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Interfaces with Other Disciplines

OR/MS research in disaster operations management

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Abstract

Disasters are large intractable problems that test the ability of communities and nations to effectively protect their populations and infrastructure, to reduce both human and property loss, and to rapidly recover. The seeming randomness of impacts and problems and uniqueness of incidents demand dynamic, real-time, effective and cost efficient solutions, thus making the topic very suitable for OR/MS research. While social sciences and humanities literatures enjoy an abundance of articles on disaster management, the OR/MS community is yet to produce a critical mass. In this paper, we survey the literature to identify potential research directions in disaster operations, discuss relevant issues, and provide a starting point for interested researchers.

Keywords: OR in societal problem analysis; Disasters; Emergency management

1. Introduction

The experience of the 2004 Indian Ocean Tsunami shows that disasters continue to cause loss of human life, environmental damage, disruption of infrastructure, and economic loss. A review of available databases such as EM-DAT, maintained by the Center for Research on the Epidemiology of Disasters and the United States Office of Foreign Disaster Assistance, DesInventar, a project of La Red and OSSO, and the Disaster Database Project, maintained by the University of Richmond (see Appendix A for the URLs of these databases) demonstrates the scale of the problem. As an example, in 2004 the Disaster Database Project added a variety of events ranging from earthquakes to maritime accidents, averaging three new disasters a day.

On 26 December 2004 the Indian Ocean tsunami killed in excess of 225,000 people and dislocated millions more in countries spread around the

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Ocean's rim from Kenya to Indonesia. The 2001 bombing of the World Trade Center in New York generated direct and indirect losses that most probably will exceed 50 billion US Dollars. And the human cost of extended genocide in a variety of countries in the last two decades has reached totals varying from 100,000 to 800,000 people per incident. These are large, intractable problems that test the ability of communities, nations, and regions to effectively protect their populations and infrastructure, to reduce both human and property loss, and to rapidly recover. Tens of thousands of dead and billions of dollars of damages signal the existence of significant problems for study by any discipline with the capability of reducing the impacts and improving the response to such events.

There is increasing recognition of the need for study of OR/MS issues in disaster management. Dr. Luk van Wassenhove from INSEAD recently wrote six cases on Humanitarian Logistics in Disaster Situations, commenting that "the subject of disaster management is an absolutely fascinating one that is growing in importance" (Van Wassenhove, 2003). Another promising development is the announcement of the EURO Management Science Strategic Innovation Prize—MSSIP 2006. The invited topic, OR/MS in Humanitarian Security, is defined as "all those situations in which the survival, the welfare, the health, or the fundamental rights and liberties of people, whether entire populations or particular social groups, are threatened". The MSSIP 2006 Jury states that "from the many challenging problems arising within the humanitarian security area, there is an emerging need to develop new methodologies or new variants of old ones, such as emergency logistics, conflict management and resolution, security assessment, strategic management of crises..." (from http://www.euro-online.org).

The objectives of this paper are to (i) point to issues in disaster operations management, (ii) survey existing OR/MS literature, (iii) suggest future research directions, and (iv) act as a tutorial for interested researchers. We believe operations research has significant application to the management of disaster preparedness programs as part of a unified community effort and to the actual conduct of disaster response operations.

In the following section we explain the boundaries of the study. A review of literature is presented in Section 3. Section 4 suggests future research directions, while Section 5 points to some problems and issues in disaster operations management. Section 6 concludes the paper. Appendix A should direct interested researchers to a sample of organizations and disaster related resources as a starting point.

2. Boundaries of the study

Much of the disaster management research relates to social sciences (see Hughes, 1991 and http://www.geo.umass.edu/courses/geo510/index.htm for a comprehensive bibliography). This type of research focuses on disaster results, sociological impacts on communities, psychological effects on survivors and rescue teams, and organizational design and communication problems. Even a comprehensive Emergency Management Related Bibliography compiled by the Federal Emergency Management Agency contains only one article from a traditional OR/MS journal (available from http://www.fema.gov). We were unable to locate any study which surveys the OR/MS literature and analyzes current efforts in disaster operations management (DOM).

2.1. Definitions of key concepts

To highlight the boundaries of the study three questions need to be answered: What is OR/MS? What is a disaster? And what constitutes disaster operations? The last question is relatively easier to answer. We consider the set of activities that are performed before, during, and after a disaster with the goal of preventing loss of human life, reducing its impact on the economy, and returning to a state of normalcy as disaster operations.

The definition of OR/MS on the other hand, is not clear cut. Churchman et al. (1957) defines OR/MS as the application of scientific methods, techniques, and tools to problems involving the operations of systems so as to provide those in control of the operations with optimum solutions to the problems (p. 9). Winston (1994) defines it as a scientific approach to decision making, which seeks to determine how best to design and operate a system, usually under conditions requiring the allocation of scarce resources (p. 1). The Association of European Operational Research Societies (EURO) web site contains the following definition: "Though there is no 'official definition' of Operational Research ('Operations Research' in the US), it can be described as a scientific approach to the solution of problems in the management of complex systems. In a rapidly changing environment an understanding is sought which will facilitate the choice and the implementation of more effective solutions which, typically, may involve complex interactions among people, materials and money" (from http://www.euro-online.org). The new "Science of Better" marketing campaign launched by INFORMS, the US counterpart of EURO, defines OR as the discipline of applying advanced analytical methods to help make better decisions (from http://www.scienceofbetter.org). These four definitions converge on "a scientific approach to aid decision making in complex systems" and this is the definition we use in this paper.

The above definition still covers a wide range of applications and methodologies of OR/MS. INFORMS also mentions that "operations researchers draw upon analytical techniques including mainly simulation, optimization, and probability and statistics". We include to this list soft OR techniques and methodologies from OR's sister areas like decision theory, systems dynamics, multi-criteria decision making, and expert systems, which are being published frequently in traditional OR journals.

This study is not limited to a certain kind of event and considers all disaster types that are of interest to the International Federation of Red Cross and Red Crescent Societies (IFRC). IFRC lists disaster types as (from http://www.ifrc.org/what/disasters/types/): (1) Hurricanes, cyclones and typhoons, (2) Floods, (3) Drought, (4) Earthquakes, (5) Volcanic eruption, (6) Epidemics, (7) Famine and food insecurity, (8) Man-made disasters, (9) Population movement, and (10) Technological disasters. The reader is referred to the IFRC web site for the definitions of these disasters. Furthermore, Green and McGinnis (2002) provide a discussion of the broad classification of these events by causation that helped frame our investigation.

For this study we define "emergency response" as response to catastrophic and disaster events and do not consider daily response of ambulance, police, or fire departments to routine emergency calls. Readers interested in research on daily emergencies are referred to Swersey (1994) and Chaiken and Larson (1972). There is general agreement that there is a clear demarcation between what are termed "routine emergencies" (Hoetmer, 1991) or "everyday emergencies" (Fischer, 2003) and more serious emergencies, disasters, and catastrophes. For the purposes of this paper, major emergencies, disasters, and catastrophes are considered to be a continuum of events that can be generically termed disasters.

A routine event is typically managed with the resources of a single governmental agency, or partial resources from several, using standard procedures, and with minimal dislocation. Operationally, the transition to a higher category of emergency occurs when resources become stressed, when non-standard procedures must be implemented to save life or when special authorities must be invoked to manage the event (Landesman, 2001; Landesman, 1996; Hoetmer, 1991; Auf der Heide, 1989). It is critical to understand that a disaster becomes a disaster when someone who is authorized to say it is a disaster does so. In other words, declarations of states of emergency and disaster are political and legal acts with specific requirements and authorities (see the provisions of the Michigan Emergency Management Act as an example (Michigan, 2002)). The legal approaches to definitions of disaster focus on identifying specific disaster causing events, much as the IFRC does, and on qualifying the governmental reaction based on the authorities of the office holder invoking a response.

2.2. The search process

To gather the bibliography several databases were utilized including ISI's Web of Science®, IFORS search engine, Business Source Premier, Cambridge Scientific Abstracts IDS, Compendex Engineering Village 2, Scirus, Econbase, Civil Engineering Database, Scitation, and SciFinder. Keywords "disaster", "emergency", "catastrophe", "extreme event" and their extensions such as "disastrous" and "catastrophic" were searched in the title, abstract and body of text of journal articles published in English. Disaster research in medicine, geophysics, forensic science, oceanography, meteorology, biology, and psychology, or research from the mathematical social sciences related to crowd management, guerilla wars, and domestic political conflict modeling were filtered using appropriate Boolean clauses. A manual scanning of articles for subject matter resulted in further eliminations due to the metaphoric appearance of the keywords in unrelated contexts such as a "public relations disaster" or a "financial emergency". Expanding the search to the citations of relevant articles added more hits directly related to the field of operations research. There is some subjectivity in deciding whether a particular article qualifies as DOM research. An article is included if the problem investigated relates to major hazards listed above. For example, optimization of inspection routines for machinery would not qualify but the same problem for system critical components of aircraft or spacecraft would. There is also subjectivity in deciding on the contribution of a research. This point is explained further in the next section.

We limited the time period of the search to 1980 forward because the sample prior to this date reflects three clear limiting factors. Prior to 1980 emergency management, emergency planning, and civil defense agencies worldwide largely focused on preparedness for population protection in nuclear war. For instance, all hazard preparedness was not a component of United States government doctrine until the establishment of the Federal Emergency Management Agency in 1977. As a result, practitioner literature dealing with natural disasters was rare, a factor compounded by the nonprofessional status of most jobs in the field. At the same time academic opposition to nuclear war preparation was limiting interest in problems addressed by agencies that had a wartime mission. And finally, university level instruction in the field did not commence on a degree granting basis until the mid 1980s in the United States, making studies of disaster problems a relatively low priority.

DOM research is by its nature significantly cross-functional. Consequently, this type of research appears in a wide variety of academic journals. Therefore, even though the main focus of this study is OR journals, to encourage interdisciplinary research we did not eliminate non-traditional OR outlets from the search. This search strategy results in a fairly comprehensive search of traditional OR/MS outlets as well as other areas where analytical approaches to disaster problems can be found such as civil and environmental engineering, mathematical social sciences, and military operations. However, this literature survey is limited to academic journals and excludes practitioner magazines, conference proceedings and books. Hence it is by no means an exhaustive bibliography of OR/MS research in DOM.

3. OR/MS research in DOM and publication trend

We employed several different classification methods, one of which is identifying with which stage of a continuum of events an article is concerned (before, during and after a disaster). We also separated articles into groups based on research methodology, research contribution, disaster type, and problem scenario.

3.1. Characteristics of articles

Our search resulted in 109 articles with 77 of them published in OR/MS related journals, and 42 of 77 in main stream OR/MS outlets: Management Science, Operations Research, European Journal of Operational Research, Journal of the Operational Research Society, RAIRO-Operations Research, Annals of OR, OR Letters, Interfaces, Naval Research Logistics, and Computers and OR. Fig. 1 displays a histogram of articles published in these journals. EJOR appears to be

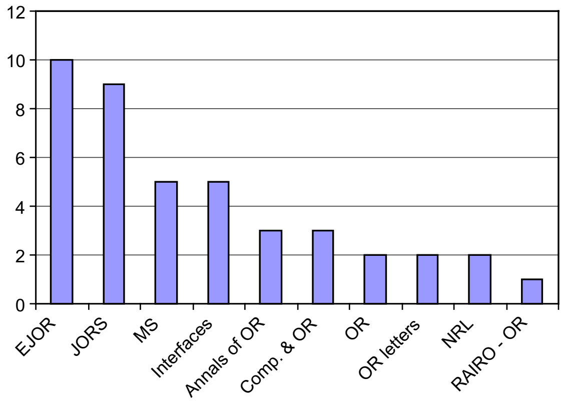

Fig. 1. Number of DOM articles in main stream OR/MS journals.

the choice of DOM researchers relatively more frequently. In contrast, only 32 articles published outside these journals contained OR/MS techniques. Even though this is not an exhaustive list, we believe it is a rather large subset of it. The list is relatively short when the breadth and depth of research potential and the population of groups holding stake in the topic is considered, and that is one of the motivations for this paper. A big part of analytical research on DOM is in the form of government agency reports, research center working papers, and white papers. More research needs to be published in academic journals to attract the attention of OR/MS researchers to the subject matter.

Table 1 provides a summary of statistics on the bibliography we have gathered. We have looked at author affiliations first. More than a third of all articles are published by authors with affiliations in the USA. The row labeled "international" indicates collaborative research among co-authors who represent two or more different countries. The fact that only 14.7% of articles are in this group suggests that DOM research can benefit from more international collaboration. Table 1 also shows that interest in disasters rose within the last two decades. Research in main stream OR/MS journals more than doubled between the 1980s and 1990s. This appears to be a result of a pre-1990s focus on urban emergency response problems. Since the beginning of the millennium

Table 1
Summary statistics of articles on DOM

	All journals	OR related outlets	Main stream OR outlets
Number of articles	109	77	42
Authors' nationality			
	%	%	%
USA	43.1	41.6	35.7
Other nations	42.2	41.6	47.6
International	14.7	16.8	16.7
Publication time			
1980s	12.8	13.0	19.0
1990s	40.4	40.2	40.5
Since 2000	46.8	46.8	40.5
Methodology			
Math Programming	32.1	36.4	42.9
Probability and Statistics	19.2	15.6	16.7
Simulation	11.9	11.7	11.9
Decision Theory and MAUT	10.1	9.1	4.8
Queuing Theory	9.2	13.0	11.9
Fuzzy Sets	5.5	3.9	0.0
Stochastic Programming	3.7	5.2	4.8
Experts Systems and AI	3.7	2.6	2.4
Systems Dynamics	1.8	0.0	0.0
Constraint Programming	0.9	1.3	2.4
Soft OR	0.9	1.3	2.4
Operational stage			
Mitigation	44.0	48.1	45.2
Preparedness	21.1	19.5	19.0
Response	23.9	26.0	33.3
Recovery	11.0	6.4	2.5
Disaster type			
Natural	28.4	22.1	11.9
Man-made	33.1	38.9	47.6
Humanitarian	0.9	0.0	0.0
All disasters	37.6	39.0	40.5
Research contribution			
Theory	26.6	27.3	23.9
Model	57.8	59.7	57.1
Application	15.6	13.0	19.0
Denizel et al. classification			
MS1	19.2	20.8	16.7
MS2	33.9	36.3	33.3
ME1	15.6	16.9	9.5
ME2	3.7	2.6	4.8
MC1	8.3	6.5	9.5
MC2	19.3	16.9	26.2

the number of papers published surpassed the number published in the 1990s. The growing economic and social impact of events, the declaration of 1990s as the International Decade of Natural Disaster Reduction, and the globalization of the threat of terrorism are probable causes of this rise in interest. This is indeed a good sign for DOM research, but not enough to produce a critical mass of research when compared to other popular topics such as supply chain management.

Table 1 shows that mathematical programming, including heuristics, is the most frequently utilized method, followed by probability theory and statistics, although the use of the latter is much less frequent. Simulation appears third in the list. Decision theory and multi-attribute utility theory are also used in DOM research, although none of the MAUT articles were published in main stream OR/MS journals. Queuing theory was used relatively frequently by OR/MS researchers, but the theory behind all of these articles, but one, was life sciences. Each of the articles using queuing theory was published by researchers from different countries without any international collaboration. Methods clearly underutilized in DOM research include systems dynamics, constraint programming and soft OR techniques.

3.2. Disaster operations life cycle and disaster types

Tufekci and Wallace (1998) suggest that emergency response efforts consist of two stages; pre-event and post-event response. Pre-event tasks include predicting and analyzing potential dangers and developing necessary action plans for mitigation. Post-event response starts while the disaster is still in progress. At this stage the challenge is locating, allocating, coordinating, and managing available resources. Tufekci and Wallace also suggest that an effective emergency response plan should integrate both of these stages within its objective. They add that separating pre- and post-loss objectives may lead to suboptimal solutions to the overall problem.

In the United States comprehensive emergency management is commonly described in terms of four programmatic phases: mitigation, preparedness, response, and recovery (Green, 2002; Waugh, 2000; Godschalk, 1991; Waugh and Hy, 1990). The four-phase approach covers all of the actions described in Tufekci and Wallace's classification while providing a more focused view of emergency management actions. Moreover, the four-phase classification is based on the Comprehensive Emergency Management concept introduced in the 1978 report of the National Governors' Association Emergency Preparedness Project.

Mitigation is the application of measures that will either prevent the onset of a disaster or reduce the impacts should one occur. Preparedness activities prepare the community to respond when a disaster occurs. Response is the employment of resources and emergency procedures as guided by plans to preserve life, property, the environment, and the social, economic, and political structure of the community. Recovery involves the actions taken in the long term after the immediate impact of the disaster has passed to stabilize the community and to restore some semblance of normalcy. Table 2 lists the typical activities involved in each of these four stages.

Table 3 lists articles in our literature review based on the stages of disaster management lifecycle. About 44% of all the papers reviewed address mitigation, with nearly half on risk analysis. Examination of the set of mitigation articles in main stream OR/MS journals reveals that all except one of the 19 papers focus on man-made emergencies such as industrial accidents, spills, and computer network crashes. This observation is not unexpected as technological emergencies, unlike their natural counterparts, may be preventable. Table 1 indicates that only 11.9% of articles in main stream OR/MS journals are on natural disasters. The rest covers man-made emergencies (47.6%) and general approaches to DOM (40.5%) designed to apply to all disaster situations, in contrast to the scenario based disaster and emergency management plans used by government agencies. No humanitarian emergencies (epidemics, famine, war and genocide) were addressed in the OR/MS related journals we examined.

Preparedness and response follow mitigation in research productivity, with 21.1% and 23.9% of articles published in these two areas, respectively.

Table 2
Typical activities of disaster operations management

Mitigation	Response
• Zoning and land use controls to prevent occupation of high hazard areas	• Activating the emergency operations plan
• Barrier construction to deflect disaster forces	• Activating the emergency operations center
• Active preventive measures to control developing situations	• Evacuation of threatened populations
• Building codes to improve disaster resistance of structures	• Opening of shelters and provision of mass care
• Tax incentives or disincentives	• Emergency rescue and medical care
• Controls on rebuilding after events	• Fire fighting
• Risk analysis to measure the potential for extreme hazards	• Urban search and rescue
• Insurance to reduce the financial impact of disasters	• Emergency infrastructure protection and recovery of lifeline services
	• Fatality management
Preparedness	**Recovery**
• Recruiting personnel for the emergency services and for community volunteer groups	• Disaster debris cleanup
• Emergency planning	• Financial assistance to individuals and governments
• Development of mutual aid agreements and memorandums of understanding	• Rebuilding of roads and bridges and key facilities
• Training for both response personnel and concerned citizens	• Sustained mass care for displaced human and animal populations
• Threat based public education	• Reburial of displaced human remains
• Budgeting for and acquiring vehicles and equipment	• Full restoration of lifeline services
• Maintaining emergency supplies	• Mental health and pastoral care
• Construction of an emergency operations center	
• Development of communications systems	
• Conducting disaster exercises to train personnel and test capabilities	

But the area in dire need for more research is, without question, disaster recovery. Only one article on recovery planning was published in main stream OR/MS outlets we studied. Only 11% of all articles in our literature survey address disaster recovery.

We categorized articles further based on their contribution to knowledge in DOM; model development, theory development and application (tool) development. Articles that develop an analytical model to solve and analyze a problem or to estimate an outcome belong to the first group. Research that tests hypotheses, investigates the behavior of a system, or provides a framework and advances our understanding of some phenomenon in the field is placed in the class of theory development. Lastly, research in which a computer tool is produced or a prototype is developed belongs into the application development group. More than half of DOM research published is on model development, followed by theory (26.6%) and application (15.6%) development.

An alternative approach to classifying OR/MS research originated with Corbett and van Wassenhove (1993) who separated published research into three groups named "management science, management engineering, and management consulting". They argue that the area of research that links theory with application, management engineering, carries the true spirit of OR/MS but is well underpopulated. Denizel et al. (2003) extends this classification further, dividing each category into two subgroups by considering attributes relating to the main features of the published study. They consider the problem setting, data, novelty of the problem, solution approach, generalization of results, and future research implications to create their scheme for classifying articles. We refer interested readers to Denizel et al. (2003) for the details of their classification algorithm. Table 1 provides a summary of the results of this classification scheme when applied to our bibliography. Table 4 lists articles in our literature survey based on the Denizel et al. classification scheme.

When applied to main stream OR/MS journals Denizel et al. classification reveals that more than a decade later, management engineering continues to be the undernourished side of OR/MS research, at least within the context of DOM. Half of the

Table 3
Articles listed by DOM lifecycle stage

Mitigation

No specified disaster type: Atencia and Moreno (2004), Current and O'Kelly (1992), Drezner (1987), Dudin and Semenova (2004), Economou (2004), Economou and Fakinos (2003), Englehardt (2002), Frohwein et al. (1999), Frohwein and Lambert (2000), Frohwein et al. (2000), Gillespie et al. (2004), Haimes and Jiang (2001), Hsieh (2004), Lee (2001), Mehrez and Gafni (1990), Perry and Stadje (2001), Peterson (2002), Rudolph and Repenning (2002), Semenova (2004), Shin (2004), Yi and Bier (1998)

Asteroid: Kent (2004)

Computer networks: Ariav et al. (1989), Artalejo and Gomez-Corral (1999), Chao (1995)

Earthquake: Dong et al. (1987), Peizhuang et al. (1986), Tamura et al. (2000)

Flood: Coles and Pericchi (2003), Esogbue (1996), Esogbue et al. (1992), Lian and Yen (2003), Suzuki et al. (1984)

Hazmat transportation: Erkut and Ingolfsson (2000), Jacobs and Vesilind (1992), Sherali et al. (1997)

Hurricane: Davidson et al. (2003)

Industrial accident: Duffuaa and Alnajjar (1995), Duffuaa and Khan (2002), Duffuaa and Nadeem (1994), Hartl et al. (1999)

Nuclear: Sampson and Smith (1982)

Oil and chemical spill: Gottinger (1998), Harrald et al. (1990), Psaraftis et al. (1986), Jenkins (2000)

Railway accident: Riddington et al. (2004)

Volcanic eruption: Leung et al. (2003)

Preparedness

No specified disaster type: Batta and Mannur (1990), Daganzo (1995), Dudin and Nishimura (1999), Gregory and Midgley (2000), Obradovic and Kordic (1986), Pidd et al. (1996), Reer (1994), Takamura and Tone (2003), Yamada (1996)

Computer networks: Ambs et al. (2000), Post and Diltz (1986)

Earthquake: Viswanath and Peeta (2003)

Flood: Hernandez and Serrano (2001), Wei et al. (2002)

Hurricane: Sherali et al. (1991)

Nuclear: Gheorghe and Vamanu (1995), Hamalainen et al. (2000), Ishigami et al. (2004)

Oil and chemical spill: Belardo et al. (1984a,b), Iakovou et al. (1996), Wilhelm and Srinivasa (1996)

Wildfire: Simard and Eenigenburg (1990)

War: Benini (1993)

Response

No specified disaster type: Barbarosoglu et al. (2002), Belardo et al. (1984a,b), Brown and Vassiliou (1993), de Silva and Eglese (2000), Haghani and Oh (1996), Hamacher and Tufekci (1987), Mendonca et al. (2000), Oh and Haghani (1997), Sarker et al. (1996), Swartz and Johnson (2004), Zografos et al. (1998)

Earthquake: Barbarosoglu and Arda (2004), Fiedrich et al. (2000), Ozdamar et al. (2004)

Flood: Shim et al. (2002)

Industrial accident: Jianshe et al. (1994), Kourniotis et al. (2001), Mould (2001)

Nuclear: French (1996), Hobeika et al. (1994), Papamichail and French (1999), Sheffi et al. (1982)

Oil and chemical spill: Psaraftis and Ziogas (1985), Srinivasa and Wilhelm (1997), Wilhelm and Srinivasa (1997)

Terrorism: Reshetin and Regens (2003)

Recovery

No specified disaster type: Bryson et al. (2002), Freeman and Pflug (2003), Guthrie and Manivannan (1992), Manivannan and Guthrie (1994), Nikolopoulos and Tzanetis (2003)

Computer Networks: Kim and Dshalalow (2002)

Earthquake: Chang and Nojima (2001), Cret et al. (1993), Song et al. (1996)

Hurricane: Boswell et al. (1999), Lambert and Patterson (2002)

Nuclear: Serdyutskaya et al. (1997)

articles in main stream OR/MS journals belong to the management science group, and another 35% of them to management consulting. Denizel et al. suggest that we need real problem settings and real data along with novel solution approaches with generalizable results and description of future research implications.

Figs. 2 and 3 show the distribution of research contribution and type within the four stages of DOM. As suggested in Fig. 2, more research is needed to develop mitigation tools, and we generally lack theory development in preparedness, response and recovery. In Fig. 3, research types are more evenly distributed within the last three stages

Table 4
Articles listed by Denizel et al. classification

MS1

Mitigation: Drezner (1987), Dudin and Semenova (2004), Esogbue (1996), Esogbue et al. (1992), Lian and Yen (2003), Riddington et al. (2004), Rudolph and Repenning (2002), Sherali et al. (1997), Tamura et al. (2000)

Preparedness: Batta and Mannur (1990), Post and Diltz (1986)

Response: Fiedrich et al. (2000), Haghani and Oh (1996), Hamacher and Tufekci (1987), Mendonca et al. (2000), Oh and Haghani (1997), Papamichail and French (1999), Reshetin and Regens (2003)

Recovery: Bryson et al. (2002), Freeman and Pflug (2003), Serdyutskaya et al. (1997)

MS2

Mitigation: Ariav et al. (1989), Artalejo and Gomez-Corral (1999), Atencia and Moreno (2004), Chao (1995), Duffuaa and Alnajjar (1995), Duffuaa and Khan (2002), Duffuaa and Nadeem (1994), Economou (2004), Economou and Fakinos (2003), Erkut and Ingolfsson (2000), Frohwein and Lambert (2000), Frohwein et al. (1999), Frohwein et al. (2000), Gillespie et al. (2004), Gottinger (1998), Haimes and Jiang (2001), Hartl et al. (1999), Jacobs and Vesilind (1992), Kent (2004), Lee (2001), Mehrez and Gafni (1990), Peizhuang et al. (1986), Perry and Stadje (2001), Peterson (2002), Sampson and Smith (1982), Semenova (2004), Shin (2004), Yi and Bier (1998)

Preparedness: Daganzo (1995), Dudin and Nishimura (1999), Yamada (1996)

Response: French (1996), Jianshe et al. (1994), Sarker et al. (1996)

Recovery: Kim and Dshalalow (2002), Lambert and Patterson (2002), Manivannan and Guthrie (1994)

ME1

Mitigation: Coles and Pericchi (2003), Englehardt (2002), Hsieh (2004), Leung et al. (2003)

Preparedness: Gregory and Midgley (2000), Reer (1994), Sherali et al. (1991), Wei et al. (2002), Wilhelm and Srinivasa (1996)

Response: Mould (2001), Ozdamar et al. (2004), Sheffi et al. (1982), Swartz and Johnson (2004)

Recovery: Boswell et al. (1999), Chang and Nojima (2001), Cret et al. (1993), Nikolopoulos and Tzanetis (2003)

ME2

Mitigation: Psaraftis et al. (1986)

Preparedness: Benini (1993), Takamura and Tone (2003)

Response: Barbarosoglu et al. (2002)

Recovery: no articles found

MC1

Mitigation: Current and O'Kelly (1992), Harrald et al. (1990)

Preparedness: Gheorghe and Vamanu (1995), Obradovic and Kordic (1986), Simard and Eenigenburg (1990)

Response: Belardo et al. (1984a,b), Hobeika et al. (1994), Kourniotis et al. (2001), Zografos et al. (1998)

Recovery: no articles found

MC2

Mitigation: Davidson et al. (2003), Dong et al. (1987), Jenkins (2000), Suzuki et al. (1984)

Preparedness: Ambs et al. (2000), Belardo et al. (1984a,b), Hamalainen et al. (2000), Hernandez and Serrano (2001), Iakovou et al. (1996), Ishigami et al. (2004), Pidd et al. (1996), Viswanath and Peeta (2003)

Response: Barbarosoglu and Arda (2004), Brown and Vassiliou (1993), de Silva and Eglese (2000), Psaraftis and Ziogas (1985), Shim et al. (2002), Srinivasa and Wilhelm (1997), Wilhelm and Srinivasa (1997)

Recovery: Guthrie and Manivannan (1992), Song et al. (1996)

of DOM relative to the distribution of research contribution in Fig. 2. Fig. 3 also hints that more management consulting research is needed for recovery efforts.

4. Future research directions

DOM lacks widely accepted measures of productivity and efficiency. There is a need for theory development and hypothesis testing but our understanding of sources and types of critical data is limited. We need a better understanding of the inputs for DOM models, specific event characteristics, and the development of new solution methods and technologies. We know that response to disasters requires good planning but should leave room for improvisation due to the unusual challenges created. Hills (1998) mentions that the phrase disaster "management" implies a degree

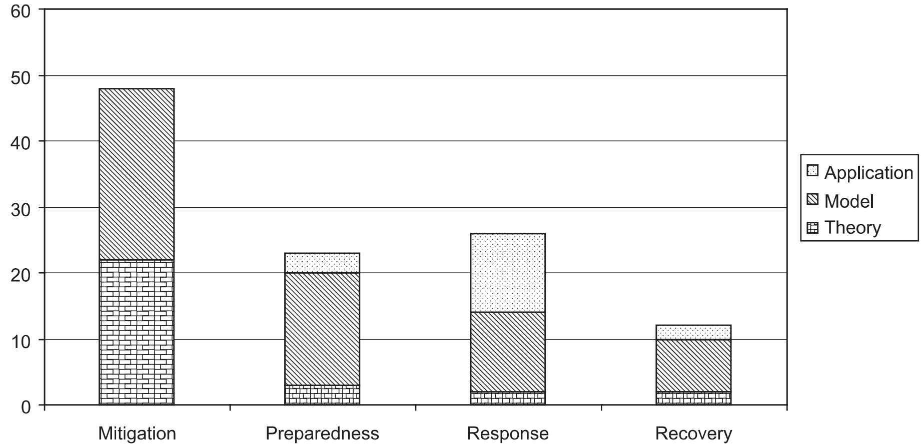

Fig. 2. Distribution of research contribution to lifecycle stages of DOM.

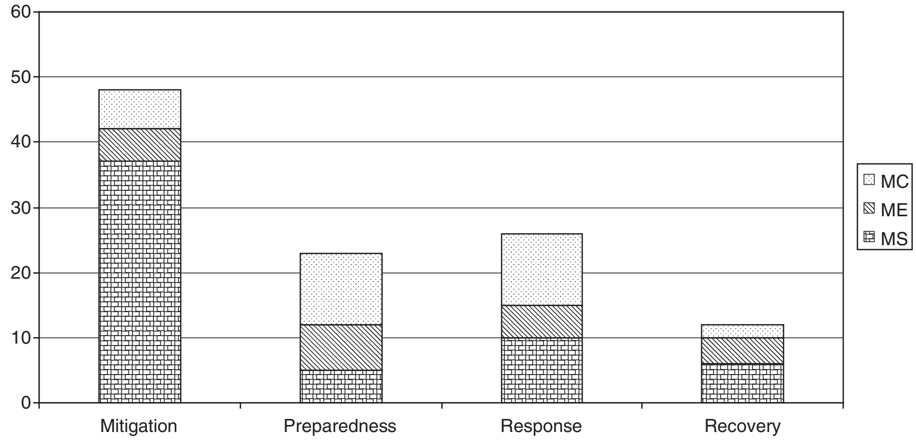

Fig. 3. Distribution of research type to lifecycle stages of DOM.

of control which rarely exists in these situations. Hence standard management methods, as we know them, may not directly apply to disaster situations. Based on our experiences in the field, the literature and an examination of over 2000 events in the disaster database project we believe that the following areas and research questions should be given priority due to their potential impact on DOM research.

4.1. Multi-agency research

DOM is by nature multi-organizational, but organizations are only loosely connected leading to managerial confusions and ambiguity of authority. Gass (1994) points that public sector problems are generally ill-defined, have high behavioral content, and are overlaid with strong political implications. Nevertheless, none of the models or applications developed in the literature recognizes this issue. The multi-functional nature and political hierarchy in emergency response organizations are well suited for hierarchical planning and multi-attribute, multi-objective approaches as various groups have different priorities before, during and after a disaster hits. Therefore a key question is what are the optimal organizational and network structures that would facilitate communications and coordination in the resolution of disasters?

The political nature of the problem also calls for ethical responsibility. Therefore it is worth investigating how and which ethical factors should be included in modeling service allocation to disaster victims? How can constraint tradeoffs and conflicting objective functions be ethically resolved in these models? Le Menestrel and van Wassenhove (2004) present methodological approaches to combine ethics with Operational Research. Gass (1994) recommends that OR/MS analysts as scientists should present facts in an unbiased manner, be open about advocating a particular point of view, and have a moral responsibility for the effects of their involvement in public policy problems.

4.2. Methods

The soft, i.e. social and political, nature of DOM problems makes this field suitable for data envelopment analysis, fuzzy systems, systems dynamics, and soft OR. The key question is how do we determine decision rules on what method to use to address specific class of disaster problems? For example, problem structuring methods seem to fit well to unstructured problem situations where multiple actors, multiple perspectives, conflicting interests, important tangibles, and key uncertainties exist in tandem (Mingers and Rosenhead, 2004). Readers interested in soft OR methods should refer to the special issue of EJOR (v. 152, n. 3).

An extension of the question above is whether new techniques could be developed to take advantage of the inherent structure of disaster problems? For situations where our knowledge is incomplete, and uncertainties do not seem to be easily resolved, Bankes (1993) suggests using comprehensive simulation models, preferably of interdisciplinary nature, to capture some aspects of natural phenomena using for example, meteorological or geological principles, and technical details via engineering and social behavior models. Gass (1994) mentions that "public sector problems are multi-objective, and solutions are good or bad, but not optimal". One may then consider the option of developing models that satisfy all or most of the system constraints without trying to optimize an objective function. For example, Papamichail and French (1999) use constraint programming to develop feasible evacuation strategies for nuclear emergencies.

4.3. Technology

In their 1998 editorial note Tufekci and Wallace submit that there is a gap between the tasks emergency managers have to administer and the commercially available technology. Efficient sensing algorithms are needed that are supported by advanced data acquisition, positioning and communications technologies to better understand the current state of operations. Naturally, effective sensing plays a critical role in real-time dynamic resource allocation decisions. The RODOS (http://www.rodos.fzk.de/) project in Europe is a good example of such efforts. But such logistical problems tend to change their nature in disaster emergency incidents. Thus the key question is what are the underlying assumptions and building blocks of logistical problems immediately before, during, and after disasters?

4.4. DOM stages

The area that lacks OR/MS research is recovery planning. Although research on recovery in other fields is abundant (Enarson and Morrow, 1998; Fischer, 1998; Froot, 1999; Hirshleifer, 1987; Kletz, 1993; Perrow, 1999; Perry and Mushkatel, 1984; Quarantelli, 1998; Sylves and Waugh, 1996; Waugh and Hy, 1990) OR/MS is far behind. Some key questions in recovery include: what are the operational problems of damage assessment and cleanup? Debris removal, for example, is a major logistical recovery problem (Lauritzen, 1998). What are the key characteristics of food and monetary aid collection, allocation, and distribution problems? Can we modify existing distribution and tracking models?

4.5. Business continuity

The attacks of September 11th left many businesses, small or large, helpless, desperately trying to fill knowledge gaps and gather forms, documents, and as much data as they could recollect. Business continuity is not simply about taking back-ups of data and is seriously neglected by academicians. In this study, only a handful of articles relate to business continuity, focusing on various areas such as recovery of computer networks (Ambs et al., 2000), buffer estimation models for data protection against computer viruses (Artalejo and Gomez-Corral, 1999), and selection of disaster recovery plan alternatives (Bryson et al., 2002). Unfortunately, disaster recovery planning for businesses still does not follow a scientific roadmap. Innovative financial and insurance tools are needed to help small and large businesses to return to normalcy (Kunreuther and Linnerooth-Bayer, 2003; Kunreuther and Kleindorfer, 1999). Company-level post-disaster logistical problems should be discussed. Answers to the following questions are critical: Why do businesses fail in the aftermath of a disaster? What is the time line of failure? What is the rate of failure? What distinguishes survivors from failing businesses?

4.6. Infrastructure design

Linkages and connectivity between critical infrastructures needs a better understanding. The major power outage affecting life in the north east of the US in 2003 is an example how infrastructure networks may cause ripple effect and escalate problems. The Journal of Infrastructure Systems provides a good starting point for investigating the vulnerability of critical infrastructures. For example, the threat of bioterrorism specifically to water supply systems is currently being considered a high possibility (Haimes et al., 1998).

Haimes and Longstaff (2002) argue that there is disconnect among the organizations that plan, design, construct, operate, maintain, and manage these complex infrastructures. Disruption management models are needed to respond and recover in a timely manner. Innovative easy-to-rebuild infrastructure network designs are needed that are robust to disruptions in the system. Both, structure-based (hardware, structures, facilities) and human-based (institutions, organizations, culture and language) infrastructures have the potential to disrupt a bigger part of the system when attacked or hit by a natural disaster. An important question then is how can we incorporate survivability as an objective in the design and maintenance of infrastructures without disturbing routine operations but improving operations under disaster conditions?

4.7. Management engineering

Corbett and van Wassenhove (1993) showed that OR/MS research is lagging in the area of "management engineering". After more than a decade this trend still lingers at least for OR/MS research in DOM. To be able to apply the theories and algorithms designed in "management science" to disaster operations problems we need a better understanding of the attributes of disaster problems. Could existing vehicle routing, location and allocation models for emergency services be improved and adapted to disaster situations and mass emergencies? Could comprehensive models be developed to coordinate mitigation and preparedness planning with response? What are the fundamental differences between disaster response operations and everyday emergency response?

During this study we have found numerous purely theoretical articles on queuing networks with catastrophes. Their theoretical foundation has applications in life sciences (extinction of species) as well as in computer networks (recovery of infected networks). We believe that these queuing models can be used to estimate disaster losses and assist in mitigation and preparedness planning. A good review of queuing networks with catastrophes is provided by Artalejo (2000).

4.8. Where to start

Readers who would like more information on disaster operations and research on disasters in general should consult Appendix A, which provides a selected list of organizations and information resources on the worldwide web. For example, the Quick Response Reports of University of Colorado's Natural Hazards Research and Applications Information Center can be obtained via internet. These reports are an excellent source for understanding issues and challenges in various types of disasters and provide good research questions such as "what local resources tend to become overwhelmed at what time points in a disaster response and recovery situation?" or "how and to what extend do local characteristics influence the point at which local resources are overwhelmed?" (Grant et al., 2002).

5. Problems and issues

You can lead a horse to water, but you cannot make him drink. Unfortunately, in agencies where the regulatory climate is founded on non-intrusiveness and a relatively high degree of local government autonomy, even the best programs developed will not be adopted by all participants, due to various reasons including time, staff availability and interest, funding, personalities, resistance to state intrusiveness, and denial. Consequently, system performance is rarely optimal. Furthermore, even if implemented, some portions of the program will not be fully digested by everyone. The closer structure and procedures are to the normal, daily routines, the better performance will be. As a result, system planning and design must allow for significant disruptions at the start of an incident and lead times to educate participants as the event is happening (Green, 2000).

Comprehensive Emergency Management follows an all-hazard approach, generalizing policies and plans for all kinds of emergencies. But we may find different optimal approaches for different specific incidents. One example stems from the fundamental changes in operational response driven by widespread terrorist activities. Traditional response to a mass casualty incident, such as a school bus accident or a disaster at a public event results in the concentration of resources for their control and accountability (Auf der Heide, 1989). If a mass casualty incident results from a terrorist action, the concentration of those resources, instead of being efficient, creates a tempting high-payoff target for a secondary attack. Dispersing resources to ensure their survival generates a plethora of new communications, coordination, and accountability issues.

The decision-making process during a disaster response differs drastically from conventional decision-making (Jianshe et al., 1994). In disaster emergency response situations important attributes of the problem are uncertain (e.g. its nature, scale, time etc.). The problem environment is changing rapidly and uncontrollably. There is very little time for making a decision but information might not be available (or, even if available, might not be reliable). Lastly, some critical disaster response decisions might be irreversible (Pauwels et al., 2000).

6. Conclusion

In search for new directions for OR/MS research, disaster operations management shows tremendous potential. Disasters have hit, and will continue hitting our communities, businesses, and economies. It is in everyone's interest to understand how we can manage them effectively and efficiently. Better management of disaster operations will improve readiness, increase response speed, and ease recovery. We have surveyed the OR/MS literature to identify publication trends, issues worthy of further investigation, and problems that have not yet been examined. Appendix A provides a starting point for OR/MS researchers who would like to get a head start in understanding disaster operations and meet others working in this area.

Appendix A. Disaster management groups/organizations/web links

This in no way is a complete list of resources on disaster management. Our intention is not to promote any one entity, but merely supply some starting points for interested researchers.

A.1. Journals and meta-sites

Disaster Prevention and Management Journal: http://www.mcb.co.uk/dpm.htm.

Disaster Recovery Journal: http://www.drj.com.

Disasters: http://www.blackwellpublishing.com/journals/DISA/.

The Electronic Journal of Disaster Science: http://www.richmond.edu/~wgreen/ejem.htm.

Notes on the Science of Extreme Situations: http://www.richmond.edu/~wgreen/notes.html.

Disaster Science Meta-Library: http://www.richmond.edu/~wgreen/benchmark.htm.

A.2. Research centers

Center for Urban and Regional Studies at the University of North Carolina—Chapel Hill: http://www.unc.edu/depts/curs/.

The Emergency Information Infrastructure Project: http://www.emforum.org/.

Asian Disaster Preparedness Center: http://www.adpc.ait.ac.th/.

Canadian Centre for Emergency Preparedness: http://www.ccep.ca/.

Center of Excellence in Disaster Management and Humanitarian Assistance: http://www.coe-dmha.org/.

Center for Disaster Studies at James Cook University: http://www.tesag.jcu.edu.au/cds/cdsweb.html.

Western Disaster Center: http://www.westerndisastercenter.org

Natural Hazards Center at the University of Colorado—Boulder: http://www.colorado.edu/hazards/.

Institute for Crisis, Disaster, and Risk Management at George Washington University: http://www.gwu.edu/~icdrm/.

Disaster Research Center at University of Delaware: http://www.udel.edu/DRC/.

Center for Disaster Management at Bogazici University (Turkey): http://www.cendim.boun.edu.tr/index.html.

Hazard Reduction and Recovery Center at Texas A&M University: http://hrrc.tamu.edu/.

Wharton Risk Management and Decision Processes Center at University of Pennsylvania: http://opim.wharton.upenn.edu/risk/.

Disaster Prevention Research Institute at Kyoto University (Japan): http://www.dpri.kyoto-u.ac.jp/.

A Comprehensive List of Research Centers: http://hrrc.tamu.edu/hrrc/related-sites/Centers.html.

A.3. Organizations and agencies

International Federation of Red Cross and Red Crescent Societies: http://www.ifrc.org.

USAID: http://www.usaid.gov.

OXFAM: http://www.oxfam.org.uk.

Medecins Sans Frontieres: http://www.msf.org.

The International Civil Defense Organization: http://www.icdo.org.

Federal Emergency Management Agency: http://www.fema.gov.

Emergency Management Australia: http://www.ema.gov.au/.

Caribbean Disaster Emergency Response Agency: http://www.cdera.org/about.htm.

National Voluntary Organizations Active in Disaster: http://www.nvoad.org.

The International Emergency Management Society: http://www.tiems.org/.

International Association of Emergency Managers: http://www.iaem.com.

A.4. Databases

The Disaster Database Project at University of Richmond: http://cygnet.richmond.edu/is/esm/disaster/.

EM-DAT: the OFDA/CRED International Disasters Data Base: http://www.em-dat.net.

AirDisaster.com: http://www.airdisaster.com.

Natural Disaster Reference Database: http://ndrd.gsfc.nasa.gov/.

The Canadian Disaster Database: http://www.ocipep.gc.ca/disaster/default.asp.

The British Association for Immediate Care: http://www.basedn.freeserve.co.uk/.

Social Studies Network for Disaster Prevention in Latin America: http://www.desinventar.org/.

A.5. Guides & directories

Disaster Resource Guide: http://www.disaster-resource.com/.

A.6. News sources

DisasterRelief.org: http://www.disasterrelief.org.

Disaster News Network: http://www.disaster-news. net.

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