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A conceptual road network emergency model to aid emergency preparedness and response decision-making in the context of humanitarian logistics

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Abstract

This paper presents a discussion on the application of different techniques (e.g. network reliability and logistics concepts) for emergency management. Special attention is given to decision-making support in the context of roading networks before, during and after stress emergency situations. It is understood that the complexity of emergencies can quickly overwhelm organizations and personnel and ultimately lead to poor decision-making and loss of life and wealth. In this respect, a method is proposed to both support network analysis and resource allocation to fix road networks prone to disasters. A Road Network Emergency Management model has been designed to assist technically-sound preparations and decision-making during emergencies. Case study results indicate that the chosen techniques and the proposed model can help organizations to better manage emergencies; however, they do not satisfy all the resource, personnel and governmental managerial needs identified for dealing with real emergencies. In this context, a new field of study, namely Humanitarian Logistics, is proposed in an effort to fill the conceptual gaps observed in many previous studies of Emergency Management.

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Keywords: Emergency management; decision-making; roading organizations; resource deployment cost modeling; disaster response

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1. Introduction

Over the past decade, Emergency Management has rapidly grown to be a topic of great concern at both academic and practical arenas. The increasing number of disasters around the world as well as the existing complex interdependencies among systems (e.g. water, power, transportation, sewage) has driven researchers and practitioners towards the proposal and development of novel approaches to manage emergencies. Among numerous objectives, life saving and economic disruptions reduction can be pointed out as the two main objectives when dealing with stress laden situations such as natural and man made disasters. Overall, governments and private organizations are focused in developing and applying response and recovery methodologies to meet the abovementioned objectives.

The scientific and technical literature presents a series of approaches for emergency management. For instance, [1] and [2] have developed sophisticated representations of evacuation systems using mathematical and probabilistic modeling. Transportation researchers have endeavored in response planning to set the best possible resource allocation and identification of bottlenecks in the transportation systems. Also, studies from [3] [4] and [5] have contributed to identifying key changes to infrastructure systems, which are expected to improve the response to disasters by minimizing the need to repair damage and speeding response. Finally, research and practice have also been conducted towards setting emergency response procedures and protocols [6] [7] [8] and [9], emergency management training to deal with potential events through scenario simulation [10] and [11] and organizational resilience assessment [12] and [13].

Despite the great range of academic research mentioned in the last paragraph, it is debatable whether or not such approaches are effective and efficient in dealing with the complexities associated with most emergencies. Poor emergency responses observed in real disasters (e.g. the 2004 Sumatra Earthquake and Tsunami and 2005's Hurricane Katrina) can be attributed to limited application of available methods and/or a lack of suitable methodologies. In this paper, we focus on further developments of emergency management theories as recent researches have indicated that available tools and methodologies are individually efficient, but fail to holistically support decision-making in the broad context of disasters [14] and [11].

Against this backdrop, a conceptual Road Network Emergency Management method is proposed in this paper. On one side of the spectrum, the proposal takes advantage of the current state of the art from both practical and theoretical fields. So, academic theories and models are considered to address emergency management needs within practical approaches, such as the Reduction, Readiness, Response and Recovery approach adopted in New Zealand [15] or the National Incident Management Systems approach adopted in the United States of America [16]. On the other side of the spectrum, challenges in developing and applying the proposed model in practical situations are discussed using case study simulations.

The paper has been divided into four sections. The next section presents the theoretical basis for the proposed method. In the third section, the Road Network Emergency Management method is presented, along with a case study simulation to evaluate the method. In the fourth section, a new research field (namely, Humanitarian Logistics) is proposed and outlined, taking account of the studies and results achieved over the last decade in the field of Emergency Management.

2. Theoretical background

Key concepts from the scientific literature have been considered in order to support the proposal of the Road Network Emergency Management model. This theoretical background includes well established fields in the transportation environment such as network reliability, path selection and cost estimation.

2.1. Network terminal reliability

The probability that at least one path exists between an origin and destination after some disaster is defined as Network Terminal Reliability or Connectivity Reliability [17]. Much research has been already conducted in the specific context of transportation to define indices and their application to Network Terminal Reliability (NTR). For instance, [5] has studied the application of NTR to identify strategies in optimizing the allocation of resources to maximize network reliability. It has also been proposed a model for hazard loss estimation under the theoretical paradigms of network reliability [18]. Lai [19] suggests that NTR can be used for both “business-as-usual” and emergency situations. However, he also states that unforeseeable/uncontrolled events (e.g. natural and man-made disasters) are of special concern as link failures can only be estimated, but not precisely defined, as usually done when maintenance and construction works are scheduled.

In this context, NTR has proven to be of potential use for Emergency Management. A good understanding of possible failures and impacts on individual links due to hazards impacts can be vital for both emergency response and recovery. For a given road network, the overall network reliability (R) depends on the probability of failure of individual links, as follows:

$$R = E \left[1 - \prod_{n=1}^{n=N} \left(1 - \prod_{a \in P_n} x_a \right) \right] \quad (1)$$

where: X_a is a binary indicator for “link a ” (and equals 1 if link a survives and equals 0 otherwise); and P_n is the n^{th} minimal path set ($n=1,2,\dots,N$).

Considering that the reliability (probability of success) for individual links can be defined by their respective expectation of survival after an event (i.e. $r = E[x]$) then the true value of the Network Terminal Reliability can be estimated. Since a road network is usually a complex structure, it is commonly necessary to break it down into basic components, namely series, parallel and bridge components. Fig. 1 to Fig. 3 illustrate each of these basic components while Equations 2 to 4 present the NTR for each network configuration.

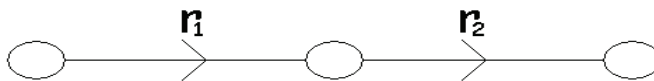


Fig. 1. Two links in series (Source: Lai, 2011)

$$R = E[1 - (1 - x_1 x_2)] = E[x_1 x_2] = E[x_1] E[x_2] = r_1 r_2 \quad (2)$$

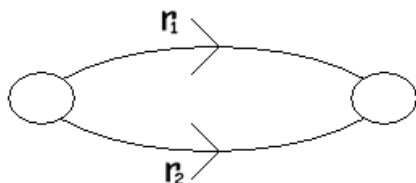


Fig. 2. Two links in parallel (Source: Lai, 2011)

$$R = E[1 - (1 - x_1)(1 - x_2)] = E[1 - x_1]E[1 - x_2] = r_1 + r_2 - r_1r_2 \tag{3}$$

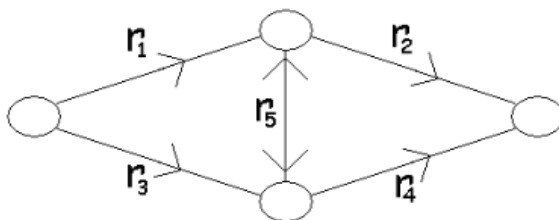


Fig. 3. Bridge network (Source: Lai, 2011)

$$R = E[1 - (1 - x_1x_2)(1 - x_3x_4)(1 - x_1x_5x_4)(1 - x_3x_5x_2)] \tag{4}$$

$$R = r_1r_2 + r_3r_4 + r_1r_5r_4 + r_3r_5r_2 - r_1r_2r_3r_4 - r_1r_2r_3r_5 - r_1r_2r_4r_5 - r_1r_3r_4r_5 - r_2r_3r_4r_5 + 2r_1r_2r_3r_4r_5$$

Further indicators and works related to Network Terminal Reliability are found in the scientific literature. Wakabayashi [20] has proposed a Criticality Index and compared results against Birnbaum’s Reliability Importance Index, while [5] described and used Birnbaum’s Index and the Criticality Index of Henley & Kumomoto [21]. Both authors aimed at identifying which index or combination could better support decision-making to maximize network reliability by allocating resources to improve individual links’ reliabilities. Recently, Lai [19] used all three indices to study a given road network in New Zealand to further explore both the advantages and disadvantages identified by Nicholson and Wakabayashi in applying such indices to road networks.

2.2. Path selection and network indices

Network connectivity is inevitably related to the number of existing paths between different origin and destination pairs and their individual relation with the network as a whole. It can be said that the number of possible paths is a function of both number of links and network configuration, which depends upon the number of nodes.

Researchers have investigated a great range of approaches and proposed a series of theories to describe network configuration. For instance, path dissimilarity has been studied by [22] and [23] proposed a Recursive Truncation Algorithm (this involves scanning minimal cut-sets to determine weak and strong

cut-sets, and comparing the failure probabilities of weak cut-sets, while the failure probabilities of strong cut-sets are ignored) and Dijkstra [24] long ago proposed an efficient algorithm for identifying the shortest path.

Network indices that quantify and compare elements of a network are also found in the scientific literature. Lai [19] presents a brief discussion on some indices, such as the road network performance [25], network density index [26], network connectivity index, which considers the relationship between the number of links and maximum number of paths [25], and the network robustness index [25], which evaluates the critical importance of a given highway segment to the overall system as a change in travel time cost associated with re-routing traffic.

From the above described literature, a combination of two indices was selected for this research. A variation of Dijkstra's shortest path algorithm, which identifies the K shortest paths and the network connectivity index proposed by Scott *et al.* [25]. The latter involves calculating the gamma index (γ) computed as follows:

$$\gamma = \frac{e}{e_{\max}} \quad (5)$$

where, e is the actual number of links in the network; and

e_{\max} is the maximum number of links in the network (i.e., all nodes are completely connected).

Note that gamma can range between 0 and 1, where 1 means a completely connected network. Also, e_{\max} can be calculated as follows:

$$e_{\max} = 3(v-2) \quad (6)$$

where, v is the number of nodes in the network.

The K-shortest paths algorithms are not described here, due to their great popularity within the transportation research community. A detailed reference for such algorithms can be found at Eppstein [27], and they have been embedded in commercial software packages, such as TransCAD [28] and others.

2.3. Cost estimation

Costs are usually considered in transportation research in order to compare the efficiency associated with different decisions either for planning or management. In the particular context of Emergency Management, two cost functions were proposed by Ferreira [11] to optimize resource allocation, namely Logistics Response Costs (LRC) and Delay Response Costs (DRC). Logistics costs are associated with resource mobilization from a given origin to a destination, while delay costs are an estimate of traffic delay due to total or partial road closure as a consequence of emergencies. They are defined as follows:

$$LRC^t = \sum_i \sum_j (r_{ij}^t * (td_{ij} * \alpha + 2LC * \beta)) \quad (7)$$

$$\text{Given: } td_{ij} = \sum_{a \in P_{ij}} L_l^a$$

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);
 B - unitary loading / unloading cost (cost per time);
 Pt_{ij} - minimum path between an origin i to a destination j ; and
 L_l^a - length value for a link belonging to the minimum path Pt_{ij} .

$$DRC^t(R^t) = \sum RC_l + \sum (F_l - C_l * (1 - D_j^t)) * \theta * \frac{1}{\sum_j \sum_k \delta_{jk}^t} \quad (8)$$

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; and
 δ_{jk}^t - adjustment factor for Cost of delay (CD_l^t).

Finally, Dantas and Ferreira [29] have assessed both cost functions and proposed a resource optimization routine. Although the formulations and optimization routine require further improvement, they generated useful information to support resource allocation in the context of emergencies. Dantas and Ferreira also discuss future research directions to facilitate the implementation of the concept in practice.

3. Road network emergency management model

As highlighted in the introductory section, the model aims to aid decision-making in the context of transportation before, during and after emergencies. Based upon established emergency management protocols, such as reduction, readiness, response and recovery, the model targets a holistic understanding of the complex decision-making environment created in any emergency. Studies have already exemplified the complexity of Emergency Management by establishing the relations among interconnected systems [30] and [31]. However, there is still a gap in the scientific literature and engineering practice in regards to decision support during emergencies. Thus, this section proposes a management model to partially fill this gap and aid emergency preparedness and response decision-making.

3.1. Conceptual framework

The model comprises three levels, namely: before, during and after the event. The approach intends to provide decision makers at both governmental and private organizations a complete tool to prepare, respond and recover from emergencies. The model has its emphasis in road networks, as organizations depend on road transport to conduct their activities during response and recovery [32]. Despite being focused on transport networks, the model was also designed to be replicated for other services by considering specific sets of indices and supporting theories. Note that strong focus is given to the two initial stages (before and during events), as recovery from emergencies (including reconstruction) has

been shown to be a multidisciplinary field involving management and policy making subjects [33] [34] [35] and [36].

Table 1 presents the proposed indices for performing the analysis method. It also states key objectives for each phase. Within the initial level (i.e. before the event) efforts are focused on preparing for emergencies by identifying hazards, potential damage and strategies to improve the system's resilience. In this context, the Network Connectivity Index (γ), along with the identification of k-shortest paths between key origin and destination pairs, is proposed, so the road network can be assessed through its vulnerabilities. Also, Terminal Network Reliability and the identification of reliability maximization strategies, as proposed by [5], are used to develop policies to increase road resilience for previously identified hazards.

Complementarily, during an emergency two key costs components were considered (i.e. Logistics Response Costs and Delay Response Costs) so resource allocation to fix the road network can be optimized. Costs formulations were intentionally simplified so data requirements could be minimized. Such an approach was adopted because experience during real disasters (e.g. the 1994 Northridge Earthquake, the 2004 Sumatra Earthquake and Tsunami, 2005's Hurricane Katrina) indicated that data availability and quality in the immediate aftermath can be very poor. Hence, in the context of limited data, the LRC depends only on the distance traveled between given origin and destination pairs, while the DRC is more comprehensively defined. For the former, costs are associated with asset repair, delay to traffic and (more importantly) to the priority estimation factor (δ_{jk}^t). This factor represents the relationship between the road network and response objectives, i.e. how best a particular link in the network can meet the needs from different services (e.g. power restoration, access to treatment facilities and affected areas, environment protection). In summary, the parameter δ_{jk}^t represents the importance of restoring a road link in a given time "t", based on its importance in the broad context of response. A more complete specification of both costs and optimization routine is given by [29].

Table 1. Road network emergency management scheme

Emergency Event		
Before	During	After
Network Connectivity – γ	Logistics Response Costs	Reconstruction Strategies
K-shortest path	Delay Response Costs	Construction Management
NTR → Birnbaum Index	Resource Allocation	Public policy making
Wakabayashi Index	----- G O A L -----	Resource needs estimation
----- G O A L -----	SUPPORT DECISION-MAKING FOR	----- G O A L -----
IMPROVE NETWORK	RESOURCE ALLOCATION	ENSURE RAPID AND EFFICIENT
RESILIENCE		RECOVERY

In order to evaluate its applicability for emergency preparedness and response, the above proposed method was assessed using a simple grid road network. The case study aimed to identify the model's potentials and limitations in the novel context of Humanitarian Logistics research.

3.2. Simulation case study

A road network affected by an earthquake was defined as illustrated in Fig. 4, which shows the damage and depot locations, capacity reduction, resource availability/need and traffic flow directions. Note that a 90% capacity reduction, as assumed for Link 14 in the immediate aftermath of the event, means that the capacity is only 10% of the pre-event capacity.

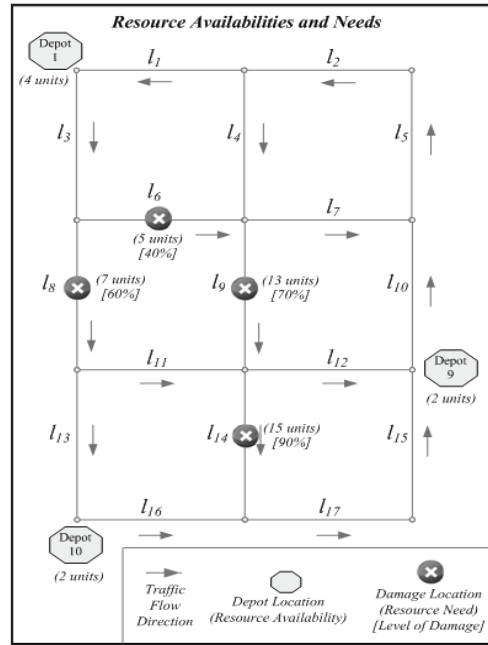


Fig. 4. Affected road network after an earthquake

Complementarily, road network data was also proposed for the network as in Table 2 below so Logistics Response Costs and Delay Response Costs could be estimated.

Table 2. Road network data

Link	Length (L_i) - km	Capacity (C_i) - veh/h	Flow (F_i) - veh/h	Repair Cost (RC_i) - \$
1	7.5	110	100	27,500
2	7.5	120	100	30,000
3	7.5	500	300	125,000
4	7.5	320	300	80,000
5	7.5	100	50	25,000
6	7.5	200	150	50,000
7	7.5	80	50	20,000
8	7.5	400	150	100,000
9	7.5	550	500	137,500
10	7.5	100	50	25,000
11	7.5	105	100	26,250
12	7.5	50	20	12,500
13	7.5	300	50	75,000
14	7.5	630	620	157,500
15	7.5	50	30	12,500
16	7.5	410	400	102,500
17	7.5	270	220	67,500

As initially proposed in the Road Network Management model (Table 1), we proceeded with an analysis of the network before the event, to generate information to improve its resilience to natural and man-made disasters. For the network illustrated in Fig. 4, the connectivity index (γ) was estimated as 0.57 with very low connectivity between an origin on the top and a destination on the bottom of the network if traffic flow directions and proposed damage were considered. The main reason associated with that is the great damage experienced in Link 14 which turns to be a key connection between the given origin and destination sets. Network Terminal Reliability indices (Birnbaum and Wakabayashi) were found impractical to be estimated due to the complexity of the derivatives involved and the difficulty in finding the algebraic equation to describe the total road network reliability. Such difficulties in finding a correct equation for terminal reliability for typical road networks can be observed in the work conducted by [19].

Network Terminal Reliability appears to be difficult to apply as the combination of basic network components illustrated in Fig. 1 to Fig. 3 (i.e. series, parallel and bridge) become very complex in this particular case. However, it can be said that simple applications of the Connectivity Index and the use of well established shortest path algorithms can provide organizations and personnel with vital information to better respond to events as well as improve resilience. For instance, if 2 new diagonal links are considered in the proposed network (in its bottom grids) the γ index would consistently rise to 0.63 as well as allow traffic to be diverted from the badly damaged Link 14 and consistently increase possible paths from top to bottom. On practical grounds, the proposal is not about building new links, but to identify detours and alternative routes according to existing road network availability. Complementarily, note that a strict assumption is made by considering that traffic only flows according to the designated directions shown in Fig. 4. Such assumption can be disregarded during real emergencies as the Civil Defence and the Emergency Controller can cordon off zones and use roads at the best convenience for response.

Finally, the cost functions to be considered for resource deployment to fix road networks during an event have already been proven efficient in the context of response [11]. Their low data requirements and simple application provide decision makers with key information about trade-offs among different strategies to address the common problem of great resource need and low resource availability in the immediate aftermath of events. Dantas and Ferreira [29] studied the case illustrated in Fig. 4 and found three optimum classes for resource deployment, as shown in Table 3. Observe that each class comprises a different number of possible resource deployment strategies. This finding highlights the applicability of the optimization routine in real cases, as it is generally agreed that during emergencies decision-making must be flexible, as priorities change as the event unfolds. The complete application of the optimization routine as well as further discussions on the multi-objective and complex environment during emergencies can be found in [11].

It is finally concluded that this case study indicated both shortcomings and potential applications for the proposed Road Network Management model. In spite of its limitations, the model can assist information generation to aid emergency preparedness and response in the roading context, but a more comprehensive approach is needed so high quality decision-making can be made before and after an event. The next section briefly outlines future research endeavors that could more effectively target emergency management in the light of the previously conducted and reported research.

Table 3. Optimum resource allocation classes

Class	Strategy	$\sum LRC$	$t = 1$	$t = 2$	$t = 3$	$t = 4$	$t = 5$	$t = 6$
			$\sum DRC$	$\sum DRC$	$\sum DRC$	$\sum DRC$	$\sum DRC$	$\sum DRC$
1	5	3435	463253.79	11049.50	5884.40	2083.17	0.00	0.00
	13	3255.00	463253.79	11049.50	5884.40	2083.17	0.00	0.00
	14	3285.00	463253.79	11049.50	5884.40	2083.17	0.00	0.00
	21	3405.00	463253.79	11049.50	5884.40	2083.17	0.00	0.00
	22	3405.00	463253.79	11049.50	5884.40	2083.17	0.00	0.00
	23	3420.00	463253.79	11049.50	5884.40	2083.17	0.00	0.00
2	4	3330.00	463253.79	11185.91	6118.24	2627.88	1034.00	0.00
	10	3105.00	463253.79	11495.90	6964.40	3457.72	1034.00	0.00
	11	3135.00	463253.79	11495.90	6964.40	3457.72	1034.00	0.00
	19	3255.00	463253.79	11679.50	6964.40	3457.72	1034.00	0.00
3	20	3285.00	463253.79	11679.50	6964.40	3457.72	1034.00	0.00
	25	3120.00	463253.79	11495.89	6964.39	3457.71	1034.00	0.00
	27	3105.00	463253.79	11679.50	6964.39	3457.71	1034.00	0.00
	28	3135.00	463253.79	11679.50	6964.39	3457.71	1034.00	0.00
	29	3270.00	463253.79	11679.50	6964.39	3457.71	1034.00	0.00
	30	3120.00	463253.79	11679.50	6964.39	3457.71	1034.00	0.00

Note: The 16 strategies proposed for the three classes above are described as follows. The table describes the number of resources to be deployed from each depot to individual damaged links.

Depot	Class	1				2				3							
		Link / Strategy	5	13	14	21	22	23	4	10	11	19	20	25	27	28	29
1	6	0	1	1	0	0	0	0	2	2	0	0	2	1	1	0	1
	8	0	0	0	0	0	0	0	0	0	1	1	0	1	1	1	1
	9	0	3	0	3	2	1	4	2	0	3	0	1	2	0	1	1
	14	4	0	3	1	2	3	0	0	2	0	3	1	0	2	2	1
9	6	1	0	0	1	0	0	1	0	0	1	1	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	9	1	0	1	0	1	1	0	1	1	0	1	1	1	1	1	1
	14	0	2	1	1	1	1	1	1	1	1	0	1	1	1	1	1
10	6	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	9	2	0	2	0	0	1	0	0	2	0	2	1	0	2	1	1
	14	0	2	0	2	1	0	2	2	0	2	0	1	2	0	0	1

4. Future research: Humanitarian logistics field

As highlighted in the introductory section and throughout this paper, research efforts have been strongly focused on building resilience (either by preparedness and readiness), improving response and ensuring proper recovery and reconstruction. However, most of studies presented by researchers and practical endeavors did not take into consideration basic concepts of logistics and operational research. Thus, approaches have indicated potentials for Emergency Management, albeit at limited levels.

Much previous research has focused on the characteristics of the network and the ability to fix the damage as quickly as practical after the event occurrence. Little attention was given to move traffic through the network and to developing methods for estimating the nature of the traffic demand after a disaster (e.g. how many trips be produced in and attracted to each area, what will be the level of trip making between the areas, and what modes of travel will be used).

It appears that, complementarily with resource allocation models and managerial protocols, further theoretical models are required to properly assess the ability of a transport system to cope with the demands upon it during and after emergencies and disasters. The development of such models would encompass operational research and logistics theories along with already proposed models to estimate the nature of travel demand and assist decision makers to manage emergencies at both operational (ensuring traffic flow) and strategic (repairing the damaged network). This area of research and development could be termed “Humanitarian Logistics”. Developments in this field will encompass multidisciplinary approaches; however, it is expected that innovative solutions derived from traditional city logistics concepts can contribute in order to allow novel proposal in a short term due to the existing urgency in the field of Emergency Management.

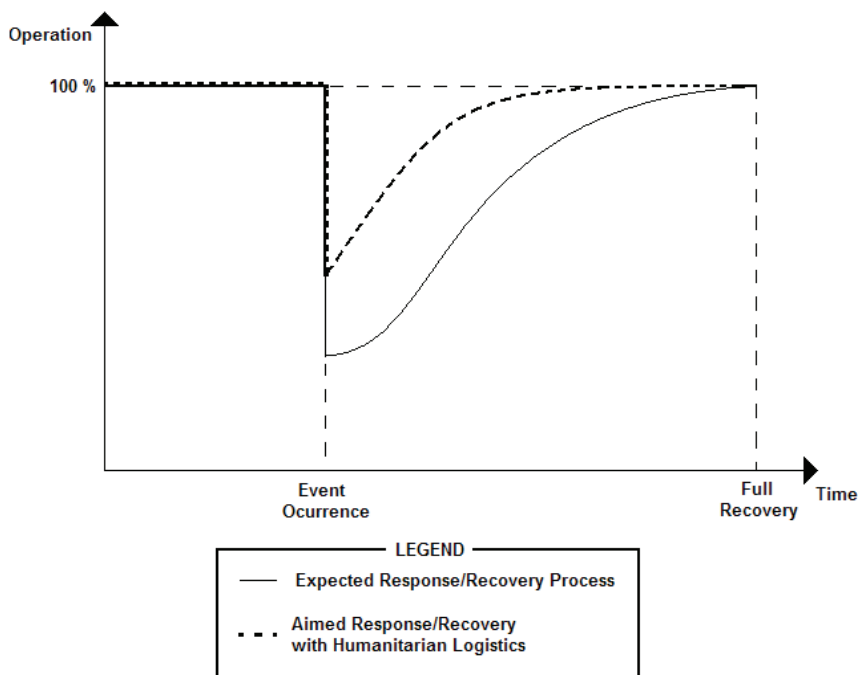


Fig. 5. Systems' operation before and after an emergency

Overall, it is expected that Humanitarian Logistics concepts will provide means to reduce the initial impacts of disasters as well as support measures to quickly restore normality as soon as practical. In this context, vehicle routing problems for debris removal, resource allocation to fix damaged infra-structure, Urban Distribution Center (UDC) locations to receive/store/distribute aid, shelter location (e.g. stadiums, schools) and travel behavior forecast are just a few research fronts to be targeted in the future. Fig. 5 illustrates the general goal of Humanitarian Logistics. Note that Humanitarian Logistics can ensure reduced loss of services in the immediate aftermath (due to high resilience and preparedness) as well as quick restoration can be associated with effective decision-making.

Complementarily, it is believed that risk management approaches can help modeling attempts for Humanitarian Logistics by reducing uncertainties. Studies from [37] [4] and [18] have shown that models using risk management theories can indeed being used to assess transport network reliability, but considerable effort is needed to estimate the probabilities of hazard events and network degradation.

In this backdrop, the Humanitarian Logistics proposal could take advantage of already developed hazards models, such as: i) Hazus-MH – Federal Emergency Management Agency [38] and [39]; ii) REDARS – Federal Highway Administration [40]; iii) MIRISK – World Bank and Kyoto University [41]; and iv) RISKCAPE – Institute of Geological and Natural Sciences, National Institute of Water and Atmospheric Research and University of Canterbury [42] and [43].

Finally, comprehensive case studies are deemed necessary so proposals can be assessed in its limitations as well as support to support future developments. Hence, two research fronts can be envisaged, being the first approaches for localized events in urban environments and the second the management of wide spread destructive events (e.g. 2004 Sumatra Earthquake and Tsunami and 2005's Hurricane Katrina).

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