Journal of the Operational Research Society (2009) 60, S126–S139 © 2009 Operational Research Society Ltd. All rights reserved. 0160-5682/09

www.palgrave-journals.com/jors/

Fifty years of operational research and emergency response

NC Simpson* and PG Hancock

University at Buffalo, Buffalo, NY, USA

Over the past 50 years, a wealth of applications has resulted from researchers turning their attention to operations such as fire suppression, law enforcement and ambulance services. The 1970s might even be argued as the 'golden age' of this particular effort, producing many of the seminal works in fire station location planning, unit assignment and ambulance queuing models. Such efforts naturally continue through to the present, but with a focus shifting away from earlier contexts of established urban emergency service systems. Simultaneously, current evidence from the field suggests that far more work remains. In this paper, we review the operational research (OR) foundation in emergency response so far, highlighting the fact that most of what has been accomplished addresses the well-structured problems of emergency services. This, in turn, offers an explanation for some paradoxical challenges from the field: most of emergency response itself is semi-structured, at best. While OR has traditionally focused on the management of an organization, emergency response ultimately requires the management of disorganization, suggesting an important OR growth area for the next 50 years.

Journal of the Operational Research Society (2009) **60,** S126–S139. doi:10.1057/jors.2009.3

Keywords: emergency response; emergency services; modelling

Introduction

Born of the logistics of World War II, it is hardly surprising to find a rich history of operational research (OR) in the context of emergency response and emergency services. Indeed, the developments in this particular sector often reflect the general issues and trends of OR. Emergency response organizations such as fire, police and ambulance services belong almost exclusively to the public sector, which has itself been characterized as 'the cradle' of OR (Papageorgiou, 1994). Furthermore, the body of published OR work on emergency response has shifted focus over time, reflecting not only the evolution of emergency services, but likewise the advancing scope of OR. Finally, examining these shifts brings us to the present day, where the remaining unmet needs of emergency services strongly suggest a growth area for OR over the next few decades.

Three of the earliest mainstream OR journal articles focused on emergency response are the fire station location planning studies of Valinsky (1955) and Hogg (1968) and the ambulance service simulation study of Savas (1969). These articles, appearing in *Operations Research*, *Operational Research Quarterly* and *Management Science*, respectively, can be argued as archetypes for a foundational stream of research that would soon follow. The next section of this paper describes the assembly of a convenience sample of 361 emergency response-related OR articles (henceforth referred to as EOR), to characterize that stream of research and its sub-currents from 1965 to 2007. In the following two sections, this body of work is explored in greater detail in two phases, starting with an earlier definitive foundation of literature modelling and improving designed urban emergency services, and then proceeding to a higher volume era of broader scope but fewer synergistic relationships among studies. This brings the discussion to a summary of problems yet to be fully addressed by the substantial body of EOR publications available in the present time, concluding with a suggested direction for OR innovation over the next 50 years. While both OR and its subset EOR began in the context of improving the performance of organized environments, emergencies by definition represent a disruption of such designs, providing a promising new domain for future work: the theoretical essence and practical needs of disorganizations.

**Correspondence: N Simpson, Department of Operations Management & Strategy, School of Management, University of Buffalo, 351 Jacobs Management Center, Buffalo, NY.*

Emergencies and OR: an overview of 1965–2007

Convenience sampling methodology

Recent reflections on EOR have typically focused on a particular sector within the field of emergency response. For example, Green and Kolesar (2004) discuss previous OR work within the context of large urban emergency service systems and 'habitual emergencies', while Altay and Green (2006) review work related to large-scale disasters and

Table 1 Focus categories and component title keywords used in construction of emergency response research articles convenience sample

	Focus Category			
	Urban Services keywords	*Disaster Services keywords*	*Hazard Specific keywords*	*General Emergency keyword*
	Fire Police Patrol Ambulance EMS	Disaster Evacuation Rescue	Hurricane/Typhoon Terrorism/Terrorist Epidemic/Pandemic Flood/Tsunami Earthquake Wildfire[1]	Emergency
Total articles in sample	120	64	72	105

[1]The majority of wildfire-related articles were identified by the keyword query 'fire', and manually re-classified as wildfire upon review of the article.

Wright *et al* (2006) summarize OR applications associated with a specific type of hazard. The purpose of this study is to examine EOR as a whole, as all these sub-currents of concern are interrelated. To pursue this objective, 361 journal articles were gathered into a single convenience sample of published EOR work. Candidates for this sample were first identified by querying the combined citation index databases of *Web of Science* for keywords in the titles of all journal articles in the management science/operations research subject area published between 1965 and 2007. Each keyword was mapped to one of four focus areas: Urban Services, Disaster Services, Specific Hazards and General Emergency, as detailed in Table 1. The resulting collection of articles was first reviewed to eliminate double-entries created by titles containing two or more keywords; 36 instances of double-entries and three instances of triple entries were resolved by assigning the article to the most specific of the keywords, as the general term 'emergency' was frequently used in conjunction with a keyword such as 'ambulance' or 'flood'. The resulting group was then reviewed again to ascertain whether the article identified by a keyword in its title did indeed represent emergency response research in that focus area. Fifteen articles were re-assigned focus areas (moving from Urban Services to Specific Hazards) and 75 articles were deleted from the sample as not applicable to emergency response. The combined result of these steps identified a total of 361 articles for the EOR convenience sample, and the resulting count of articles in each of the focus areas appears in Table 1.

The purpose of this sampling procedure is not to define the set of absolutely all EOR work available in the literature between 1965 and 2007, as searching for keywords in titles across only those journals tracked by *Web of Science*® will not fully populate such a group. Rather, the purpose of the convenience sampling process is to systematically identify a sufficient proportion of the overall body of published knowledge in this sector such that trends in volume, focus or outlet might become apparent. The four focus categories are intuitive groupings based on both observation of the data and synthesis of previous studies. The Urban Services group is intended to collect those articles dedicated to emergency response in the context of established municipal services such as fire and police departments and who comprise the focus of Green and Kolesar (2004), who note a drop in such publications after 1989. Urban Services imply emergencies which can be resolved largely by the resources of a single organization, whereas the Disaster Services and Specific Hazards are intended to gather references to large-scale emergency response, such as surveyed recently by Altay and Green (2006). Finally, the General Emergency group is kept as an open category to collect any EOR work that did not feature any of the specific associated keywords, for subsequent study.

EOR activity across time

Figure 1 displays the distribution of published work in the convenience sample along the timeline of 1965–2007. Clearly, publication of EOR articles has seen an increase in recent years; furthermore, the peak year in the time series is the most recent year of 2007, in which the combined total of 40 papers published is more than double any other year in the series with the exception of 2001. Whether the distinct variations in total annual volume are motivated by related events is unclear, as can be seen by the selection of high-profile incidents likewise indicated along the Figure 1 timeline. While it is intuitive to assume that peaks in EOR publications could represent research motivated by needs revealed during some large-scale incident a few years prior, publications in the convenience sample do not necessarily reference any distinct motivating incidents, and even fewer model or analyse particular events. As an example, only a third of the 40 papers appearing in 2007 make reference to distinct incidents in either opening arguments or analysis, with six of the 40 working with data from a past incident. Logically, these papers fall almost exclusively in the Disaster Services or Hazard Specific groups within the convenience sample, such as the modelling of quick response

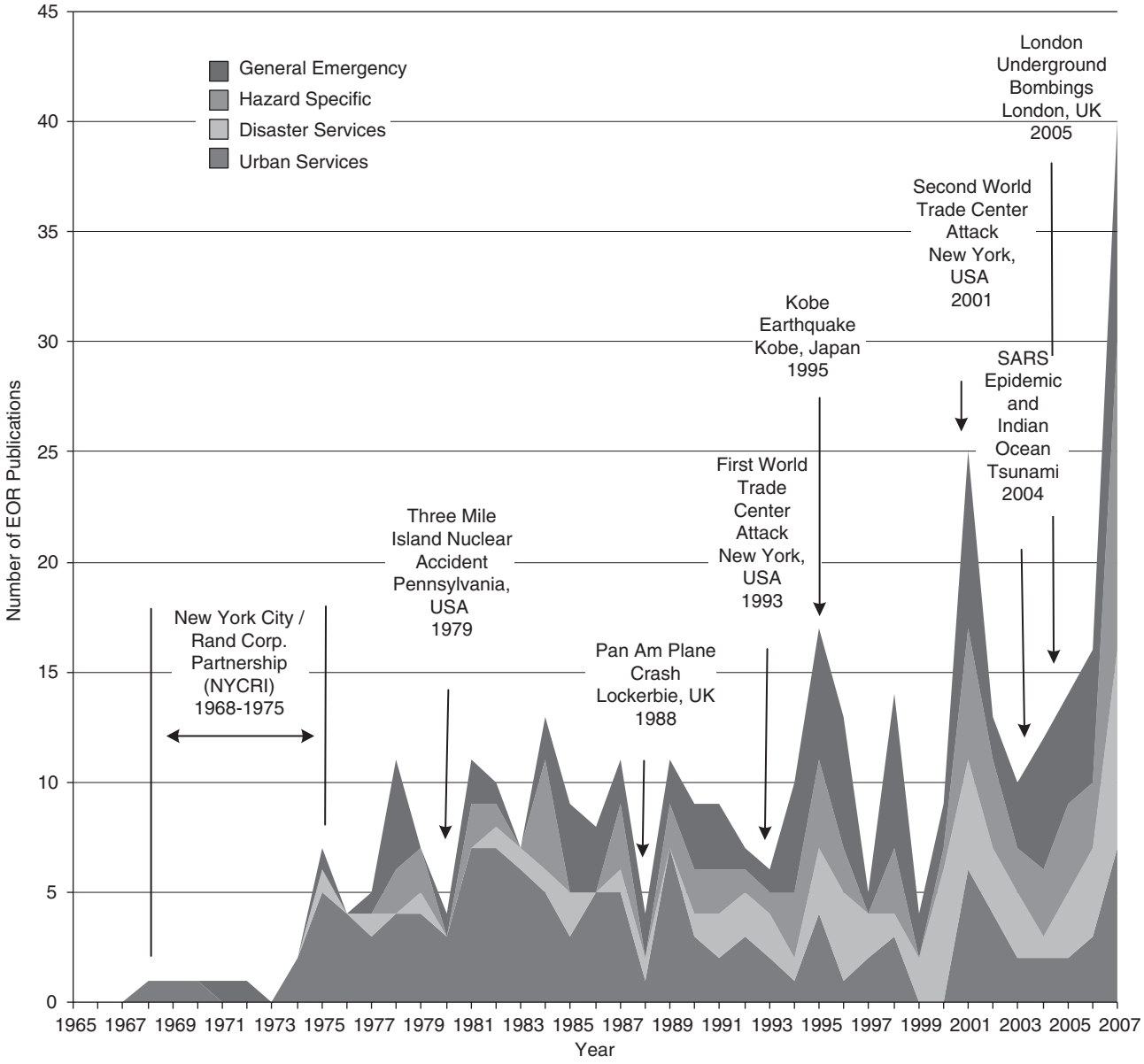

Figure 1 Emergency response research (EOR) articles in convenience sample, by year of publication.

in the context of disaster relief by Sheu (2007), using data from a major earthquake that struck Taiwan in 1999.

EOR journal outlets

Table 2 displays the same set of 361 EOR papers, sorted by journal outlet. The convenience sampling process ultimately netted 36 distinct journal outlets from the broader set tracked by the *Web of Science*® database service; however, Table 2 shows that two-thirds of these publications were published in seven of those journals. Interestingly, two of the top three journals in terms of paper count are not mainstream OR journals, but engineering-oriented journals with a multidisciplinary approach to the issues of safety and reliability of systems. This dominance is even more compelling when considering the fact that, unlike most of the top mainstream OR journals, neither of these journals published under those titles throughout the entire 1965–2007 period. In the context of Figure 1, top-ranking *Reliability Engineering & System Safety* does not begin contributing to published EOR until 1982 and *Safety Science* does not emerge until 1991.

Of mainstream OR journals, the *Journal of the Operational Research Society* (*JORS*), combined with the activity under its earlier title of *OR Quarterly*, claims the highest proportion of articles within the convenience sample. As Table 2 illustrates, this is followed by the substantial published

Table 2 Emergency response research articles in convenience sample, by journal outlet

	Urban Services	*Disaster Services*	*Hazard Specific*	*General Emergency*	*Total*
Reliability Engineering & System Safety	11	3	13	19	46
Safety Science	8	14	9	13	44
Jrnl of the Operational Research Society (OR Quarterly)	18	6	5	15	44
European Jrnl of Operational Research	13	11	4	9	37
Management Science	20	2	2	8	32
Interfaces	8	3	4	4	19
Operations Research	9	1	3	6	19
Computers Environment & Urban Systems	10	1	2	2	15
Computers & Operations Research	3	1	1	8	13
Expert Systems with Applications	2	3	2	5	12
INFOR	4	0	5	3	12
International Jrnl of Systems Science	0	1	9	1	11
All other journals in sample	14	18	13	12	57

EOR contributions of the *European Journal of Operational Research* (*EJOR*), *Management Science*, *Interfaces* and *Operations Research*, this approximate mix being consistent with the disaster-oriented findings of Altay and Green (2006). Not apparent in the summary of Table 2, however, is the overall pattern of journal outlet involvement between 1965 and 2007. As noted earlier, the majority of EOR publications appearing in *Management Science* appear before 1990, while over half of the convenience sample contribution of *Operations Research* had appeared by 1978. In contrast, the balance of the mainstream OR journals mentioned contributed articles in a chronological pattern similar to that of the overall aggregate volume within the sample.

EOR methodology

Table 3 breaks the convenience sample down by OR methodology, again yielding results nearly identical to the earlier survey of Altay and Green (2006). Mathematical programming is the most common OR approach to the difficulties of emergency response, followed by probability and statistics and then by simulation. Table 3 shows this general ranking is likewise fairly consistent across the component EOR focus categories, with a few interesting exceptions. Math programming, for example, is the most common methodology within each of the focus categories with the exception of Hazard Specific, where statistical analysis dominates. Probability and statistics otherwise ranks second, unless the focus is Disaster Services, where the problems inherent in analysing historical data of infrequent and exceptional events are likely influencing its relegation to fourth. Half of all articles applying decision theory or multi-attribute utility theory (MAUT) appear in the Urban Services category, as well as two-thirds of all instances of soft OR.

While Figure 1 strongly suggests that emergency services and emergency response comprise a current growth sector for OR research, observations of downward trends such as offered by Green and Kolesar (2004) are consistent if one examines the Urban Services focus category in particular—this is the only sub-sector that does not follow the overall pattern. These application-oriented investigations into the operation of police, fire and ambulance services are the genesis of the general body of published EOR knowledge, as the early works of Valinsky (1955), Hogg (1968) and Savas (1969) all fall solidly into the category of Urban Services. If the public sector is the 'cradle' of OR, then urban emergency response service is the 'cradle' of EOR, as discussed in detail in the next section.

Convenience sample, part I: the early era of urban services

Figure 1 illustrates how research articles appearing before 1978 belong almost exclusively to the Urban Services focus category, which likewise dominates the overall research accomplished during its peak era of 1981–1984. Many of the works embedded in these early years address what could be argued as the original EOR problems: fire station location planning and its companion issue of fire company assignment. Following the thread of Valinsky (1955) and Hogg (1968), such papers contributing to Urban Services EOR before 1984 include Walker (1974), Rider (1976), Plane and Hendrick (1977), Schilling *et al* (1980) and Schreuder (1981). Indeed, examining the few non-Urban Services EOR publications from the 1970s reveals that the majority of these are nonetheless focused specifically on the issue of location planning, such as the influential articles of Toregas *et al* (1971) and Aly and White (1978). It is also interesting to note that locating fire stations not only comprises the original EOR problem, this research activity likewise continues through to present day, such as the harnessing of the earlier analytical approaches in conjunction with 'soft constraints' representing the realities of stakeholder perceptions (Hewitt, 2002), or the application of genetic algorithms to this enduring problem (Yang *et al*, 2007).

Table 3 Emergency response research articles in convenience sample, by methodology

	Number of articles	*Percent of convenience sample*	*Ranking within focus category*			
			Urban Services	*Disaster Services*	*Hazard Specific*	*General Emergency*
Math programming, including stochastic and constraint programming	131	36.3	1	1	2	1
Probability and statistics	75	20.8	2	4	1	3
simulation	45	12.5	3	2	5	2
Decision theory & MAUT	35	9.7	7	3	3	5
Systems dynamics	27	7.5	4	7	6	4
Fuzzy sets and expert systems	24	6.6	8	6	4	6
Queuing theory	14	3.9	6	5	7	8
Soft OR	10	2.8	5	8	8	7

While EOR work began in earnest in the fire service, the subsequent peak in the Urban Services category during 1978–1984 was due mostly to the emergence of a large body of work focused on police services: over 38% of all police-specific research investigations gathered into the convenience sample were published during this time period. Much of this work was an outgrowth of a highly productive partnership between the City of New York and the RAND Corporation during that era, recounted recently in Larson (2002) and Green and Kolesar (2004), and likewise responsible for many of the earlier fire service-related publications discussed. Like many other papers motivated by the efforts of the New York City RAND Institute (NYCRI), police-oriented EOR work such as the patrol car allocation modelling of Chaiken and Dormont (1978a, b) often appeared in *Management Science*. Many of the findings of NYCRI were then accumulated into two influential books representing NYCRI's fire *versus* police OR activities: Walker *et al* (1979) *Fire Department Deployment Analysis: A Public Sector Case Study*, and Larson's (1972) *Urban Police Patrol Analysis*.

Later in the 1980s EOR work devoted to ambulances then reaches its peak, with nearly half of all the convenience sample papers with 'ambulance' in the title being published in this interval between 1984 and 1990. Interestingly, placement of ambulances was the subject of some of the earliest EOR work (Savas, 1969; Fitzsimmons, 1973), representing landmark introductions of simulation as a tool to motivate policy. It is likely that the growth in ambulance-oriented EOR studies more than a decade later reflected OR support during the expansion of that particular emergency discipline. While the essential processes and infrastructure of city firefighting and law enforcement were long established at the outset of OR's involvement in those activities, the nature of the ambulance service was evolving dramatically during that same period. In the United States, the early 1970s witnessed the introduction of the concepts of 'pre-hospital care' and the launch of the civilian paramedic as a profession, propelled by a series of government initiatives to foster local adoption (Grant *et al*, 1994). In contrast to the body of NYCRI-related work, the majority of the subsequent ambulance-oriented cohort of investigations appeared in *JORS* and *EJOR*, often case-oriented and featuring locations ranging from Bangkok (Fujiwara *et al*, 1987) to the Dominican Republic (Eaton *et al*, 1986).

Nonetheless, NYCRI is recognized as the source of much of the early work in emergency services (Green and Kolesar, 2004; Wright *et al*, 2006). Not only did this partnership produce a substantial body of published EOR employing tools such as linear and integer programming, queuing theory and simulation against the urban landscape of New York City (NYC), the inter-relationships between these projects created a foundation of work framing much of what has been accomplished since. One early and influential member of the NYCRI publication cohort is Kolesar and Blum (1973), who derived general principles of the relationships of distance, response time and the number of fire stations assigned to a response area. During the balance of the convenience sample interval, 1973–2007, this 'square root law' of fire response has been cited by 31 other OR papers as tracked by *Web of Science*®, and these papers have in turn been cited by 178 additional OR investigations. Of this combined cohort of 210 journal articles, 68 of those publications concern emergency response, whose identities and citation relationships are illustrated in Figure 2.

Publications associated with the NYCRI, representing either direct products, direct NYC-based extensions or extensive discussions of same, are indicated with darker nodes in Figure 2, and the 'seed' reference of Kolesar and Blum (1973) that defines the network, or 'citation map', can be located at its centre. Any node within the illustration heavily ringed with arrowheads indicates a highly influential article in terms of subsequent citations; nodes with an unusual number of arcs radiating away to connect elsewhere are typically literature surveys. While a single arc does not communicate the degree of influence one research study had upon another—the arcs in Figure 2 represents instances ranging from cursory

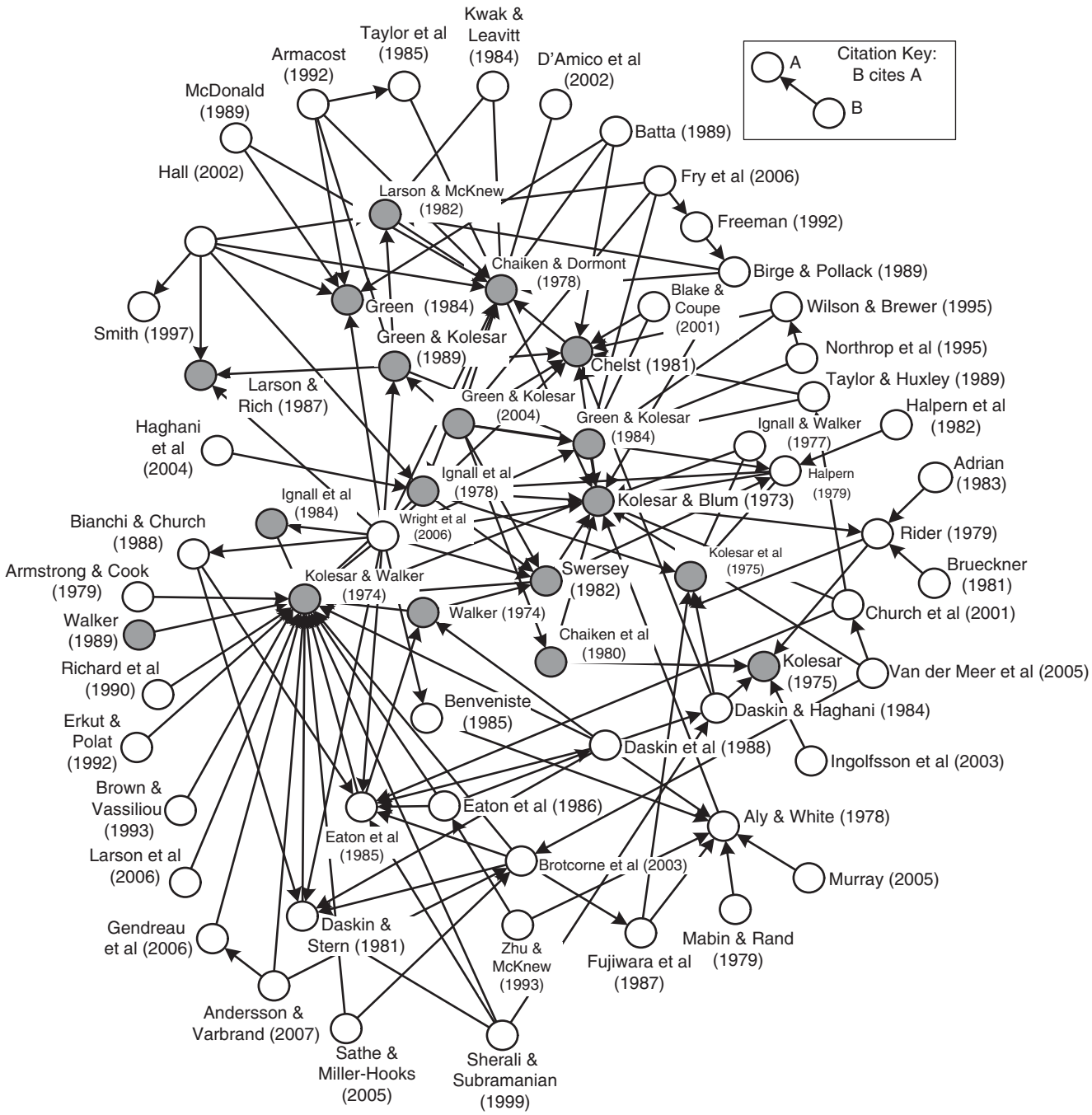

Figure 2 Emergency response research articles citing Kolesar and Blum (1973) and those citing the citers of same. Darker nodes indicate New York City Rand Institute (NYCRI)-related papers (full references available at the end of this paper).

mention in opening arguments to direct extensions of the previous studies—the resulting citation map is a useful visualization of overall research streams. The upper half of the diagram contains almost exclusively police-oriented EOR efforts, building upon the foundation NYCRI cohort of Larson and Rich (1987), Green (1984), Green and Kolesar (1984, 1989), Chaiken and Dormont (1978a, b) and Chelst (1981). Many of the papers in the upper border of the citation network represent EOR extending the modelling and analysis of police services beyond distinctly urban environments, such as Markov modelling of rural patrol services (Birge and Pollock, 1989), route planning in the limited access context of motorways (Taylor *et al*, 1985; Smith, 1997) or route and allocation planning of aircraft for law enforcement patrol of coast lines (Armacost, 1992). Those NYCRI papers at or below the centre of the network (Kolesar and Blum, 1973;

Kolesar and Walker, 1974; Kolesar *et al*, 1975; Ignall *et al*, 1982; Swersey, 1982) focus on urban fire services, but related non-NYCRI papers comprising the lower half of the network are not likewise dominated by this particular focus. Unlike the upper region of Figure 2, relatively few publications here represent continuing research into fire service beyond urban settings, such as revisiting the fire station location planning problem in a rural context (Richard *et al*, 1990). Rather, the original location, travel and allocation NYCRI models are cited in many studies considering the same issues in contexts such as emergency medical services (Daskin and Stern, 1981; Eaton *et al*, 1985; Zhu and McKnew, 1993; Brotcorne *et al*, 2003), or search and rescue operations (Armstrong and Cook, 1979; Van der Meer *et al*, 2005). An important distinction between the 68 EOR publications in Figure 2 and the broader EOR convenience sample is that the Figure 2 publications appear almost exclusively in mainstream OR journals, with *Management Science*, *Operations Research*, *EJOR* and *JORS* accounting for over half of them.

Chaiken and Larson (1973), a contemporary of the Figure 2 seed reference Kolesar and Blum (1973), described OR's role in emergency services as that of determining the optimal number and location of response units and attending to their associated issues of patrol routes, response jurisdiction and temporary reallocation. In summary, over 80% of the publications pictured in Figure 2 fit that description exactly. EOR's early focus on location and allocation within established emergency service systems is likely a reflection of OR's prevailing emphasis on *optimization* during that same era (Kirby, 2007). Also dubbed 'classical OR' (Checkland, 1981), such approaches inherently rely on a situation to provide both enough data and enduring relationships such that a reasonable mathematical surrogate of the situation can be created and solved to identify what would best serve some objective in reality. The problems posed by locating facilities and distributing assets in anticipation of emergencies strongly support such assumptions, thus providing a logical start and foundation to EOR activity.

One final compelling feature of Figure 2 is what does *not* appear in the illustration, the 142 non-EOR articles omitted in the interest of clarity. These publications relate and extend the findings within the Figure 2 network to a broad spectrum of other OR applications, ranging from the scheduling of technicians providing field service for office equipment (Chu and Lin, 1993; Haugen and Hill, 1999) to deriving the relationship between the number of freight terminals maintained within a shipping network and the average distance freight will travel (Hall, 1984) to the partitioning of geographical regions for the provision of general health-care (Pezzella *et al*, 1981; Malczewski, 1990). This demonstrates how EOR activity has not only supported and enhanced emergency response, its findings have likewise informed and assisted many other fields, including commercial logistics.

Convenience sample part II: shifting focus in the 1990s

Most of the foundational EOR work in urban service settings was accomplished during what has come to be viewed as 'the golden era' of management science (Denizel *et al*, 2003). When reflecting on the entire timeline of the EOR convenience sample, another pattern suggests a microcosm of the development of OR as a whole. Most of the urban services applications discussed at the outset of the EOR chronology could be characterized as 'management engineering', the solving of practical problems through the creative adaptation of existing OR tools (Corbett and Van Wassenhove, 1993). As time progresses, less EOR work of this description appears, in favour of a mild polarization of focus that Corbett and Van Wassenhove (1993) describe as the 'pure theory' of management science *versus* the 'pure practice' case studies of management consulting. As Figure 1 illustrates, EOR publications viewed in aggregate begin to shift category focus during the 1990s. As the volume of publications concerning the mathematical modelling of urban service systems began to decline, investigations with the word 'disaster' in their titles begin appearing consistently in the convenience sample as of the year 1990. Before this, the few papers belonging to the Disaster Services cohort focused on a specific process such as search and rescue, and often mirrored the location-and-allocation framework of the concurrent Urban Services papers, such as the use of goal programming to assign rescue aircraft to deployment bases in Armstrong and Cook (1979), visible on the left-hand side of Figure 2. Indeed, there is a dispute concerning the overall 'start' of EOR centred in this time period—while much of earlier EOR work can be directly linked to the earlier NYCRI initiative, Chiu and Zheng (2007) state that emergency response research began primarily in the wake of the Three Mile Island nuclear accident in 1979, responsible for a dramatic revisiting and reform of associated regulatory policies in the United States. More accurately, the particular EOR branch of Disaster Services does establish itself subsequent to that milestone event, perhaps further galvanized by a series of similar industrial accidents that followed, such as the 1984 Union Carbide tragedy in Bhopal, India or the 1986 Chernobyl nuclear accident.

Appearing lower on the left-hand border of Figure 2 is the Disaster Services cohort member Brown and Vassiliou (1993), one of the more influential papers in terms of citation count outside of the Urban Services group. Brown and Vassiliou (1993) present a decision support system (DSS) for real-time allocation and assignment of response units in the context of disaster relief, allowing human intervention in the underlying optimization and simulation processes. Figure 3 displays the resulting EOR citation network of this study, using the same process described in the generation of Figure 2 around Kolesar and Blum (1973). Comparing Figures 2 and 3 demonstrates another shift in the nature of EOR publications outside of the Urban Services group: even highly cited works do not represent members of well-established EOR research streams such

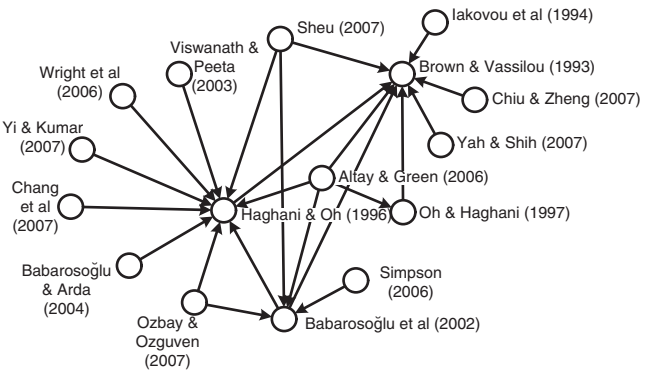

Figure 3 Emergency response research articles citing Brown and Vassiliou (1993) and those citing the citers of same (full references available at the end of this paper).

as pictured in Figure 2. While it should be noted that the internal relationships of Figure 3 can be expected to be less complex than Figure 2 because the seminal paper is 20 years younger, thus leaving less time to build up citation relationships, scaling back the research stream relating to Kolesar and Blum (1973) to only those publications appearing between 1973 and 1989, an interval comparable to Figure 3, would still yield a group of 41 publications, whereas Figure 3 displays less than half that number. Furthermore, a large part of what inter-relationships are visible in Figure 3 beyond isolated one-to-one citation relationships are being provided by inclusion in the disaster operations literature survey of Altay and Green (2006). Otherwise visible in Figure 3 are primarily theoretical papers focused on disaster relief, many building on the multi-commodity, multi-modal network flow modelling of Haghani and Oh (1996) and Oh and Haghani (1997).

Within the Disaster Services cohort, publications applying OR tools such as network analysis and simulation to the process of evacuation were relatively rare until the 1980s, but this changes dramatically after the mid 1990s. Many such EOR investigations appear in the multidisciplinary journal *Safety Science*, such as adapting fluid modelling to simulate crowd flow (Thompson and Marchant, 1995), validating building evacuation simulations against actual evacuations (Olsson and Regan, 2001), or debating the relative merits of models available to plan ship evacuations (Lee *et al*, 2003; Vanem and Skjong, 2006). Much of the growth of the Hazard Specific category after the year 2000 is owed to the introduction of EOR publications with 'terrorism' or 'terrorist' in their titles, many of which are discussed in the survey of Wright *et al* (2006) on that same subject. Before this time period, no specific hazard dominated that particular focus category.

However, the largest part of the growth in EOR volume over time is owed to the increasing number of articles that fall into the General Emergency category. A small part of this growth is arguably a partial return to urban services: as ambulances progressed from being vehicles for retrieving victims to being the initiators of field-based medical care, associated EOR articles were less likely to frame their titles in terms of 'ambulances' *versus* the newer discipline of 'emergency medical services'. Despite this increasing scope, it is not uncommon to find that studies in the newer category, for example, the queuing models in Iannoni and Morabito (2007), often build from frameworks established in the earlier NYCRI/Urban Services era, such as the influential hypercube queuing model of Larson (1974). In the mid-1990s the book *Operations Research and the Public Sector* (Pollock *et al*, 1994) had brought together OR contributions to areas as varied as fire, police, health care, urban transportation and sports. Nonetheless, the various applications described are all consistent with the modelling-and-optimization methodologies of the earliest era of EOR. Ironically, although NYCRI dissolved in 1975, the Rand Corporation maintained active involvement in EOR throughout this later time period, and many of its findings likewise culminated into books available to the public. Recent examples include *Protecting Emergency Responders: Lessons Learned from Terrorist Attacks* (Jackson *et al*, 2002), *New Challenges, New Tools for Defense Decisionmaking* (Johnson *et al*, 2003) and *Estimating Terrorism Risk* (Willis *et al*, 2005).

A more significant source of growth in the General Emergency category is relatively recent attention to the front-line process of emergency response itself. One example includes a distinct research stream appearing in *Reliability Engineering & System Safety*, modelling and evaluating the issue of task complexity in industrial response to emergencies (Park *et al*, 2001a, b, 2002) and investigating the potential disparity between defined and actual procedures in emergency situations (Park and Jung 2003a, b). More recently still, OR researchers have begun study of the essential nature of emergencies themselves, highlighting the interaction of the event timeline with the response activity as central to furthering the cause of EOR (Larson *et al*, 2006; Simpson, 2006).

As the volume of EOR activities began to grow later in the 1990s, conferences and special issues supporting the dissemination of such findings can likewise be found emerging in this interval. Twenty-four papers within the convenience sample appear in one of four EOR-themed special issues of *Safety Science* published between 1995 and 2006, three of those issues showcasing work presented at the annual conference of The International Emergency Management Society (TIEMS), itself founded in 1993 to bring researchers and practitioners together for the advancement of emergency management. Mainstream OR journals often collect and present work on a specific hazard or service when dedicating a special issue, and these are appearing with increasing frequency in recent years. Examples of such issues include a 2006 special issue of *Interfaces* dedicated to 'homeland security' OR applications, a 2007 issue of *Computers and Operations Research* dedicated to hazardous materials transportation, and a 2007 issue of *Transportation Science* addressing disaster relief logistics. Ironically, EOR presented outside the more specialized forums sponsored by relatively young organizations

such as TIEMS or International Disaster and Emergency Resilience (IDER) must often join a track based on underlying methodology or overall problem structure. Annual conferences of the larger mainstream OR societies such as the Operational Research Society, the Institute for Operations Research and the Management Sciences (INFORMS) or the Decision Sciences Institute (DSI) do not yet typically feature tracks specifically for emergency management or response, the closest kinship being long-standing tracks in public sector or military/defence applications.

Current gaps and opportunities

Reflecting on the foundation of EOR available in the literature not only draws out an impressive array of accomplishments to date, it ironically highlights many of the challenges ahead. Drawing from the body of work discussed previously, four major areas of opportunity are presented here, summarized as soft *versus* hard OR, information and DSSs, volunteers and temporary organizational structures, and performance metrics in the context of emergency response.

'Soft' versus 'hard' OR

Earlier discussion of OR methodology within the convenience sample made clear that 'hard' or 'classical' OR, with its emphasis on quantitative modelling to derive definitive solutions, is the dominant approach within the sample. Figure 2 demonstrates that those articles citing a seminal hard EOR publication, being themselves hard OR undertakings, further display a preference for referencing other hard EOR articles when building their arguments, yielding a complex yet distinctly cohesive network of citations. In contrast, instances of soft OR methodology, with its emphasis on modelling for problem insight and learning as opposed to distinct solutions, are relatively rare in the sample. Table 3 indicates that only 2.8% of articles fit that description, a proportion that is not likely the result of the convenience sampling process, in that it echoes the 0.9% soft OR articles within the earlier survey of Altay and Green (2006), who employed a completely different methodology for the gathering of EOR publications. Much of the 'soft EOR' in the current convenience sample has appeared relatively recently (eg Hewitt, 2002; Edwards *et al*, 2005), and mostly within the Urban Services category.

The relative dearth of soft EOR is puzzling for several reasons, one being that soft OR problem structuring methods such as Soft Systems Methodology intuitively seem well suited to capturing insight into the highly dynamic and ill-formed nature of problems posed by emergencies. But perhaps most compelling are existing observations that relatively few of the 'successful' modelling studies of EOR's earlier era had direct impact on associated policy-making and practice (Walker, 1982). One factor identified as central to this failure was a lack of involvement of the policy-makers in model formulation itself, promoting a lack of ownership in the resulting analysis. OR analysts in this context had even been characterized as arriving late, leaving early and thus divorcing themselves from issues of implementation (Heiss, 1974). If there does exist a causal relationship between these disjoints and a lack of impact on policy and practice, it follows that the more inclusive problem structuring approaches inherent in 'soft' OR techniques would be the next step toward achieving such impact.

Information and decision support systems

Reflecting on the successful reanimation of the fire company re-location algorithm of Kolesar and Walker (1974) into a more widely accessible microcomputer application, Walker (1989) identified the DSS as an emerging area of opportunity in OR. Larson *et al* (2006) recounts how the model of Kolesar and Walker (1974) was active three decades later in the unprecedented reallocation of New York City fire companies in the aftermath of the 2001 World Trade Center attack, maintaining the average response time to other emergencies within a minute of the system's long-term average despite the sudden horrific drain on resources created by the disaster site. Yet this powerful testimonial to the enduring value of early work in EOR exists simultaneously with paradoxical evidence of generally slow progress on DSS development in the context of emergency management. Returning to the literature, Tufekci and Wallace (1998) echo Walker's (1989) observations concerning the potential of DSS for emergency response, but nearly a decade later. Characterizing this dimension as a 'long neglected area of research and development', Tufekci and Wallace (1998) stressed the need to develop the underlying decision-support models of successful emergency management. Recently, Thompson *et al* (2006) return to this theme, highlighting the semi-structured nature of the decision-making environment of the emergency manager as a key challenge and observing that the quality of data entered into emergency management DSS often degrades as the incident grows larger, thwarting the value of this technological support. In reviewing a series of large-scale incidents, Larson *et al* (2006) highlight a need for better use of information technology for inventory management at the site of disasters, but a recent field report (Fritz Institute, 2007) has characterized humanitarian relief as 'rife with failed implementations of centralized commercial ERP (Enterprise Resource Planning) systems' that could not cope with the complexities particular to disaster logistics.

The literature reviewed here is not without some successful work on emergency management decision support, but this work often follows the theme of developing a DSS for a specific facility and its attending hazards, thus narrowing the complexity of the underlying decision models and providing greater opportunity for automatic data acquisition. For example, Dai *et al* (1994) provide a comprehensive theoretical model of distributed emergency decision support, but the application piloting this model is developed specifically for a coal mine. Other DSS research incorporating

emergency response focus on settings such as dams and flooding (Henandez and Serrano, 2001) or nuclear power plants (Kobare and Kafka, 1992; Yang *et al*, 1994; Gheorghe and Vamanu, 1995). However, like the broader body of more recent EOR studies, work in DSS for emergency management does not benefit from a cohesive ongoing research stream of investigations informing and advancing subsequent investigations. Witness to this is Figure 3, in which 17 other EOR publications relate to the proposed DSS of Brown and Vassiliou (1993), but none of the subsequent studies involve any particular other DSS application, focusing rather on underlying theoretical model development. It is also noteworthy that even computer applications in the context of established urban response systems, the area in which DSS have met with the greatest success in improving emergency response, are paradoxically the source of some of the greatest failures in state-of-the-art decision support. Indeed, it was the 1992 introduction of a computer-aided dispatching system to the world's largest ambulance system, the London Ambulance Service (LAS), which provided one of the most notorious case studies in information systems failure. Implicated in the 20–30 deaths before it was terminated less than 48 h later, the successful re-introduction of such a system to LAS 4 years later is somewhat less well known (Fitzgerald and Russo, 2005). More recently, launching the newest technology supporting fire, police and ambulance services in Dallas, Texas has inadvertently introduced problems and perilous inefficiencies where such complexities had not existed previously (Eiserer, 2008).

Volunteers and temporary organizational structures

Larson *et al* (2006) explicitly identify the issue of coordinating volunteers and so-called second and third tier responding agencies as an area of need in emergency management, one in which OR can likely do much to assist, a reoccurring sentiment in recent EOR other contributions (eg, Buck *et al*, 2006 or Wright *et al*, 2006). Much of earlier EOR work assumes emergency response deploys from a designed base, indicative of localized emergencies such as single structure fires or automobile accidents. However, a disaster is often distinguished from the latter type of emergency as being of sufficient size that no single organization available has the resources to resolve it (Haddow and Bullock, 2006). Protocols do exist for the temporary amalgamation of multiple agencies into a single organization for emergency response, such as the Incident Command System (ICS) followed by most emergency response services in the United States. While practitioners have found ICS to generally work well in coordinating firefighting organizations, a comparative study of nine large-scale incidents in the United States conducted by Buck *et al* (2006) supports previous criticisms of ICS in the field: this current state-of-the-art protocol makes little provision for incorporating the presence of unorganized volunteers and emergent groups who often play pivotal roles in the earliest phase of a large-scale emergency. Efforts to create multi-agency frameworks in anticipation of large-scale emergencies often find professional and volunteer groups at odds with one another, such as described by Gregory and Midgley (2000). The significance of the role of volunteers in the wake of very large events should not be underestimated, as evidenced by the 2004 Tsunami disaster. In one survey, over 90% of those interviewed in Indonesia reported being rescued by fellow civilians (Fritz Institute, 2005), and broader review of the entire incident concluded that virtually all live-saving activities and initial emergency response were provided by local volunteers (Telford *et al*, 2006).

Performance measurement

Performance metrics in emergency response remain underdeveloped, particularly in the context of large-scale emergencies, made evident by surveying EOR literature (Altay and Green, 2006) or by observing the activities of disaster relief agencies directly (Fritz, 2007; Telford *et al*, 2006). At least some of these difficulties arguably stem from EOR's membership in the public sector. OR in the public sector is typically complicated by multiple stakeholders in any single investigation, yielding additional complexities when stating objectives and measuring effectiveness (Papageorgiou, 1994; Walker, 1982). OR literature provides numerous examples of performance measurement or optimization of processes; however, this is typically within the context of a known design or operation such as airline scheduling in Yan *et al* (2008). Within EOR the inherent difficulty is that the incident develops in a unique and semi-structured manner, resulting in an inevitable inseparability of planning and implementation of response solutions. Therefore, familiar efficiency measures lose meaning in such a context, as there is no pre-existing design to benchmark against; once emergent factors are sufficiently known to allow application of traditional optimization techniques, the response has often moved on, making the 'solution' obsolete.

Conclusion

Much of what has been accomplished by OR in emergency response can be described as work within the well-structured, designed domain of emergency services. In this environment, emergencies are small and familiar enough that response processes such as fire suppression or traffic control can be defined and provided by a single organization. This provides the OR analyst with an inventory of deterministic *knowns*, such as an inventory of response apparatus, and stochastic *known unknowns*, such as the likelihood of a unit's availability, insight into which can be garnered from past data of the system. These are the building blocks that the methods of 'classical' OR can convert into highly relevant models of the response system, and seek improvement in its existing design. A substantial, cohesive stream of ongoing research has resulted from the pursuit of this objective, and it is here

that computer information systems and DSSs have met with their greatest successes.

However, as noted in the previous section, even in the most organized context of emergency response, computer information systems have a mixed reputation for success. Likewise, 'classical' OR studies set in this context cannot be assumed to have had any influence on policy or practice there. Historically, some EOR projects of this description have been spectacularly successful on that dimension, such as the hypercube queuing model recounted by Larson (2002), which began within the realm of NYCRI, but began almost immediate migration to cities around the world, assisting in police patrol planning in implementations ranging from nearby Boston, USA to Caracas, Venezuela. In stark contrast, other EOR modelling studies of that era had little or no discernable impact on practice, such as discussed in Walker (1982). The source of these distressing inconsistencies may be related to a distinct research opportunity: only recently has OR turned its attention to the nature of emergency response as a process or to the various stakeholders in that process. The traditional OR focus on location planning, unit allocation and dispatch treats emergency response as a homogeneous commodity upon arrival at an emergency, but this is hardly a good characterization of reality. Developing a strong theoretical understanding of the nature of work accomplished in the context of an emergency can not only advance the sophistication of systems supporting emergency response, it is likely that such findings would be of interest to non-emergency enterprises at work in increasingly dynamic and disruptive environments.

Following initial success in improving urban emergency services, EOR has since left the realm of designed response-bases and begun addressing the issues of large-scale emergencies and disaster, in which initial response capabilities may have been damaged and successful response will require the efforts of more than one organization. It appears that here is where the greatest amount of work remains to be done. It also appears that 'old habits die hard', in that both this study and previous research find math programming the favoured OR tool for this environment, despite the fact that it is arguably the least conducive to addressing *unknown unknowns*, or the potential emergent aspects of any disruption that, by definition, defy prior anticipation and explicit modelling. The larger the scale or scope of a disaster, the higher the likelihood that decision-makers will be confronted with one or more distinctly emergent issues, and thus will be obligated to develop and implement unique solutions with incomplete information *during* the response. A disturbing symptom of the general lack of attention paid to the intersection of emergency conditions and emergency services can be observed within the convenience sample of this study: 361 EOR papers are cleanly divided into four areas, two of which focus on services and two of which focus on hazards. Furthermore, one seminal paper from one focus category typically generates a citation map of EOR articles largely contained by the same focus category. Where are the papers studying the service activity in the context of the disruptive hazard, potentially synthesizing the findings of work within these focus areas?

At this point, all the various gaps and opportunities highlighted in this paper can be condensed into three inter-related questions for researchers:

- What is the essential nature of emergency response operations?
- How can OR best support operations under emergency conditions?
- What tools will best serve OR in successful pursuit of the first two questions?

While responders and policy-makers are assumed the direct beneficiaries of these inquiries, it is highly likely that future progress will be stymied unless these parties also serve as participants. Indeed, it can even be argued that policy sometimes drives EOR, as in the apparent initiation of disaster and evacuation research driven by policy-making in the wake of a major nuclear accident in the United States (Chiu and Zheng, 2007).

In conclusion, a single thread unites the particular areas of research opportunities discussed earlier in the paper: each is a problem of working in a *disorganized* environment. OR has naturally focused on operations in the context of organization, in that any other context would be inherently sub-optimal. Yet emergency response, particularly large-scale emergency response, requires operation under conditions distinctly disorganized by the emergency itself. Thus, otherwise successful Enterprise Resource Planning systems can falter during disaster relief because of a reliance on assumptions such as the identities of all items and means of conveyance can be stated in advance of the disaster. When indigenous response systems have been disrupted, emergent groups must be coordinated into temporary *ad hoc* organizations, and here the familiar measures of productivity and efficiency lose their utility, in that these constructs evaluate performance with respect to an underlying design. Far from representing intractable calamity, these challenges represent the opportunity to re-visit and re-define OR over the domain of disorganization, a likely and worthwhile OR growth area for the next 50 years.

References

Adrian C (1983). Analysing service equity—Fire services in sydney. *Environ Plann* **15**(8): 1083–1100.

Altay N and Green WG (2006). OR/MS research in disaster operations management. *Eur J Opl Res* **175**(1): 475–493.

Aly AA and White JA (1978). Probabilistic formulation of the emergency service location problem. *J Opl Res Soc* **29**(12): 1167–1179.

Anderson T and Varbrand P (2007). Decision support tools for ambulance dispatch and relocation. *J Opl Res Soc* **58**: 195–201.

Armacost RL (1992). A 0–1 non-linear programming model for coast guard fisheries law enforcement aircraft patrols. *Eur J Opl Res* **56**(2): 134–145.

Armstrong RD and Cook WD (1979). Goal programming models for assigning search and rescue aircraft to bases. *J Opl Res Soc* **30**(6): 555–561.

Barbarosoğlu G and Arda Y (2004). A two-stage stochastic programming framework for transportation planning in disaster response. *J Opl Res Soc* **55**(1): 43–53.

Barbarosoğlu G, Ozdamar L and Cevik A (2002). An interactive approach for hierarchical analysis of helicopter logistics in disaster relief operations. *Eur J Opl Res* **140**(1): 118–133.

Batta R (1989). A queueing location model with expected service time-dependant queuing disciplines. *Eur J Opl Res* **39**(2): 192–205.

Benveniste R (1985). Solving the combined zoning and location problem for several emergency units. *J Opl Res Soc* **36**(5): 433–450.

Bianchi G and Church RL (1988). A hybrid FLEET model for emergency medical service system design. *Soc Sci Med* **26**(1): 163–171.

Birge JR and Pollock SM (1989). Modelling rural police patrol. *J Opl Res Soc* **40**(1): 41–54.

Blake L and Coupe RT (2001). The impact of single and two-officer patrols on catching burglars in the act. *Br J Criminol* **41**(2): 381–396.

Brotcorne L, Laporte G and Semet F (2003). Ambulance location and relocation models. *Eur J Opl Res* **147**(3): 451–463.

Brown GG and Vassiliou AL (1993). Optimizing disaster relief—Real-time operational and tactical decision support. *Nav Res Log* **40**(1): 1–23.

Brueckner JK (1981). Congested public goods—The case of fire protection. *J Public Econ* **15**(1): 45–58.

Buck DA, Trainor JE and Aguirre BE (2006). A critical evaluation of the incident command system and NIMS. *J Homel Sec Emerg Mngt* **3**(3): 1–27.

Chaiken JM and Larson RC (1973). Methods for allocating urban emergency units: A survey. *Mngt Sci* **16**(4): 110–130.

Chaiken JM and Dormont P (1978). A patrol car allocation model: Background. *Mngt Sci* **24**(12): 1280–1290.

Chaiken JM and Dormont P (1978). Patrol car allocation model—Capabilities and algorithms. *Mngt Sci* **24**(12): 1291–1300.

Chaiken JM, Ignall E, Kolesar P and Walker W (1980). Response to communication on Rand–HUD fire models. *Mngt Sci* **26**(4): 422–432.

Chang MS, Tseng YL and Chen JW (2007). A scenario planning approach for the flood emergency logistics preparation problem under uncertainty. *Transport Res E-Log* **43**(6): 737–754.

Checkland PB (1981). *Systems Thinking, Systems Practice*. John Wiley: Chichester, UK.

Chelst KR (1981). Deployment of one- vs two-officer patrol units—A comparison of travel times. *Mngt Sci* **27**(2): 213–230.

Chiu YC and Zheng H (2007). Real-time mobilization decisions for multi-priority emergency response resources and evacuation groups: Model formulation and solution. *Transport Res E-Log* **43**(6): 710–736.

Chu SCK and Lin CKY (1993). A manpower allocation model of job specialization. *J Opl Res Soc* **44**: 983–989.

Church R, Sorensen P and Corrigan W (2001). Manpower deployment in emergency services. *Fire Technol* **37**(3): 219–234.

Corbett CJ and Van Wassenhove LN (1993). The natural drift: What happened to operations research?. *Opns Res* **41**(4): 625–640.

Dai J, Wang S and Yang X(1994). Computerized support systems for emergency decision making. *Ann Opns Res* **51**: 315–325.

D'Amico SJ, Wang SJ and Batta R (2002). A simulated annealing approach to police district design. *Comput & Opns Res* **29**: 667–684.

Daskin MS and Haghani A (1984). Multiple vehicle routing and dispatching to an emergency scene. *Environ Plann* **16**(10): 1349–1359.

Daskin MS and Stern EH (1981). A hierarchical objective set covering model for emergency medical-service vehicle deployment. *Transport Sci* **15**(2): 137–152.

Daskin MS, Hogan K and Revelle C (1988). Integration of multiple, excess, backup, and expected covering models. *Environ Plann B* **15**(1): 15–35.

Denizel M, Usdiken B and Tuncalp D (2003). Drift or shift? Continuity, change and international variation in knowledge production. *OR/MS Opns Res* **51**(5): 711–729.

Eaton DJ, Daskin MS and Simmons D (1985). Determining emergency medical service vehicle deployment in Austin, Texas. *Interfaces* **15**(1): 96–108.

Eaton DJ, Sanchez HM and Lantigua RR (1986). Determining ambulance deployment in Santo Domingo, Dominican Republic. *J Opl Res Soc* **37**(2): 113–126.

Edwards JS, Hall MJ and Shaw D (2005). Proposing a systems vision of knowledge management in emergency care. *J Opl Res Soc* **56**(2): 180–192.

Eiserer T (2008). Dallas police, firefighters frustrated with automated dispatch system. *The Dallas Morning News*, 9 March.

Erkut H and Polat S (1992). A simulation model for an urban fire fighting system. *Omega-Int J Mngt S* **20**(4): 535–542.

Fitzgerald G and Russo NL (2005). The turnaround of the London Ambulance Service Computer-Aided Dispatch system (LASCAD). *Eur J Inform Syst* **14**(3): 244–257.

Fitzsimmons JA (1973). A methodology for emergency ambulance deployment. *Mngt Sci* **19**(6): 627–636.

Freeman JM (1992). Planning police staffing levels. *J Opl Res Soc* **43**(3): 187–194.

Fritz Institute, *Lessons from the Tsunami: Survey of Affected Families in India and Sri Lanka*. Fritz Institute: San Francisco.

Fritz Institute, *Humanitarian Logistics: Enabling Disaster Response*. Fritz Institute: San Francisco.

Fritz L (2007). Making global connections: One organization attempts to mend the disconnect in disaster response. *San Francisco Med*, 20–21 March.

Fry MJ, Magazine MJ and Rao US (2006). Firefighter staffing including temporary absences and wastage. *Opns Res* **54**(2): 353–365.

Fujiwara O, Makjamroen T and Gupta KK (1987). Ambulance deployment analysis—A case-study of Bangkok. *Eur J Opl Res* **31**(1): 9–18.

Gendreau M, Laporte G and Semet F (2006). The maximal expected coverage relocation problem for emergency vehicles. *J Opl Res Soc* **57**(1): 22–28.

Gheorghe AV and Vamanu D (1995). A pilot decision support system for nuclear power emergency management. *Safety Sci* **20**(1): 13–26.

Grant HD, Murray RH and Bergeron JD (1994). *Emergency Care*, 6th edn. Brady/Prentice-Hall: Englewood Cliffs, New Jersey.

Green LV (1984). A multiple dispatch queueing model of police patrol operations. *Mngt Sci* **30**(6): 653–664.

Green LV and Kolesar PJ (1984). The feasibility of one-officer patrol in New York City. *Mngt Sci* **30**(8): 964–981.

Green LV and Kolesar PJ (1989). Testing the validity of a queueing model of police patrol. *Mngt Sci* **35**(2): 127–148.

Green LV and Kolesar PJ (2004). Improving emergency responsiveness with management science. *Mngt Sci* **50**(8): 1001–1014.

Gregory WJ and Midgley G (2000). Planning for disaster: Developing a multi-agency counselling service. *J Opl Res Soc* **51**: 278–290.

Haddow GD and Bullock JA (2006). *Introduction to Emergency Management*, 2nd edn. Elsevier Butterworth-Heinemann: Burlington, MA.

Haghani A and Oh SC (1996). Formulation and solution of a multi-commodity, multi-modal network flow model for disaster relief operations. *Transport Res A-Pol* **30**(3): 231–250.

Haghani A, Tian Q and Hu HJ (2004). Simulation model for real-time emergency vehicle dispatching and routing. *Transp Network Mod* **1882**: 176–183.

Hall RW (1984). Travel distance through transportation terminals on a rectangular grid. *J Opl Res Soc* **35**(12): 1067–1078.

Hall RW (2002). Incident dispatching, clearance and delay. *Transport Res A-Pol* **36**(1): 1–16.

Halpern J (1979). Fire loss reduction—Fire detectors vs fire stations. *Mngt Sci* **25**(11): 1082–1092.

Halpern J, Sarisamlis E and Wand Y (1982). An activity network approach for the analysis of manning policies in firefighting operations. *Mngt Sci* **28**(10): 1121–1136.

Haugen DL and Hill AV (1999). Scheduling to improve field service quality. *Decision Sci* **30**(3): 783–804.

Heiss FW (1974). *Urban Research and Urban Policy Making: An Observatory Perspective*. Bureau of Governmental Research, University of Colorado-Boulder: USA.

Henandez JZ and Serrano JM (2001). Knowledge-based models for emergency management systems. *Expert Syst Appl* **20**: 173–186.

Hewitt RL (2002). Siting a fire station by leveraging soft constraints and supporting science. *Interfaces* **32**(4): 69–74.

Hogg J (1968). The siting of fire stations. *Opl Res Q* **19**(3): 275–287.

Iakovou E, Douligeris C and Korde A (1994). A synthesis of decision models for analysis, assessment, and contingency planning for oil spill incidents. *Omega-Int J Mngt S* **22**(5): 457–470.

Iannoni AP and Morabito R (2007). A multiple dispatch and partial backup hypercube queuing model to analyze emergency medical systems on highways. *Transport Res E-Log* **43**(6): 755–771.

Ignall E and Walker WE (1977). An analysis of the deployment of ambulances in Washington DC. *J Urban Anal* **4**(1): 59–92.

Ignall E, Kolesar P and Walker W (1978). Using simulation to develop and validate analytic models—Some case studies. *Opns Res* **26**(2): 237–253.

Ignall E, Carter G and Rider K (1982). An algorithm for the initial dispatch of fire companies. *Mngt Sci* **28**(4): 366–378.

Ingolfsson A, Erkut E and Budge S (2003). Simulation of single start station for Edmonton EMS. *J Opl Res Soc* **54**(7): 736–746.

Jackson BA, Peterson DJ, Bartis JT, LaTourrette T, Brahmakulam IT, Houser A and Sollinger JM (2002). *Protecting Emergency Responders: Lessons Learned from Terrorist Attacks*. Rand Corporation: Santa Monica, CA.

Johnson SE, Libicki MC and Treverton GF (eds.) (2003). *New Challenges and New Tools for Defense Decisionmaking*. Rand Corporation: Santa Monica, CA.

Kirby MW (2007). Paradigm change in operations research: Thirty years of debate. *Opns Res* **55**(1): 1–13.

Kobare SK and Kafka P (1992). Expert systems for emergency alarms analysis during accident situations in nuclear reactors. *Reliab Eng Syst Safe* **37**(2): 139–149.

Kolesar P (1975). A model for predicting average fire engine travel times. *Opns Res* **23**(4): 603–613.

Kolesar P and Blum EH (1973). Square root laws for fire engine response distances. *Mngt Sci* **19**(12): 1368–1378.

Kolesar P and Walker WE (1974). An algorithm for the dynamic relocation of fire companies. *Opns Res* **22**(2): 249–274.

Kolesar P, Walker W and Hausner J (1975). Determining the relation between fire engine travel times and travel distances in New York City. *Opns Res* **23**(4): 614–627.

Kwak NK and Leavitt MB (1984). Police patrol beat design—Allocation of effort and evaluation of expected performance. *Decis Sci* **15**(3): 421–433.

Larson RC (1972). *Urban Police Patrol Analysis*. MIT Press: Cambridge, MA.

Larson RC (1974). Hypercube queueing model for facility location and redistricting in urban emergency services. *Comput & Opns Res* **1**: 67–95.

Larson RC (2002). Public sector operations research: A personal journey. *Opns Res* **50**(1): 135–145.

Larson RC and McKnew MA (1982). Police patrol-initiated activities within a systems queueing model. *Mngt Sci* **28**(7): 759–774.

Larson RC and Rich TF (1987). Travel-time analysis of New York City police patrol cars. *Interfaces* **17**(2): 15–20.

Larson RC, Metzger MD and Cahn MF (2006). Responding to emergencies: Lessons learned and the need for analysis. *Interfaces* **36**(6): 486–501.

Lee D, Kim H, Park JH and Park BJ (2003). The current status and future issues in human evacuation from ships. *Safety Sci* **41**(10): 861–876.

Mabin VJ and Rand GK (1979). Problematic presentation of the emergency service location problem. *J Opl Res Soc* **30**(9): 837.

Malczewski J (1990). The spatial planning of health services: Case studies in Warsaw, Poland. *Prog Plann* **33**(2): 113–174.

McDonald CJ (1989). Law enforcement simulation system. *Simulation* **53**(3): 122–128.

Murray AT (2005). Geography in coverage modeling: Exploiting spatial structure to address complementary partial service of areas. *Annals Ass Am Geogr* **95**(4): 761–772.

Northrop A, Kraemer KL and King JL (1995). Police use of computers. *J Crim Just* **23**(3): 259–275.

Oh SC and Haghani. Testing and evaluation of a multi-commodity multi-modal network flow model for disaster relief management. *J Adv Transport* **31**(3): 249–282.

Olsson PA and Regan MA (2001). A comparison between actual and predicted evacuation times. *Safety Sci* **38**(2): 139–145.

Ozbay K and Ozguven EE (2007). Stochastic humanitarian inventory control model for disaster planning. *Transport Res Rec* **2022**: 63–75.

Papageorgiou JC (1994). The role of the public sector in introducing operations research/management science within developing countries. *Public Admin Develop* **14**(3): 293–312.

Park JY and Jung WD (2003a). The operators' non-compliance behavior to conduct emergency operating procedures—Comparing the work experience and the complexity of procedural steps. *Reliab Eng Syst Safe* **82**(2): 115–131.

Park JY and Jung WD (2003b). The requisite characteristics for diagnosis procedures based on the empirical findings of the operators' behavior under emergency situations. *Reliab Eng Syst Safe* **81**(2): 197–213.

Park JY, Jung WD and Ha JJ (2001a). Development of the step complexity measure for emergency operation procedures using entropy concepts. *Reliab Eng Syst Safe* **71**(2): 115–130.

Park JY, Jung WD, Kim J, Ha JJ and Shin Y (2001b). The step complexity measure for emergency operating procedures—comparing with simulation data. *Reliab Eng Syst Safe* **74**(1): 63–74.

Park JY, Jung WD, Ha JJ and Park CK (2002). The step complexity measure for emergency operating procedures: Measure verification. *Reliab Eng Syst Safe* **77**(2): 45–59.

Pezzella F, Bonanno R and Nicoletti B (1981). A system approach to the optimal health-care districting. *Eur J Opl Res* **8**(2): 139–146.

Plane DR and Hendrick TE (1977). Mathematical programming and location of fire companies for the Denver fire department. *Opns Res* **25**(4): 563–578.

Pollock SM, Rothkopf MH and Barnett A (1994). *Handbooks in Operations Research and Management Science: Operations Research in the Public Sector*. Amsterdam: North-Holland.

Richard D, Beguin H and Peeters D (1990). The location of fire stations in a rural environment—A case study. *Environ Plann* **22**(1): 39–52.

Rider KL (1976). Parametric model for allocation of fire companies in New York City. *Mngt Sci* **23**(2): 146–158.
Rider KL (1979). Economics of the distribution of municipal fire protection services. *Rev Econ Stat* **61**(2): 249–258.
Sathe A and Miller-Hooks E (2005). Optimizing location and relocation of response units in guarding critical facilities. *Network Model* **1923**: 127–136.
Savas ES (1969). Simulation and cost-effectiveness analysis of New York's emergency ambulance service. *Mngt Sci* **18**(12): 608–626.
Schilling DA, Revelle C, Cohon J and Elzinga DJ (1980). Some models for fire protection locational decisions. *Eur J Opl Res* **5**(1): 1–7.
Schreuder JAM (1981). Application of a location model to fire stations in Rotterdam. *Eur J Opl Res* **6**(2): 212–219.
Sherali HD and Subramanian S (1999). Opportunity cost-based models for traffic incident response problems. *Transport Eng-J Asce* **125**(3): 176–185.
Sheu JB (2007). An emergency logistics distribution approach for quick response to urgent relief demand in disasters. *Transport Res E-Log* **43**(6): 687–709.
Simpson NC (2006). Modeling of residential structure fire response: Exploring the hyper-project. *J Opns Mngt* **24**(5): 530–541.
Smith DK (1997). Police patrol policies on motorways with unequal patrol lengths. *J Opl Res Soc* **48**(10): 996–1000.
Swersey AJ (1982). A Markovian decision model for deciding how many fire companies to dispatch. *Mngt Sci* **28**(4): 352–365.
Taylor PE and Huxley SJ (1989). A break from tradition for the San Francisco police: Patrol officer scheduling using an optimization-based decision support system. *Interfaces* **19**(1): 4–24.
Taylor BW, Moore LJ and Clayton ER (1985). An integer nonlinear goal programming model for the deployment of state highway patrol units. *Mngt Sci* **31**(11): 1335–1347.
Telford J, Cosgrove J and Houghton R (2006). *Joint Evaluation of the International Response to the Indian Ocean Tsunami: Synthesis Report*. Tsunami Evaluation Coalition: London.
Thompson PA and Marchant EW (1995). Computer and fluid modelling of evacuation. *Saf Sci* **18**(4): 277–289.
Thompson S, Altay N, Green III WG and Lapetina J (2006). Improving disaster response efforts with decision support systems. *Int J Emergen Mngt* **3**(4): 250–263.
Toregas C, Swain R, ReVelle C and Bergman L (1971). The location of emergency service facilities. *Opns Res* **19**: 1363–1373.
Tufekci S and Wallace WA (1998). The emerging area of emergency management and engineering. *IEEE T Eng Mngt* **45**(2): 103–105.
Valinsky D (1955). A determination of the optimum location of fire-fighting units in New York City. *Opns Res* **4**(3): 494–512.
Van der Meer RB, Quigley J and Storbeck JE (2005). Using regression analysis to model the performance of UK Coastguard centres. *J Opl Res Soc* **56**(6): 630–641.
Vanem E and Skjong R (2006). Designing for safety in passenger ships utilizing advanced evacuation analyses—A risk based approach. *Saf Sci* **44**(2): 111–135.
Viswanath K and Peeta S (2003). Multicommodity maximal covering network design problem for planning critical routes for earthquake response. *Transport Netw Model* **1857**: 1–10.
Walker WE (1974). Using the set-covering problem to assign fire companies to fire houses. *Opns Res* **22**: 275–277.
Walker WE (1982). Models in the policy process: Past, present, and future. *Interfaces* **12**(5): 91–100.
Walker WE (1989). Fire company relocation and the future of applied operations research. *Opns Res* **37**(3): 507–508.
Walker WE, Chaiken J and Ingall E (1979). *Fire Department Deployment Analysis: A Public Sector Case Study: The RAND Fire Project*. North-Holland: New York.
Willis HH, Morral AR, Kelly TK and Medby JJ (2005). *Estimating Terrorism Risk*. Rand Corporation: Santa Monica, CA.
Wilson C and Brewer N (1992). One- and two-person patrols—A review. *J Crim Just* **20**(5): 443–454.
Wright PD, Liberatore MJ and Nydick RL (Nov.-Dec. 2006). A survey of operations research models and applications in homeland security. *Interfaces* **36**: 514–529.
Yan SY and Shih YL (2007). A time-space network model for team scheduling after a major disaster. *J Chinese Inst Eng* **30**(1): 63–75.
Yan SY, Tang CH and Fu TC (2008). An airline scheduling model and solution algorithms under stochastic demands. *Eur J Opl Res* **190**(1): 22–39.
Yang JE, Jeong KS and Park CK (1994). Development of an emergency operation supporting system for nuclear power plants. *Reliab Eng Syst Safe* **43**(3): 281–287.
Yang L, Jones BF and Yang SH (2007). A fuzzy multi-objective programming for optimization of fire station locations through genetic algorithms. *Eur J Opl Res* **181**(2): 903–915.
Yi W and Kumar A (2007). Ant colony optimization for disaster relief operations. *Transport Res E-Log* **43**(6): 660–672.
Zhu ZW and McKnew MA (1993). A goal programming workload balancing optimization model for ambulance allocation—An application to Shanghai, PR China. *Socio Econ Plan Sci* **27**(2): 137–148.

Received May 2008;
accepted September 2008 after one revision