted in travelling network for manage multiple events. When the system is stable or tend to be over-capacitated the relief teams have more time to select the best request to process and to implement pre-emption. Moreover, some time the pre-emption success is conditioned to the distance of the territory affected by the disaster in relation to the place where is dislocated the rescue facility. In the studied settings the NonPreempt procedure results the most efficient.
stable when the frequency of relief request have strong changes.

6. Concluding remarks

Logistics in emergency scenarios is strongly affected by uncertainty. Moreover, the time following the occurrence of a disaster is characterized by highly changes in the rates of relief requests and relief resources availability. Simulation modelling may be used as a strong tool for supporting the decisions regarding the relief operations management. Under this context, the work described in this paper approach the modelling and the analysis through simulation of standard relief procedures actuated by relief teams. The procedures can be both static and dynamic and consider both the gravity of the occurred events and they chronological time of occurrence. By following the aim of the research project under which the work was developed, the simulation model considered multi-risk based event occurrence. Therefore the experiments considered two types of events to be managed in parallel, fires and floods. The procedures have been compared when the rate of the relief requests strongly change with the aim to put in evidence the procedure performances in relation to disaster dynamicity. Apart of the detailed simulation results, the paper demonstrated the usefulness of the simulation modelling in emergency logistics. Simulation modelling must be used in conjunction with other decision support methods as optimization as actuated in the research project SIGMA to catch up with non-standard optimization objectives, uncertainty and tight respond times. Future works will consider higher integration among the cited support tools for better management and optimization of emergency logistics.

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