DYNAMIC RESPONSE RECOVERY TOOL FOR ROADING ORANISATIONS

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ABSTRACT

Natural and man made disasters have been increasingly affecting societies world wide. Damage range from deaths to business disruptions and can impact regional and local development at different scales. In this respect, response needs to be quickly and effectively deployed in order to reduce life and economic losses. The complex environment of disaster management can overwhelm organisations and decision-makers; therefore, generate poor response and resource usage. General recommendations and optimum resource deployment strategies can facilitate decision-making and ultimately reduce social / economic impacts. Hence, a decision support system, namely Dynamic Response Recovery Tool, is proposed in this paper according to a number of findings gathered from previous experiences in observing emergency exercises and performing game simulations as well as a logistics conceptualization of physical resource deployment during disaster situations. The proposed system is to be assessed in future research endeavours using a specific method in order to confirm its efficiency and applicability in real scenarios as well as to identify design shortcomings before an operational version can be developed and deployed for roading organisations.

INTRODUCTION

Recent disasters such as the 1994 Northridge Earthquake (USA), the 1995 Kobe Earthquake (Japan), the 2004 Sumatra Earthquake and Tsunami (Asia), 2005's Hurricane Katrina (USA), the 2009 Samoan Tsunami and the 2010 Haitian Earthquake have harmed societies worldwide. The International Federation of Red Cross and Red Crescent Societies (2002) estimates that the last decade alone accounted for 535,000 deaths and US$ 684 billion in losses from direct damage to infrastructures and crops due to disasters.

Responses from both academia and industry are commonly observed by improving communication protocols and technologies, increasing aid support networks, researching different topics (e.g. decision-making, policy development, mathematical modelling), retrofitting existing infrastructures (Earthquake Engineering), updating building code standards and etc.

Nonetheless, it is acknowledged that communities have different capacity (or resilience) to cope with disasters, that extreme events are hard to be managed and many times cannot be precisely predicted (e.g. Earthquake, Tsunami). Thus, response has to be timely and effective so lives can be saved and economic disruptions reduced. Researchers highlight that well-informed, integrated and timely decisions "can save lives, reduce damage and disruption, and enable faster recovery" (GNS Science & NIWA, 2006).

In this context, this paper proposes a decision support system (namely Dynamic Response Recovery Tool – DRRT) for the specific case of roading organisations. Decision-making factors during stress laden circumstances have been identified and analysed based upon knowledge and experiences acquired from the observation of emergency exercises and real events as well as the development of a game-based disaster scenario simulation (Ferreira *et al.*, 2009; Ferreira *et al.*, 2010a and Ferreira *et al.*, 2010b). Hence, the vast decision-making knowledge reported in the abovementioned references is used to propose the DRRT system. Additionally, operational research, logistics and information technology (in specific Expert Systems) concepts were considered in the proposal and description of the DRRT.

The paper is divided into four sections. Initially, the DRRT conceptual framework is presented along with its conceptual model. In the third section, the DRRT System is defined and its two main modules, namely Procedural Recommendations and Logistics Environment, are specified. Closing remarks and findings are presented in the final section with special attention draw to a future assessment framework to be applied in order to identify inadequacies in the DRRT system design for roading organisations.

THE DYNAMIC RESPONSE RECOVERY TOOL CONCEPTUAL FRAMEWORK

The DRRT is conceptualized as a logistics sub-system as part of Disaster Management, which is considered to be a sub-topic of Emergency Management. During a disaster, DRRT shall facilitate decision-making in mobilizing responding organisations as well as deploying human and physical resources. These activities are considered to be typical logistics tasks, which, in the specific context of emergency management, aim at saving lives, restoring businesses and reducing economic impacts associated with disasters situations. Overall, they are part of continuous efforts performed in order to better achieve numerous organisations' goals during disasters, according to specific situations and resource availability / need. The goal of decision support is achieved by providing efficient and accurate information to end-users so decisions can be continuously made until a stable state of "normality" is reached. DRRT's basic paradigms are intrinsically associated with the broad process of Reduction, Readiness, Response and Recovery adopted by the Ministry of Civil Defence and Emergency Management in New Zealand (MCDEM, 2009).

In this context, DRRT is geared towards supporting response and recovery activities by providing:

- **Procedural recommendations:** group of recommendations for effective and efficient organisational arrangements to conduct response processes. It comprises a series of guidelines to support decision-making towards communication set up, information sharing procedures, physical assessment of affected infrastructures and prioritization; and

- **Physical resource deployment recommendations:** complimentarily to procedural recommendations, optimization routines are provided in order to facilitate human and physical resource allocation. Logistics concepts (e.g. total cost minimization, distribution channels, players) and Geographic Information Systems Platforms are used to develop and deploy an optimization routine to minimize the total cost of response with the ultimate aim of saving lives and reducing economic impacts of disasters.

In summary, DRRT provides response recommendations to manage disasters and optimum strategies to deploy resources from origins (availability) to desired destinations (required locations). It is furthermore, expected that available resources will meet organisations' needs within previously agreed or optimum schedules and costs; hence, "normality" can be restored as soon as practical. A schematic representation of the logistics environment in which the DRRT operates is illustrated in Figure 1. In order to achieve a consistent decision support platform for resource deployment, three main components are considered: i) Participating Parties; ii) Data Input and iii) Support Systems. These three components are responsible to meet the information needs to operationalise the three existing logistics mechanisms considered for the DRRT system as described as follows:

- **Resource Needs:** gear and materials needed to conduct repair at response stages and perform reconstruction plans. Resource types and quantities originate from previous studies or field assessments conducted immediately after the event occurrence;

- **Resource Availability:** available resources from both public and private organisations as well as international aid agencies support (i.e. resources to be promptly deployed to disaster zones); and

- **Damage Location:** specific geo-spatial information about physical damage occurred at systems' infrastructures (e.g. road, sewage, power, telecommunications) within disaster zones.

Note in Figure 1 that damage location, resource need and availability information are processed using inputs originated from three logging components (i.e. Participating Parties, Data availability and Support Systems). Processing steps follow the model conceptualization presented in the DRRT Logistics Environment sub-section and outcomes are presented as simple recommendations to end-users, such as the most likely optimum deployment strategy, a response procedure check list and etc. These results were finally designed to facilitate the deployment of resources (both human and physical) as described after Figure 1.

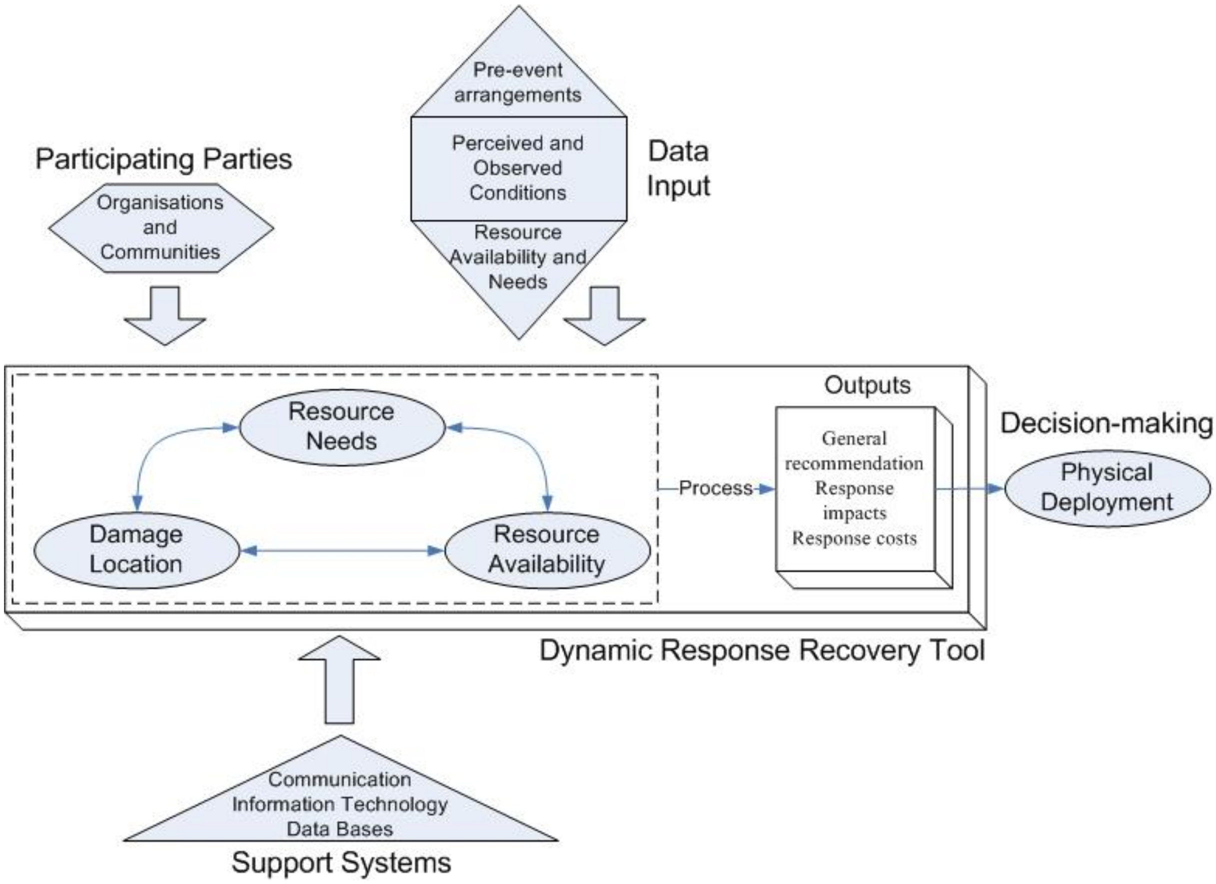

Figure 1 – Conceptual DRRT Environment.

The Physical Deployment activity should ideally take place after considering the complete set of information processed by the three abovementioned logistics mechanisms. It comprises the actual decision-making process about the distribution of resources throughout the disaster zone according to priorities, needs, availabilities and asset damage patterns in accordance to a holistic analysis of the disaster situation.

At practical grounds, DRRT's procedural level refers to management processes and protocols such as communication, information sharing and prioritization. They are outcomes from complex and interrelated relationships existing among staff and organisations. Being hard to be modelled according to engineering paradigms, they were identified and recorded after observing organisations and communities during a series of real and simulated emergencies as well as studying contingency, business continuity and response plans. Finally, optimization routines aim at supporting the physical deployment of resources and personnel in order to meet organisations' needs according to resource availabilities and community needs. Hence, data processed by logistics tools (e.g. shortest path, total cost minimization) are expected to facilitate decision-making processes and maximize response effort performance by providing simple, but key information to decision makers.

The next section describes the DRRT System according to its conceptual context. Thus, both procedural DRRT and its logistics environment are presented, with special attention to the logistics model formulation.

THE DYNAMIC RESPONSE RECOVERY TOOL SYSTEM

The DRRT System was proposed following a five phase method. Initially, DRRT system's requirements such as field of application, data input formats, information needs and logistics tools were defined. Subsequently, conceptual components of the DRRT as a decision support system were designed, e.g. Knowledge Base, Inference Engine, Modelling Routines and Graphical User Interface. The implementation phase comprised envisaging, planning, developing and testing the Information Technology Solution. Thus, an initial IT Solution was implemented and tested (i.e. verified) according to design parameters and intended performance. Theoretical case studies were conducted in order to assess how the proposed system could perform during real events. Finally, a series of case studies (not presented in this paper) will be performed in future research endeavours in order to assess the system and identify its inadequacies before a prototype DRRT version can be developed and deployed for the case of roading organisations. Along with this final phase, software maintenance routines will also be proposed.

The following two sub-sections present the basic DRRT components, namely Procedural Recommendations and Logistics Environment. Together they aim at providing recommendations to support extreme events decision-making at both general and specific levels, i.e. basic response processes and optimum resource deployment strategies.

Procedural DRRT: Decision-making Procedural Recommendations to Support Emergency Response Within Roading Organisations

The DRRT system was schematically designed (Figure 2) based on an adaptation of Berkes *et al.* (2001) Expert System model. Complimentarily, lessons learned from exercise observations and game simulations (Ferreira *et al.*, 2009; Ferreira *et al.*, 2010a and Ferreira *et al.*, 2010b) and basic logistics concepts (Daganzo, 2005) were also considered in order to propose a complete system for extreme events decision-making support.

Note in Figure 2 that DRRT's Knowledge Base receives data from the emergency environment and it is modelled by Participating Parties, i.e. organisations and communities. Data is collected using Support Systems such as communication technologies, data gathering devices (e.g. traffic flow), Geographic Information Systems (GIS), infrastructure assessment frameworks and etc. They ultimately represent emergency's situations and resource need / availability as illustrated in Figure 1. These data is further filtered, accordingly to specific organisational information needs, before it is processed in order to generate recommendations and specify optimum resource allocation strategies. This process takes place at the Inference Engine, which also considers previous actions in order to generate recommendations according to a time dependent model. Recommended decision-making solutions are finally prompted in a friendly user interface so decision makers can have access to comprehensive information before response strategies are deployed.

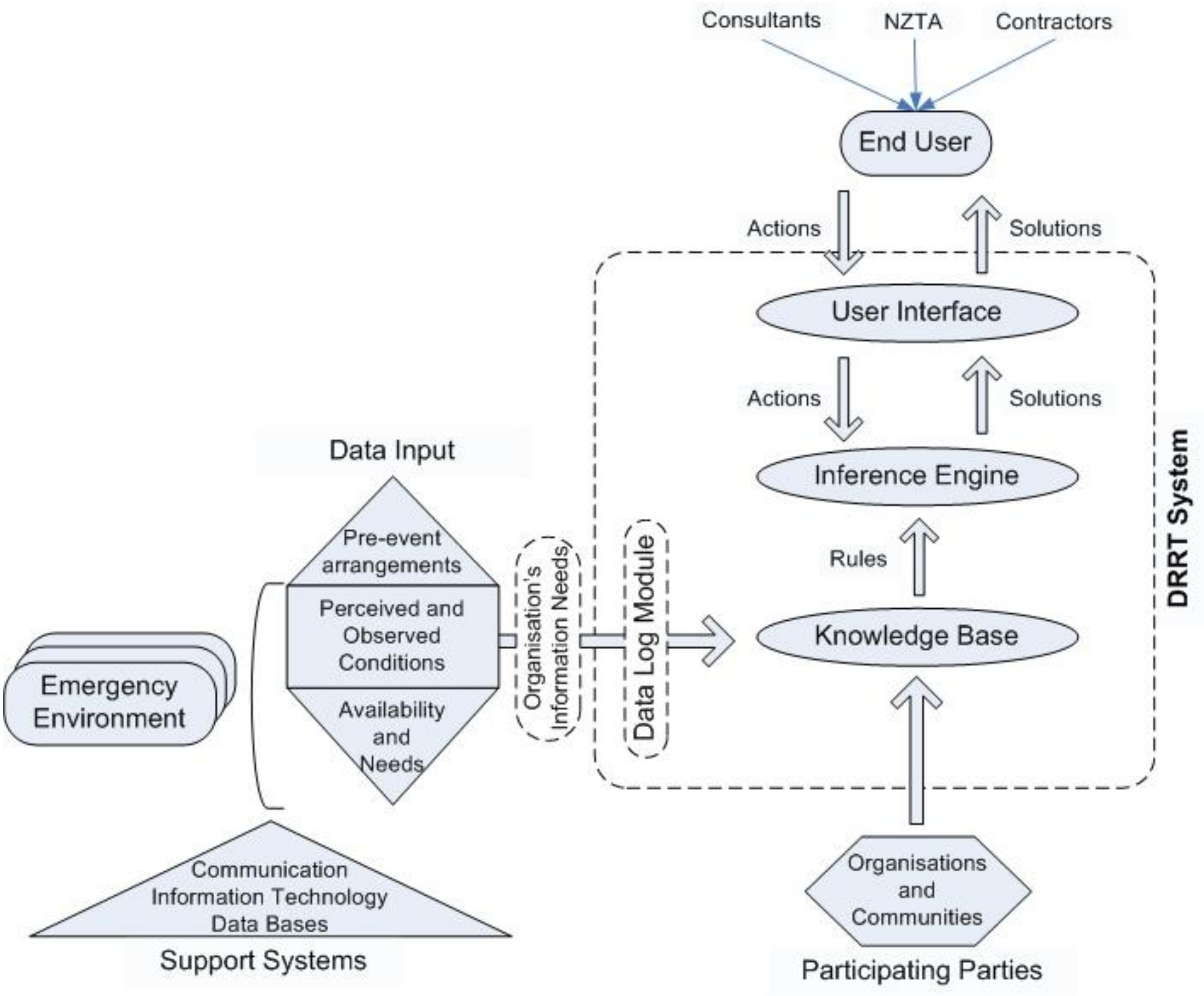

Figure 2 – DRRT System.

Berkes *et al.* (2001) model shapes the main core of the DRRT System, i.e. operations among Data Input, Knowledge Base, Inference Engine and User Interface. As described in scientific literature (Siler & Buckley, 2004; Feigenbaum, 1977 *apud* Jackson, 1999; Beerel, 1987; Giarratano & Riley, 1998; AIM Expert Systems, 2008; Biondo, 1990 and Arockiasamy, 1993), the Knowledge Base is a set of rules used to process external inputs and transform it into information. Data processing takes place in the Inference Engine, which contains the operational algorithm to compare external inputs with available knowledge (i.e. rules) in order to find appropriate solutions. Finally, a User Interface presents both external inputs and solutions (or outputs) in ease formats so decision-making can be facilitated. Note that the Knowledge Base (KB) is fed by general data and adapted according to Participating Parties, representing the real time emergency environment and community / organisations' needs, respectively.

In principle, the KB is static (i.e. rules do not change over the course of a particular event), but findings and lessons from individual emergencies can be further incorporated by creating new sets of rules. Hence, the system becomes more robust over time as new lessons are learned so decision-making can be better supported. Finally, Support Systems (e.g. communication, Information Technology) capture data about Perceived and Observed

Conditions as well as Resource Availability and Needs. These data are filtered by a human operator, according to individual organisation's needs, and finally logged into the DRRT System.

The vital DRRT System components are described as follows:

- **Data Log Module:** it is the interface between the emergency environment and the Knowledge Base. It is responsible to filter incoming data according to individual organisation's needs and system data formats;

- **Knowledge Base (KB):** it is the component which contains the set of operational rules and optimization routines used to process data into supporting information for decision-making;

- **Inference Engine (IE):** it is the computational component responsible to run searching and/or optimization algorithms to process incoming data. For the first case, the IE identifies rules (according to data fed into the system) which provide procedural response recommendations to the end-user. In the later case, an algorithm is used to identify optimum resource deployment strategies according to resource availability and needs; and

- **User Interface:** a graphical interface that presents incoming data and outcomes (e.g. recommendations, resource deployment strategy) to end-users in customized formats in order to support / facilitate decision-making.

Operationally, the DRRT System processes external data according to two sub-sets of "knowledge", i.e. Operations Decision-making and Logistics Tools. Both categories provide recommendations / information to end-users either as decision-making processes or optimum resource deployment strategies. Figure 3 illustrates this process, which is finalized by presenting information in an appropriate graphical interface with ease visualization.

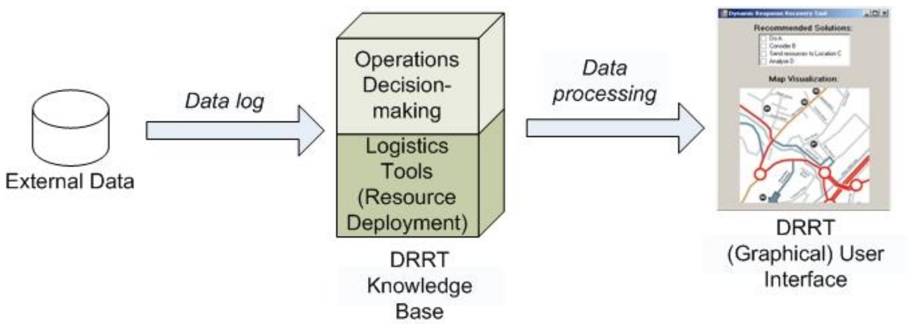

Figure 3 – Operational DRRT.

In specific for supporting decision-making operations, the DRRT System is designed to operate according to binary codes. Thus, external data is coded and compared with knowledge (i.e. rules) recorded within the KB. When matching codes are found, recommended solutions are withdrawn from the KB and presented to the end-user. Figure 4 exemplifies this process. For instance, consider that external data has been coded as patterns 0001, 0101, 1010 and 1001. When searching the KB Operations Decision-making sub set, the Inference Engine identifies two matching patterns: 0001 and 1010. These patterns are extracted from the KB, decodified and prompted in the DRRT's User Interface as recommendations (e.g. "Check landline phone, cell phone, Satellite phone, RTs, internet and e mail services", "Run test calls for confirmed operational technologies" and "Arrange Emergency Operations Centre - EOC", "Assign management positions").

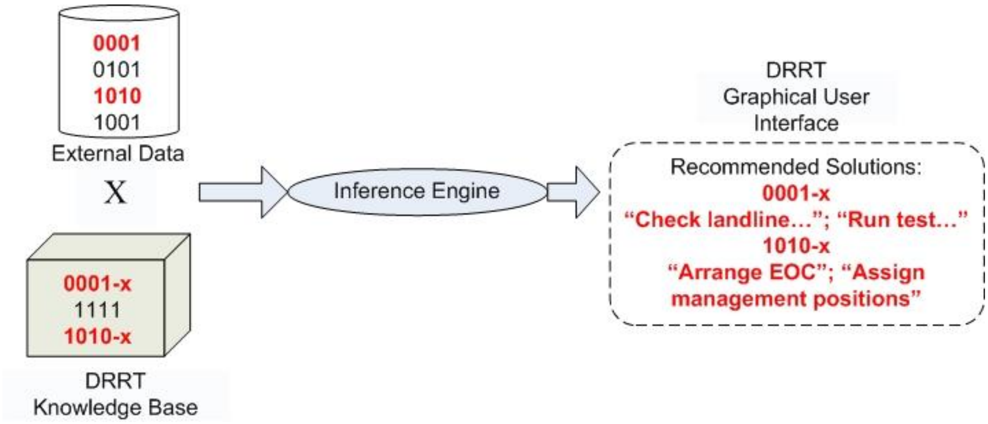

Figure 4 – DRRT Inference Engine Processing.

The complimentary KB sub-set (i.e. Logistics Tools) is presented in the following sub-section. The logistics environment along with resource allocation optimization recommendations are proposed in order to facilitate resource allocation decision-making by identifying optimum deployment strategies.

DRRT Logistics Environment: Tools for Optimizing Resource Allocation

Logistics problems can be usually solved through a three step process: i) gathering as much information as possible about the problem; ii) defining logistics systems and cost functions; and iii) developing mathematical optimization routines (Daganzo, 2005).

Following the process abovementioned, vast experiences were collected about how organisations and communities operate during emergency events (exercises and real event observation). Information gathered were further specified on how physical resources are deployed, according to availabilities, needs and priorities, during disasters (game simulations). These experiences have helped us in comprehending the complex management environment, in which disaster response and recovery activities take place.

Within this background, we have initially modelled the possible logistics systems that response organisations operate during disasters and proposed cost functions for each case (step two). Furthermore, on step three, an optimization routine was defined in order to identify optimum resource deployment strategies. These development activities are further described and consist of what we have named as DRRT Logistics Environment.

Logistics Systems Configurations

Three distribution channels were defined: i) Resource Depot (D), ii) Resource Availability Location (A) and iii) Resource Demand Location (R). Both "D" and "A" represent locations where resources are available as it can be found either at depot(s) or on the field due to maintenance, repair or construction works. Additionally, the distribution channel "R" represents asset locations where damage was experienced and need to be repaired. In this context, two scenarios are likely to occur, namely i) Direct Resource Allocation or ii) Indirect Resource Allocation. In the first scenario, resources are deployed straight from depot(s) to points of need (required locations). It is assumed therefore, that machinery is shifted directly from origins to destinations as loading activities are not required due to all necessary physical and human resources (e.g. driver, fuel, material) been available at the depot(s). The second deployment scenario includes the possibility of resources been available at numerous locations throughout a region and not only at depots. It represents machinery been used for construction or maintenance operations that can be scattered in a region. In this respect, resources can be deployed to required destinations for emergency response either directly (considering that all material and labouring needs are already available) or with a stop at depot(s) to load materials or collect additional personnel. From the observation of real emergency events (e.g. the 1994 Northridge Earthquake - USA, the 1995 Kobe Earthquake - Japan, the 2004 Sumatra Earthquake and Tsunami - Asia, and 2005's Hurricane Katrina - USA), the second scenario is the most likely to occur during disasters.

Logistics theory indicates four possible classes of problems: i) one origin and one destination; ii) one origin and many destinations; iii) many origins and one destination and iv) many origins and many destinations. The study of recent disasters as the ones previously mentioned and the observation and simulation of emergency exercises as reported by Ferreira *et al.* (2009, 2010a, 2010b) and Giovinazzi *et al.* (2008) strongly indicate that only the last two classes are likely to occur during an emergency. This is due to the fact that resources will be likely available at multiple locations and it might be required either at single (e.g. fire event, flash flood, traffic accident) or multiple locations (e.g. earthquake, volcanic eruption, tsunami). Finally, Resource Depot channels (D) can be single or multiple depending on specific environment configurations (e.g. number of contractors, existing management systems, affected area). Figure 5 illustrates these possible logistics systems configurations.

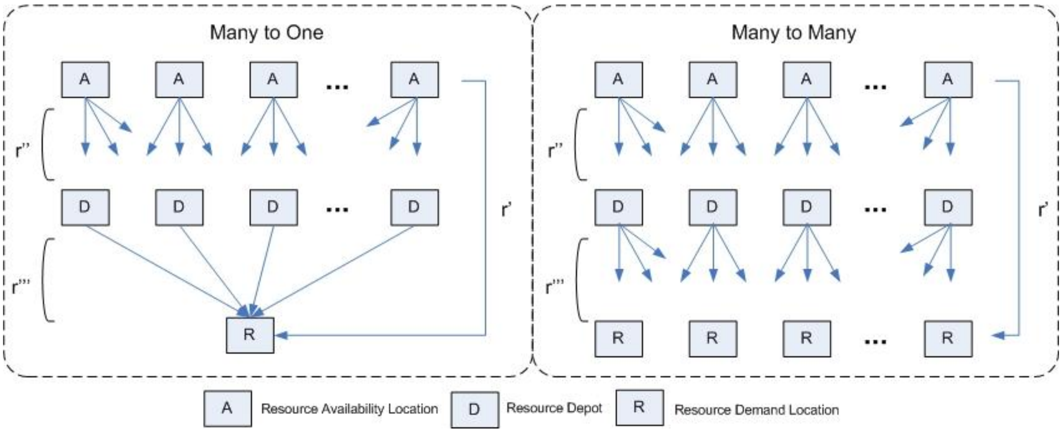

Figure 5 – Logistics Systems and Problems in Disasters Situations.

Finally, as previously described, resources can be deployed directly from available locations to final destinations (e.g. depot to required location: r''', or available location on field to required location: r') or with a stop at a depot distribution channel – D, i.e. from available location on field to required location with a stop at depot: r'' + r'''. These deployment strategies are modelled in the next sub-section through a mathematical description of cost functions and the proposal of an optimization routine to identify optimum resource deployment strategies in a complex disaster environment.

Mathematical Cost Functions Formulation

Consider an organisation performing response activities immediately after an extreme event, which affects an area of analysis and its road transport network. Roading organisations, at any given time *t*, can deploy available resources R^t located at any location *i* such as R_1^t, R_2^t, $R_3^{\,t}$, $\ldots R_i^{\,t} \ldots$ $R_n^{\,t}$ to support response efforts (asset damage repair, rescue operations, evacuation management, lifeline support, etc) at any damaged location *j* such as D_1^t, D_2^t, D_3^t, $\ldots D_j^{\,t}$ … D_m^t. Resource deployment is further subject to a set of priorities P^t assigned to each response effort such as P_1^t, P_2^t, $P_3^{\,t}$, … $P_k^{\,t}$. Thus, a set of resources $r_{ij}^{\,t}$ are allocated to individual damaged locations in order to support response efforts.

In this context, a resource optimization routine is defined considering two cost components, namely Logistics Response Cost (*LRC*) and Delay Response Cost (*DRC*). Both *LRC* and *DRC* comprise the Total Response Cost (*TRC*), which is minimized subject to a set of conditions under the decision makers' control. The remaining of this sub section presents the Logistics Response Cost, the Response Delay Cost and the Total Response Cost minimization approach. Tables 1 and 2 present the variables and indexes defined for the DRRT resource allocation optimization model, respectively.

Table 1 – Variables.

Variable	Definition
R^t	Available Resources at time *t*
$R_i^{\,t}$	Resource at origin *i* at time *t*
$D_j^{\,t}$	Damage at destination *j* at time *t* (affected road asset)
L_l	Link length
C_l	Link capacity
F_l	Link flow
RC_l	Link repair cost
$r_{ij}^{\,t}$	Resource allocation from origin *i* to destination *j* at time *t*
td_{ij}	Travel distance from *i* to *j*
A	Unitary travel cost (cost per distance)
B	Unitary loading / unloading cost (cost per time)
LT	Loading time
UT	Unloading time
LC	Logistics cost (total time for loading and unloading)
Pt_{ij}	Minimum path between an origin *i* to a destination *j*
$P_k^{\,t}$	Priority for the k^{th} response objective at time t^{th}
LRC	Logistics Response Cost
DRC	Delay Response Cost
$CD_l^{\,t}$	Cost of delay for link *l* at time *t*
θ	Unitary cost of delay per vehicle
$\delta_{ik}^{\,t}$	Adjustment factor for Cost of delay (CD_l^t)
TRC	Total Response Cost

Table 2 – Indexes.

Index
i: origin; $1 \le i \le n$
j: destination; $1 \le j \le m$
k: response objective; $1 \le k \le o$
l: links; $1 \le l \le z$
t: response time; $1 \le t \le r$

Logistics Response Cost (*LRC*)

LRC is defined as the travel cost plus loading and unloading costs. As defined in Equation 1, travel costs are directly proportional to allocated resources (r_{ij}^{t}) and travel distance. Loading / unloading costs are only dependent on the volume of allocated resources.

$$LRC = r_{ij} * [(td_{ij} * \alpha) + (LT + UT) * \beta] \quad \text{(Equation 1)}$$

Where: r_{ij}: allocated resources from origin i to destination j
td_{ij}: travel distance from i to j
α: unitary travel cost (cost per distance)
LT: Loading time (average time taken to load one resource unit with necessary materials and fuelling time)
UT: Unloading time (average time taken to unload materials transported by one resource unit)
β: unitary loading / unloading cost (cost per time)

Note that the travel distance (td_{ij}) regards to the sum of lengths for links containing in the minimum path between an origin i to a destination j (Pt_{ij}). Furthermore, for a given time t and considering Loading Time equal Unloading Time for the sake of simplification, we have:

$$LRC^{t} = \sum_{i}\sum_{j}((r_{ij}^{\ t} * td_{ij} * \alpha) + (r_{ij}^{\ t} * (LC + LC) * \beta)) \quad \text{(Equation 2)}$$

Simplifying Equation 2, we have Equation 3 which represents the Logistics Response Cost for any given time t.

$$LRC^{t} = \sum_{i}\sum_{j}(r_{ij}^{\ t} * (td_{ij} * \alpha + 2LC * \beta)) \quad \text{(Equation 3)}$$

$$\text{Given: } td_{ij} = \sum_{a \in Pt_{ij}} L_{l}^{a}$$

Where: r_{ij}^{t}: allocated resources from origin i to destination j at time t
td_{ij}: travel distance from i to j
α: unitary travel cost (cost per distance)
LC: Logistics cost (total time for loading and unloading)
β: unitary loading / unloading cost (cost per time)
Pt_{ij}: Minimum path between an origin i to a destination j
L_{l}^{a}: Length value for a link belonging to the minimum path Pt_{ij}

Delay Response Cost (*DRC*)

The Delay Response Cost (*DRC*) represents the fixed asset repair cost plus the cost incurred to vehicles impeded to travel on a given link due to lost road capacity. Equation 4 generalizes the *DRC* at any given time *t*.

$$DRC^t\left(R^t\right)=\sum_j RC_l+\sum_j CD_l^{\,t}[r_{ij}^{\;t}]*\frac{1}{\sum_j\sum_k \delta_{jk}^{\;t}} \quad \text{(Equation 4)}$$

Where: *DRC*: Delay Response Cost
R^t: Available Resources at time *t*
RC_l: Link repair cost
$CD_l^{\,t}$: Cost of delay for link *l* at time *t*
r_{ij}^t: allocated resources from origin *i* to destination *j* at time *t*
$\delta_{jk}^{\,t}$: Adjustment factor for Cost of delay ($CD_l^{\,t}$)

Note that the total cost of delay is a function of allocated resources (r_{ij}^t) as repair occurs according to the number of resources available at damaged locations. *DRC* is finally given by the Cost of Repair (RC_l) plus the Cost of Delay ($CD_l^{\,t}$) for all damaged links at destinations *j* times the inverse factor $\delta_{jk}^{\,t}$. The introduction of $\delta_{jk}^{\,t}$ intends to incorporate the response priorities (P_k^t) as emergency decision-making has shown to be a naturalistic decision process as well as $CD_l^{\,t}$ alone cannot be considered as the sole variable in extreme events decision-making (Ferreira *et al.*, 2009; Ferreira *et al.*, 2010a and Ferreira *et al.*, 2010b). Furthermore, $\delta_{jk}^{\,t}$ expresses a direct proportional relation between response objectives and network links, reason why its inverse function needs to be considered (i.e. greater the relationship response planning / road network links, lesser is the cost to deploy resources to such locations). In this light, *DRC* can be specified through the following set of equations 5 and 6.

$$CD_l^t=(F_l-C_l*(1-D_j^t))*\theta \quad \text{(Equation 5)}$$

$$\text{Given: } D_j^t>0$$

Where: $CD_l^{\,t}$: Cost of delay for link *l* at time *t*
L_l: Link flow
C_l: Link capacity
D_j^t: Damage at destination *j* at time *t* (affected road asset)
θ: unitary cost of delay per vehicle

Given a set of response objectives (1 ≤ *k* ≤ *o*), priorities P_k^t for *o* response objectives are time dependent (*t*) and specified by a responding organisation according to Equation 6. Furthermore, the Adjustment Factor (δ_{jk}^t) is equal to priorities P_k^t accordingly to the relation road network and services offered by its individual links, e.g. Link l_1 is likely to be used for evacuation purposes, Link l_2 is likely to be used to access residential areas for search and rescue activities, Link l_3 provides access to the CBD where the businesses centre is located etc.

$$P_k^t=f(t) \quad \text{(Equation 6)}$$

$$\text{Given: } \sum_k P_k^t=100 \text{ for } t = 1, 2, 3 \ldots t \ldots r$$

Where: P_k^t: priority for the k^{th} response objective at time t^{th}

Finally, Delay Response Cost is given by Equation 7.

$$DRC^t\left(R^t\right) = \sum_j RC_l + \sum_j \left(F_l - C_l * (1 - D_j^t)\right) * \theta * \frac{1}{\sum_j \sum_k \delta_{jk}{}^t} \quad \text{(Equation 7)}$$

Where: $CD_l{}^t$: Cost of delay for link *l* at time *t*
RC_l: Link repair cost
F_l: Link flow
C_l: Link capacity
D_j^t: Damage at destination *j* at time *t* (affected road asset)
θ: unitary cost of delay per vehicle
$\delta_{jk}{}^t$: Adjustment factor for Cost of delay ($CD_l{}^t$)

Note: $\delta_{jk}{}^t$ is to be estimated according to priorities established by responding organisations and relation road network and services provided by its individual links.

Total Cost

The Total Response Cost comprises both Logistics Response Cost (*LRC*) and Delay Response Cost (*DRC*). *TRC* is given by the sum of *LRC* and *DRC* for all times *t* as presented in Equation 8. Thus, organisation's staff will attempt to allocate specific set of resources r_{ij}^t in order to minimize the Total Response Cost (*TRC*), which expresses the overall contribution to response and recovery efforts towards minimizing life losses and physical disruptions. The Total Response Cost Minimization Routine or Resource Allocation Minimization Routine along with and conditions are specified as follows.

$$TRC = \sum_t LRC^t + \sum_t DRC^t \quad \text{(Equation 8)}$$

Resource Allocation Optimization Routine

Organisation's staff will attempt to allocate specific set of resources r_{ij}^t in order to minimize the Total Response Cost; therefore, identify the best resource deployment strategy. This optimization process is represented by the minimization of *TRC* as shown in Equation 9 subject to a set of conditions. It ultimately expresses the overall contribution to response and recovery efforts towards minimizing life losses and physical disruptions.

$$\min\left(\sum_t TRC^t\right) = \min\left(\sum_t (LRC^t + DRC^t)\right)$$

$$\min\left(\sum_t \left([\sum_i \sum_j (r_{ij}{}^t (td_{ij} \cdot \alpha + 2LC \cdot \beta))]^t + [\sum_j RC_l + \sum_j \left(\frac{F_l - C_l \cdot (1 - D_j^t)) \cdot \theta}{\sum_j \sum_k \delta_{jk}{}^t}\right)]^t\right)\right)$$

(Equation 9)

Subject to:

$\sum_i \sum_j r_{ij}^t = R^t$	Sum of resources deployed at t^{th} time from origin *i* to destination *j* - r_{ij} - shall be equal the total available resources at t^{th} time - R^t

$td_{ij} = \sum_{a \in P_n} L_l^a$	Travel distance from origin *i* to destination *j* is the sum of link lengths L_l for the minimum path P_n
$\sum_k P_k^t = 100$	Sum of priorities for *k* response objectives at a given time *t* shall be equal to 100 (i.e. 100%)

The process described by Equation 9 and its optimization conditions is ultimately implemented by estimating *LRC*, *DRC* and *TRC* for all possible resource deployment strategies, i.e. different combinations of resource assignment to all possible origin / destination sets.

Results are to be presented in friendly user interfaces in form of recommendations in order to support / facilitate decision-making during disasters situations. Numerous frameworks can be used to develop a Decision Support System for emergency management depending on available resources as well as end users needs. Nevertheless, spatial representations provided by Geographic Information Systems (GIS) have already shown positive results as spatial information and mapping capabilities can play key roles during emergencies (Transit NZ, 2007 and Transit NZ, 2008) and are therefore proposed for the future implementation of the Dynamic Response Recovery Tool (DRRT) for roading organisations.

CLOSING REMARKS AND FUTURE RESEARCH

Previous reported experiences (Ferreira *et al.*, 2009; Ferreira *et al.*, 2010a and Ferreira *et al.*, 2010b) have already indicated a strong potential for the DRRT System in the context of emergency management within roading organisations.

In one side of the spectrum, practitioners' involvement (Transit NZ, 2007 and Transit NZ, 2008) have demonstrated that procedural recommendations (i.e. structured emergency management processes) and well established technologies (e.g. Geographic Information Systems) can support decision-making and finally improve response performances. On the other side of the spectrum, initial assessments of the proposed Resource Allocation Optimization Routine have indicated potential contribution for a quick and efficient analysis of numerous resource deployment strategies in order to facilitate decision-making. For instance, a simple case study considering a road network with seventeen links, twelve nodes, three resource availability locations and random generated damage at four links fomented the analysis of more than two thousand resource deployment strategies and the identification of the most cost efficient deployments.

In this context, a key future research endeavour will be the development of a DRRT Demonstrator in order to assess the DRRT's efficiency and suitability for roading organisations' disasters management. Thus, both procedural and resource deployment recommendations will be assessed in their decision support capacity. This new set of case studies are intended to be conducted with academics and practitioners in New Zealand in order to collect valuable trustworthy data to assess the currently proposed DRRT System design, indentify shortcomings and finally propose an updated DRRT version before developing / deploying the first operational DRRT System. Along with such future development a case study has been already initially developed and implemented for a seventeen road link network. Case study results as well as an assessment of the practicability of the proposed method in the context of emergency response can be found in Dantas and Ferreira (2010). Such results are not presented here due to the intended scope of the paper. Finally, a better understanding on how link lost capacity affects the cost estimation formulation proposed in this paper still needs to be sought.

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