UNIVERSIDAD DEL NORTE
Department of Industrial Engineering
Barranquilla, Colombia

ROAD RESTORATION PLANNING ORIENTED TO FACILITATE POST-DISASTER RELIEF OPERATIONS

CONSTRUCCIÓN DE PLANES DE RESTAURACIÓN DE VIAS ORIENTADOS A FACILITAR OPERACIONES DE LOGÍSTICA HUMANITARIA

Master thesis presented by:

Juliette Paola García Alviz

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Advisor: Gina Galindo, Ph.D.
Co-advisor: Julián Arellana, Ph.D.

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Abstract

Disruptions in the transportation network are one of the hardest consequences of a disaster. They have the potential of hampering the performance of emergency aid organizations, reducing the opportunities of saving critical victims during response and recovery phases. The strategic restoration of road network implies the prioritization of those affected roads whose rehabilitation would reduce travel times, allowing emergency relief vehicles, civilians and restoration machines to move faster through the network. Humanitarian Road Restoration Problem (HURREP) is a relatively new topic in comparison with other research topics on disaster management. In this study, we present a mathematical model which schedules and routes restoration machines and relief vehicles working in parallel on the same network. We adopt the minimization of weighted sum of attention times to communities as the objective function, seeking for a restoration plan totally dedicated to provide support to relief plan. Among other features, our methods are able to deal with different relief modes working in parallel, road disruptions that are naturally removed over time (e.g. by evaporation) and vehicle-dependent starting times. We also provided an heuristic algorithm able to solve large size instances of our problem in less than the 2.7% of the runtime limit suggested by the Administrative Department for Prevention, Attention, and Recovery from Disasters in Antioquia, Colombia (DAPARD). We validated the applicability of our methods on real world disaster scenarios through a study case based on the Mojana's floods occurred in northern Colombia on the 2010-2011.

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Chapter 1

Introduction

Every year, hundreds of disasters take place all over the world, causing large economic losses and thousands of deaths. According to the Centre for Research on the Epidemiology of Disasters - CRED[1], only in the period 2010 - 16, 450.228 people lost their lives and more than 1.000 million people were affected on a total of 2.553 disasters. There is a consensus on both, research and practice, about the great importance of disasters as a risk factor for humans welfare, and the need of developing effective strategies for mitigating their impact (Ibrahim et al., 2011; Guha-Sapir, Vos, Below, Penserre, et al., 2012; Galindo & Batta, 2013).

Post-disaster Relief Operations[2] (Post-ROp) conducted during disaster response phase, are majorly supported on the road system (Sakuraba, Santos, & Prins, 2016). It comes from the fact that roads are the most extended transport mean over the world, and often result much more efficient for Post-ROp than other alternatives such as rail, water or air transport. Unfortunately, road networks are prone to the destructive influence of disasters, which usually cause partial or total capacity loss in various road segments. Such capacity detriment, in turn, has a negative impact on the performance of emergency response teams, and ultimately on the suffering that the affected community experiences. This is why, post-disaster road network restoration has been regarded as a prior task in disaster management (Li, Hu, & Xie, 2009; Ajikata & Kobayashi, 2010). This thesis focuses on the coordination between post disaster road network restoration and disaster relief operations performed during response phase. Specifically, we aim to minimize the suffering experienced by affected communities.

Restoration addressed in this thesis is related to fast rehabilitation of roads functionality. It does not correspond by no means with a total recovery process, where roads are restructured to a top functionality level. Road restoration activities often begin in parallel to Post-ROp. First contact with survivors must be performed in the first few days after the disaster, in order to stabilize the community, evacuate people from risky places and assist victims in critical condition (Aksu & Ozdamar, 2014). Road restoration takes a lead role in this stage, providing access to isolated communities. Once the population has been stabilized, the distribution of relief goods to hospitals and shelter centers starts. This activity may last for some weeks of even months, depending on the number of people affected and the severity of their condition. In Colombia for example,

[1]CRED: D. Guha-Sapir, R. Below, Ph. Hoyois - EM-DAT: The CRED/OFDA International Disaster Database - Université Catholique de Louvain – Brussels – Belgium (n.d.)

[2]Activities executed after disaster for assisting the affected communities, such as distribution of relief goods, evacuation, among others

the Atlantico Department has recurrently suffered important floods; the one concurred in 2010 left thousands of vulnerable people living in dire conditions (Refugees International - USA, 2011). Tons of food and relief kits where provided to community through a series of deliveries, which lasted for more than one year. In this study, we focus in this kind of restoration scenarios, where Post-ROp last sufficiently to allow not only the rehabilitation of accessing routes, but also the dynamic improvement of travel times through restoration activities performed in parallel to relief operations. The rationale behind such methodology is that best paths connecting relief sources with communities, may imply large restoration times, so that it becomes more convenient to reestablish the access through alternative paths that could be restored faster, and then think on restoring better paths while community is assisted.

As regards the restoration plan, our model determines which roads should be repaired during the response phase, assigns each chosen road to a particular machine, and specifies the route that each machine should cover in order to complete its schedule. Moreover, our model is able to deal with different types of machines specialized in the removal of certain types of damages. As far as we know, our model is the first one in the response-oriented literature, able to deal with different kinds of disruptions and heterogeneous machines for the combined problem of road restoration and disaster relief planning.

Motivation

This research is motivated by multiple recent events where road network disruptions caused major setbacks for the execution of Post-ROp. Just to mention a few of them, we refer to the Haiti earthquake (2010), the Thailand flood (2011), and the Peru earthquake (2011). In the former case, a Mw 7.0 earthquake caused impressive infrastructure damages on Haiti. The destruction of its main port at Port-au-Prince city and the large number of roads that became blocked by debris, significantly hampered the execution of Post-ROp (Pedraza Martinez, Stapleton, & Van Wassenhove, 2010). In the second case, the most devastating flood in the history of Thailand left more than 3.300 totally or partially damaged roads. Disruptions hindered the normal execution of Post-ROp, causing significant delays in the distribution of food and medicines (Lertworawanich, 2012). By its side, the 2015 Mw 8.4 Peruvian earthquake left blocked by rocks, the roadway connecting Arequipa city and various nearby districts. This time, road network disruptions delayed the access of rescuers to the affected zone (lainformación.com, 2016).

However, not all cases are examples of bad experiences. The Mw 0.9 great Tohoku earthquake which hit Japan on 2011, is a case where the potential benefits of a smart road restoration plan were evidenced. In that case, the disaster affected hundreds of roads and left seventy one fallen bridges. For two weeks, relief supply distribution to islands was limited to the use of helicopters (Mimura, Yasuhara, Kawagoe, Yokoki, & Kazama, 2011). Fortunately, an emergency road restoration plan allowed to reestablish traffic flow and emergency response agencies became able to provide full attention to the victims (Itabashi, Sakai, Kusakabe, & Asakura, 2015).

In this thesis we aim to provide a mathematical model, able to provide the road restoration plan that best contributes to the efficient assistance of affected communities.

Justification and contributions

As evidenced in the examples provided above, the road restoration plan has a strong influence on the performance of relief teams during response-phase. Bad decisions in this context translate into harder suffering for survivors and a greater number of fatalities. Hence, the great importance of developing smart strategies for road restoration planning, accounting for the impact of restoration decisions on the effectiveness of Post-ROp.

Some work has recently been performed on road restoration planning integrated with Post-ROp in parallel. However, there still present important gaps in the field that considerably limit the application of available models in real scenarios. First, the majority of studies in the area do not provide the routing plan for restoration machines. Second, most studies do not either provide machines schedule (assignment of jobs to machines and order of execution of jobs at each machine). Third, none of the studies is able to deal with heterogeneous disruptions/machines. Fourth, all studies in the area discretize the time. Fifth, studies in restoration integrated with Post-ROp in parallel represent a minority of the general literature in post-disaster road network restoration planning. Most part of the studies deal with the road restoration problem independently of the relief planning problem or assume that the restoration plan is completed before Post-ROp take place.

In this thesis we seek to address these shortcomings. In particular we make the following contributions to the field:

1. We provide the first formulation in the literature that accounts for: i) selection of restoration tasks to be done, ii) scheduling and routing or restoration machines, iii) scheduling and routing of relief vehicles, iv) coordination between road restoration and relief operations, v) handling of different types of disruptions/machines, and vi) no discretization of time. Our model can be solved to optimality for small and medium size instances in a reasonable time.

2. We develop a novel heuristic able to solve large instances of our problem in a reasonable time. The algorithm combines Ant Colony Optimization for road restoration planning with a custom-made GRASP for relief planning.

Organization of the manuscript

The remaining of the manuscript is structured as follows: Chapter 2 presents our literature review. Chapter 3 formally states the optimization problem addressed here and provides and stated the objectives of this thesis. Chapter 4 provides the mathematical programming formulation for the problem under study and evaluates practical runtimes through a screening experiment. Chapter 5 introduces our heuristic algorithm oriented to solve large instances of the problem, and compares it in performance with a MILP solver implementing our formulation. Chapter 6 presents some extensions of our model and heuristic. Chapter 7 presents the evaluation of our methods, solving a real world study case, corresponding to Mojana floods occurred in Colombia in the 2010-2011. Finally, Chapter 8 provides our conclusions and suggest a set of promising future research avenues.

Chapter 2

Literature review

This chapter presents a literature review of Humanitarian Road Restoration problem, hereon called (HURREP). Such review allowed us to identify a set of research gaps present in current literature, which are fulfilled through the execution of this thesis.

2.1 The Humanitarian Road Restoration Problem

Despite the great importance of road network restoration for the effective attention of disasters, this topic just became popular within the academic community during the late 90s. In the past and even in the present, some studies still assume that the network remains intact after the disaster, and therefore all links are enabled (Widener & Horner, 2011; Yi & Kumar, 2007). Other studies just remove blocked links from the network in a step previous to the run of the model (Balcik, Beamon, & Smilowitz, 2008; Gholami, Ghavidel, & Alizade, n.d.). The problem with studies that do not explicitly account for blocked links is that they may: i) generate unfeasible routes passing through blocked links, or ii) generate inefficient routing plans that do not exploit the dynamic rehabilitation of blocked links.

Scientific production in the HURREP is still considerably short in comparison to other subjects in emergency logistics such as search and rescue, evacuation, facility location or distribution of relief items (Caunhye, Nie, & Pokharel, 2012; Galindo & Batta, 2013). In fact, to the best of our knowledge, up to date there is no any review article on the matter. Therefore, in this section we aim to provide a global perspective of current state of the art in this area before delving into our proposal.

This review comprehends a total of 50 studies, including doctoral theses, journal articles and conference papers published in the period 1999 - 2017. The following databases were used for the search of the items: ASCE, EBSCO, EMERALD, IEEE Xplore, Jstor, INFORMS PubsOnline, Operations Research Journals, Transportation Science, PROQUEST, ScienceDirect, SpringerLink, Taylor & Francis. The key words and phrases used for the search were: *debris clearance*, *debris removal*, *debris management*, *clearance operation*, *debris cleanup*, *disrupted network*, *emergency repair plan*, *network restoration*, *restoration of blocked links*, *highway restoration*, *mass evacuation*, *transportation network reconstruction*, *evacuation planning*, *evacuation*, *relief goods distribution*, *routing in damaged roads*, and combinations of these words and phrases with the words *disaster*, *post-disaster* and *humanitarian*.

Our list of reviewed studies is by no means an exhaustive bibliography of research in the HURREP within the period covered by our study, since it only includes studies obtained from the databases mentioned before. However, it may be considered as a representative sample of up to date work in the area, and sufficiently diverse to make it suitable for the purposes of this thesis.

The scope of our review is limited to studies addressing the HURREP under an approach based on Operations Research. Studies related to post-rehabilitation processes, such as debris management (e.g. collection, sorting, storage and recycling) were not included in our sample. Also, studies related to preventive repair of bridges in the day-to-day operation of the road network, were not considered by us, since the objectives adopted in those studies differ significantly to objectives in the post-disaster context. Finally, Studies addressing restoration problem for networks different than road network (water, electricity, gas and other resources) are beyond the scope of this thesis.

After obtaining the initial sample of articles and applying the mentioned filters, we performed forward and backward reference search over the list of preserved studies. This process was repeated until no new studies were found.

In the remainder of this chapter, we present the findings of our review as follows: first, the main versions of the HURREP, addressed in the literature, are described. Then, we provide a discussion of the main features in the version of the problem that concerns to this thesis. This chapter ends with a list of research gaps found in the literature, which are intended to be fulfilled through the execution of this thesis.

2.2 Versions of the HURREP

HURREP literature can be classified in five groups, each one corresponding to a different version of the problem. A short description of each version is provided below:

- ***Hum. Road Restoration Problem - Total Independent from Post-ROp* (HURREP - TI)**: Given a set of restoration machines, the problem consists of determining the best way of restoring each single affected road on the network, so that it contributes to an efficient execution of Post-ROp. Considering the fact that restoring the whole network could take various months or even years, this problem fits better in the recovery phase. Wider models for this problem provide the schedule and the route for each restoration machine.

  Some models in the HURREP-TI are able to select the company that will be responsible of executing the restoration plan (Orabi, El-Rayes, Senouci, & Al-Derham, 2009b; El-Anwar, Ye, & Orabi, 2013, 2015a, 2015b). In the same track, Furtado and Alipour (2014) proposes a methodology to establish incentives for restoration companies, oriented to motivate them to complete the plan in a shorter time than usual.

- ***Hum. Road Restoration Problem - Total Integrated with Post-ROp in Parallel* (HURREP - TP)**: Given a set of machines and a set of relief vehicles, the problem consists on determining the best combination of road restoration and relief plans. Similarly to the HURREP-TI, the HURREP-TP imposes that each single affected road must be repaired. Thus, in spite that this problem involves the construction of a relief plan, the restoration plan tends to be oriented to recovery phase. Wider models for this problem provide the schedule and route for both, restoration machines and relief vehicles.

  There is only one study in our sample, addressing the HURREP-TP (Yan & Shih, 2009). In that study, authors propose a model based on spatio-temporal networks, seeking for an easy way to represent displacements over the road network. A weakness on this approach is that spatio-temporal networks impose a discrete time framework on the model. The discretization of time makes it necessary to define a planning horizon prior to solving the model, which in practice could be difficult. On the other hand, it causes inaccuracies between the abstraction of the problem given by the model and the reality, due to the mandatory dilatation or contraction of real times under this approach.

- ***Hum. Road Restoration Problem - Partial Independent from Post-ROp* (HURREP - PI)**: As in the case of the HURREP-TI, the HURREP-PI departs from a set of restoration machines and consists of finding the restoration plan that best contributes to an efficient execution of Post-ROp. Two important characteristics of the PI version are: i) it does not impose the restoration of all the affected roads, which makes the corresponding models suitable for the response phase, and ii) even though the restoration plan is intended to improve relief operation, the problem does not involve the constitution of the relief plan. Most complete models for this problem provide the schedule and routing plan for each restoration machine. Given that some affected links may not be repaired, models for the HURREP-PI should also select which restoration tasks must be done.

  The HURREP-PI has been solved mostly under three schemes: i) total reconnection, ii) partial reconnection and iii) voracious reconnection. As their names suggest, the three schemes are based on the concept of reconnection, which in turn comes from the concept of connectivity between nodes. According to Garrison and Marble (1965), a pair of nodes is connected if there is available (i.e., functional) at least one path between them, regardless of its duration, cost or distance. Each of these schemes is described below. For this purpose, let us make the following definitions:

  - ***Demand points*:** subspaces of the affected region, allocating a specific number of affected population. A demand point typically has at least one building that can serve as reception point for humanitarian deliveries.
  - ***Supply points*:** buildings that serve as warehouses and distribution centers during relief operations.

a) Total reconnection: this scheme consist of enabling a path from each demand point to at least one supply point. Total reconnection models do not present time or cost constraints, so the operation ends when all demand points are connected. Itabashi et al. (2015); Akbari and Salman (2016); Li et al. (2009) implement this scheme. In particular, Itabashi et al. (2015) develop their model under the assumption that all links in the network are blocked, Itabashi et al. (2015) use spatio-temporal networks in their modeling, and Akbari and Salman (2016) consider different starting times for machines.

b) Partial reconnection: in contrast to the total reconnection scheme, partial reconnection considers resource limitations that may prohibit enabling one path connecting each demand point with some supply point. In other words, some demand points could remain isolated under this scheme. Feng and Wang (2003) and (Matisziw, Murray, & Grubesic, 2010) implement partial reconnection. Matisziw et al. (2010)

impose a limit of 72 hours to perform restoration tasks, which is a time limit adopted in search and rescue as a threshold after which the probability of rescuing people alive falls dramatically. Instead of considering a time limit, Feng and Wang (2003) impose a budget constraint.

c) Voracious reconnection: this third scheme consists of enabling the best path (i.e., the least costly one) between each pair of nodes. Even if all nodes are already connected between them, if best paths are not enabled yet, the model considers that there is still work to be done. A weakness of this approach is that it does not prioritize providing access to nodes, Thus, it is possible to leave some nodes isolated for a very long time until best paths connecting other nodes are enabled.

Lertworawanich (2012) proposes two models which work together to solve the problem under voracious reconnection. The first model ensures connection between each demand node and some supply node (total reconnection). The second model improves paths enabled by the first model until best paths become available. Özdamar, Aksu, and Ergüneş (2014) use the accessibility indicator proposed by Chang and Nojima (2001) as an objective function for the network restoration. The accessibility indicator is the ratio of the sum of shortest distances between each pair of nodes before disaster, to the sum of shortest distances after disaster. Similarly, Sohn (2006) propose a new accessibility indicator and take it as criterion to construct a ranking of the blocked links that should be restored with greater urgency. The indicator proposed by Sohn (2006) weighs travel time increments due to the disaster and the flow passing through each link in a regular operating condition.

Duque, Dolinskaya, and Sörensen (2016) determine the route for a single restoration machine which must visit all demand points, enabling access to them. Aksu and Ozdamar (2014) propose a methodology intended to identify the ideal restoration plan as support for an evacuation. However, as a HURREP-PI study, Aksu and Ozdamar (2014) only provide decisions for the restoration plan. To do so, the authors pre-compute the shortest paths connecting each demand point with some supply point and enforce the restoration model to repair links belonging to such paths.

- ***Hum. Road Restoration Problem - Partial Integrated with Post-ROp in Series*** **(HURREP - PS)**: This problem requires the construction of both, restoration plan and relief plan. In this version, it is assumed that the whole restoration plan is performed instantaneously before relief plan starts. Thus, no scheduling or routing of machines is required. The only part of the restoration plan, delivered by models addressing the HURREP-PS, is the set of restoration tasks that should be completed. This problem tends to fit well in the response phase, since it allows to repair only a subset of all the affected links. Nonetheless, the assumption that all selected roads will be restored before relief plan starts, is often unrealistic, hindering the application in real scenarios. Most complete models for this problem provide both, the routing and scheduling of relief vehicles.

  Some studies addressing the HURREP - PS consider the distribution of relief goods as the relief operation being performed, these are Berktas (2014) , Sahin, Kara, and Karasan (2016), Ransikarbum and Mason (2016b), Sen, Ying-wu, Yun-jun, and Yong-ping (2011), Liberatore, Ortuño, Tirado, Vitoriano, and Scaparra (2014) and the third of the models proposed by Şahin (2013). Some others relate the relief operation with an evacuation (C.-Y. Wang & Hu, 2005, 2007; C.-Y. Wang & Chang, 2012; J. Wang, Ip, & Zhang, 2010; Ho & Sumalee, 2014). These last assume that people move through the road network by their own means, instead of being transported by relief vehicles. Therefore, these studies take into consideration people's behavior during the evacuation.

In contrast to other studies considering distribution of relief goods as the relief operation, Sen et al. (2011) assumes that relief vehicles execute both restoration and distribution operations. Although mathematical modeling is facilitated under this assumption, restoration machines are generally quite different from relief vehicles, and the latter are not equipped adequately to perform restoration activities.

- ***Hum. Road Restoration Problem - Partial Integrated with Post-ROp in Parallel* (HURREP - 2P)**: This problem considers a set of restoration machines available for repairing a subset of all the affected roads, and a set of relief vehicles designated to assist the affected community. In contrast to the HURREP-PS, the HURREP-2P assumes that road restoration and Post-ROp start in parallel, which means that relief vehicles will perceive improvements in the network as roads are repaired. This version, fits better than any other version to the true conditions during response phase, since restoration tasks in this phase are totally devoted to improve the performance of Post-ROp.

  Wider models for this problem are able to chose the set of roads to be repaired, and also to build the schedule and routing plan for restoration machines and relief vehicles.

2.2.1 Synthesis

Table 2.1 summarizes the main features of each HURREP variation. A detailed list of the 50 articles reviewed in this study is provided in Table 2.2. The problem under study here maps well to the HURREP-2P, since we are looking for a methodology to identify the subset of damaged road whose restoration will make the major benefit to Post-ROp performed in parallel to road restoration. Despite the great ability of HURREP-2P to incorporate the purpose of the restoration plan in the response phase (which is to improve Post-ROp), we found only six studies addressing this version of the HURREP, representing the 12.0% of our sample. An overview of the each one of these six studies is provided below.

Table 2.1: Versions of the HURREP

Phase	**Problem**	**Restoration extent**		**Relief Operation**			**Studies**	
		Partial	Total	Independent	Integrated		#	%
					Series	Parallel		
Recovery	HURREP - TI		x	x			19	38%
	HURREP - TP		x			x	1	2%
Response	HURREP - PI	x		x			12	24%
	HURREP - PS	x			x		12	24%
	HURREP - 2P	x				x	6	12%

Table 2.2: HHURREP studies in our literature review

Problem	Studies	Production	Percentage
HURREP-TI	Lee and Kim (2007), Pourmohammadi (2008), Karamlou and Bocchini (2014), Bocchini and Frangopol (2010), Chen and Tzeng (1999), Furuta, Ishibashi, Nakatsu, and Hotta (2008), Yan and Shih (2007), Tang, Yan, and Chang (2009), Yan and Shih (2012), Yan, Chu, and Shih (2014), Orabi et al. (2009b), Orabi, El-Rayes, Senouci, and Al-Derham (2009a), El-Anwar et al. (2013), El-Anwar et al. (2015a), El-Anwar et al. (2015b), Furtado and Alipour (2014), Sohn, Kim, Hewings, Lee, and Jang (2003), Zhang, Wang, and Nicholson (2017), Chen and Tzeng (2000)	19	38,0%
HURREP-TP	Yan and Shih (2009)	1	2,0%
HURREP-PI	Itabashi et al. (2015), Akbari and Salman (2016), Akbari and Salman (2017), Li et al. (2009), Feng and Wang (2003), Matisziw et al. (2010), Lertworawanich (2012), Özdamar et al. (2014), Sohn (2006), Duque et al. (2016), Duque and Sörensen (2011), Aksu and Ozdamar (2014)	12	24,0%
HURREP-PS	Berktas (2014), Sahin et al. (2016), Ransikarbum and Mason (2016b), Sen et al. (2011), Liberatore et al. (2014), Ransikarbum and Mason (2016a), Şahin (2013), C.-Y. Wang and Hu (2005), C.-Y. Wang and Hu (2007), C.-Y. Wang and Chang (2012), J. Wang et al. (2010), Ho and Sumalee (2014)	12	24,0%
HURREP-2P	Şahin (2013), Forbes (2015), Torabi, Baghersad, and Meisami (2013), Sakuraba et al. (2016), Çelik, Ergun, and Keskinocak (2015), Xu and Song (2015)	6	12,0%

Şahin (2013) proposes two models for the HURREP-2P under the following assumptions: i) there is a single relief vehicle, ii) the relief vehicle is able to remove debris from its way, iii) each demand point needs to be visited only once, iv) the relief vehicle is able to visit any number of demand points without replenishment at the supply node. Forbes (2015) solves the problem for multiple restoration machines and relief vehicles. In order to simplify modeling, they aggregate all source points on a single artificial source point, and all demand points on a single artificial demand point. This aggregation eliminates the possibility of assigning particular priorities to demand points. In practice, it represents a major limitation since different demand points typically experience different levels of affectation due to disaster and thus, should receive different priority. In Torabi et al. (2013) the problem is also solved considering multiple restoration machines and multiple relief vehicles. In this study, it is assumed that restoration tasks are performed by work-troops composed by different types of machines. However, each work-trop is identical to the other one and acts as a single entity. The main characteristic of this study is that the proposed model considers the potential failure of links during operation. In this regard, the model maximizes the reliability of the routes to be selected. This study assumes a single supply point. Sakuraba et al. (2016) also works with the concept of work-troops. Their model assumes multiple relief vehicles, multiple supply points and multiple demand points, these lasts allocating a known amount of population to be served. Çelik et al. (2015) models the problem through a partially observable Markov decision process. Their method reestablishes connectivity between source and demand points in a way that maximizes the benefit obtained through demand satisfaction. In order to incorporate dynamic changes in the network, the authors propose a methodology based on multiple runs of the model, where each run takes into account updated data on demand and state of the network. Xu and Song (2015) model the interaction between multiple restoration machines and relief vehicles by means of spatio-temporal networks. They consider multiple suplly and demand points, these lasts possessing different priorities. They also incorporate the effect of bad weather during the post-disaster scenario, on the efficiency of restoration activities.

2.3 Features of the HURREP-2P

Despite current progress in the modeling of HURREP-2P, there are still important tasks to do. Specifically, our review allowed us to identify imperative need of development in the following features: i) the majority of reviewed studies do not provide neither routing plan nor schedule for restoration machines. Models in Şahin (2013), Torabi et al. (2013) and Çelik et al. (2015) assume that restoration machines instantaneously move from one restoration task to another, which is totally unrealistic. ii) studies mentioned in the previous bullet determine which roads should be repaired, but do not specify which tasks should be performed by each machine. Sakuraba et al. (2016) manages work-troops actions (displacements and restorations) by means of flows on the links. However, they do not assign restoration tasks to specific work-troops or provide individual routes for them. Such a methodology may be valid in cases where all work-troops are homogeneous, and thus, the flow over links provide sufficient information to implement the solution. However, if we relax the assumption of homogeneity, it would result a challenge to translate flows into routes. iii) none of the studies in the area is able to deal with different types of disruptions/machines. In practice, there could appear different types of road interruptions requiring specialized equipment to be removed. A proper assignment of restoration tasks to machines will require modeling such heterogeneity. iv) most part of articles in HURREP literature, and all the studies addressing the HURREP-2P, perform over discrete time frameworks. These models impose the dilatation or contraction of real times, causing inaccuracies between the model and reality. Discrete-time models also require the specification of a planning horizon before the model is solved. If such horizon is fixed too short, part of the affected population will not be included in the solution. In contrast, an excessively large planning horizon will require a set of useless variables in the model, increasing its solution time. The ideal planning horizon is usually unknown before solving the problem, which makes these types of models virtually doomed to one of these two issues.

The six HURREP-2P studies included in our survey are classified in Table 2.3 based on the four features of the problem described above. This table allows an easy identification of latent research gaps in the literature. These gaps are formally presented

Table 2.3: Gaps on the HURREP-2P

Study	Machines routing	Machines scheduling	Heter. disruptions / machines	Continuous time (No discretiz.)
(Şahin, 2013)				
(Torabi et al., 2013)				
(Forbes, 2015)	x	x		
(Sakuraba et al., 2016)				
(Xu & Song, 2015)	x	x		
(Çelik et al., 2015)				
This thesis	**x**	**x**	**x**	**x**

2.4 Research gaps

To summarize, these are the set of research gaps that we found latent in the HURREP-2P:

1. **The majority of HURREP-2P studies do not provide the routing plan for restoration machines.**

   Much of the HURREP-2P studies ignore the routing of the restoration machines. In practice, the machines routing is a crucial feature of the restoration plan, since the weight and size of machines makes their displacement a challenge, specially over affected roads. Restoration plans that do not account for machines routing are prone to present the following difficulties: 1) inability to move between restoration tasks due to disruptions in the network, and 2) longer travel times than required, given that improvements in the network are not considered during displacements.

2. **The majority of HURREP-2P studies do not provide machines schedule.**

   Most studies in HURREP-2P do not include assigning machines to tasks and sequencing tasks for each machine. It is necessary to determine which machine is specifically assigned to each task, to ensure that it is able to fulfill its assignments.

3. **None of the HURREP-2P studies is able to deal with heterogeneous disruptions/machines.**

   None of the studies considered heterogeneous machines/interruptions. All studies consider a single type of disruption that can be addressed by any of the available machines. In real scenarios, there are different types of disruptions, which generally require different equipment to be addressed. For example, removal of a fallen tree requires a type of restoration machine different from that required to suck liquid. The assumption of homogeneous machines/interruptions significantly limits the application of restoration models in practical scenarios.

4. **All studies in HURREP-2P discretize the time.**

   A large number of the studies identified in the review, including all HURREP-2P studies, discretized the time in their models. The discretization of time implies the following limitations for the model:

- Restoration and routing times must necessarily coincide with some period of time. For a better understanding, consider the following example: suppose the periods of time are 5 hours, which means that the restoration times must be multiples of 5. If in a real case the restoration time is on average 8 hours, it is necessary to choose if that restoration time is equivalent to 1 period of time or 2 periods of time, losing accuracy in decisions. The studies that consider spatio-temporal networks have the deficiency that the start and end times of the displacements must necessarily coincide with the predefined time instants. This means that the actual times must be extended or contracted to fit the chosen discretization, to be included in the model.
- It is necessary to define a time horizon. In discrete models, a time horizon must always be defined for the operations before solving the model. However, on many occasions it is very difficult to know which is a suitable horizon. A too large planning horizon will involve the use of unnecessary variables in the model and will force the model to make more decisions than necessary. On the other hand, a too short planning horizon will prohibit avoid the satisfaction of all demand.

5. **Scarce integration between road restoration and Post-ROp performed in parallel**

   Only 6 studies, over 50 reviewed studies, integrate restoration and Post-ROp simultaneously, during response phase. As explained in the literary review, both operations are dependent on each other. The simultaneous studies HURREP-2P are the only ones that make a dynamic use of the links, that is, they allow the relief vehicle can be routed through the restored links as soon as they are enabled. These models have dynamic decision rules, which indicate which links to restore depending on the benefits they will generate to Post-ROp. For this reason, the greatest benefit in the Post-ROp can only be achieved by integrating both operations into a single model capable of quantifying the benefit of different restoration decisions on Post-ROp. The low number of studies that take into account this feature show an opportunity to significantly improve the results of Post-ROp that are developed over obstructed networks. This is achieved by the dynamic use of the links that are being restored, obtaining better and faster route times, which translates into shorter waiting times of the victims for the necessary attention. This is a line of the recent RRVP problem, with the first article located in 2009. Only 12% of the studies found in our review construct models of this type.

In addition to be a minority, to the best of our knowledge, none of the studies addressing the HURREP-2P considers all the features mentioned above. Thus, this thesis is the first study to take them into account. Both, our mathematical model and our heuristic are able to provide the routing plan and schedule for both, a set of heterogeneous restoration machines and a set of relief vehicles. Instead of discretizing the time as is the rule in previous studies, we developed our methods over a continous-time framework, which allows restoration machines and relief vehicles to complete displacements and perform tasks at any time required.

Chapter 3

Problem description

3.1 Problem statement

In this thesis, we are interested in decision making for cases of disasters, rather than catastrophes. In this regard, we base our concepts of disaster and catastrophe in the definitions provided by Holguín-Veras, Jaller, Van Wassenhove, Pérez, and Wachtendorf (2012). Catastrophes are high-consequence events whose strength is enough to totally collapse the ability of regional systems to cope with the event. During catastrophes, it is typically necessary to request external aid in order to assist the population; private supply chains are severely destroyed than these cannot aid in response and the most part of infrastructure becomes totally damaged. In most cases, disasters can be managed by regional authorities and infrastructure is partially instead of totally destroyed.

Suppose a disaster hits drastically a populated area, causing damage to the infrastructure and leaving a large number of people injured and fatal victims. The precarious condition of the population due to the disaster implies the immediate execution of post-disaster relief operations oriented to stabilize the community. These operations include the search for missing survivors, the evacuation of people to shelter areas and the distribution of relief goods. There is available a fleet of vehicles, responsible of the transportation of rescuers, members of humanitarian agencies, residents of the affected region and relief goods. Unfortunately, a large part of the road network became heavily affected due to the disaster. Some roads are passable with great difficulty, and some others are even impossible to navigate, due to structural damages and debris accumulation. The access to some areas is only possible making large detours and some other areas are totally isolated by land.

In order to solve this situation, there is available a set of restoration machines, able to perform different restoration tasks on the network. Among restoration tasks are displacement of obstacles to the sides of the road, debris removal and fast building of temporal bridges only with the purpose of rehabilitating the road. The experience of the restoration operator and the local authorities play a decisive role in the constitution of the restoration plan, which should specify the roads to be intervened, the set of roads in change of each machine and the order of execution of tasks for each machine. In addition, it will be necessary to build a routing plan for the machines, which should consider the obstacles in the network. Due to the great amount of solutions that could appear in a real world instance, the problem under consideration is challenging. Just consider the amount of combinations of roads that could be selected for intervention, the possible number of matches between restoration machines and restoration tasks, the number of work sequences that could be constituted for each machine and the amount of possible paths that could be traced over the network. Thus, it is quite difficult, even for experienced decision makers to deliver the restoration plan that generates the greatest benefits to Post-ROp.

In these situations, intuitive rules such as unlocking roads belonging to the shortest paths, or unlocking roads that require the least amount of time to be restored, do not guarantee the best solution for Post-ROp. In the first case, roads belonging to the shortest paths may require long restoration times. Solutions based on this rule may result in a large amount of demand being satisfied before shortest paths become available, which translates in a relatively low benefit from restoration, perceived by Post-ROp. In the second case, roads involving the lowest restoration times could release relatively long travel times, which may be equal or even worse than those of the already available routes.

This thesis is oriented to scenarios where: i) the disaster has left a large number of affected people and important damages in the network, so that several visits of relief vehicles to the affected region are necessary, and ii) the duration of restoration tasks is sufficiently large, so that multiple visit to zones can be performed in parallel to a single restoration activity.

Taking into account the high dependence that Post-ROp have on the restoration plan and the difficulty associated with this decision, this thesis proposes to answer the following question: what should be the restoration plan that generates the greatest benefit for Post-ROp in terms of the waiting time of the victims for aid? Given that both problems are dependent, the answer to this question requires not only the construction of the road restoration plan, but also of the relief plan. Here we implement Operations Research principles and techniques to provide a method to simultaneously solve the combined problem of post-disaster road restoration and relief planning.

3.2 Objetives

3.2.1 General objective

To design a methodology for the constitution of road restoration plans that will result in the highest benefit to Post-ROp in terms of waiting time of victims for aid.

3.2.2 Specific Objective

- To characterize the scientific literature in the combined problem of post-disaster road restoration and relief planning as operations being performed in parallel and to identify latent research gaps.
- To design a mathematical model integrating road restoration with Post-ROp planning as two activities that are developed simultaneously.
- To develop a solution method for the proposed problem offering a balance between solution quality and processing time.

Chapter 4

Formal problem description and formulations

This chapter introduces the problem of scheduling and routing restoration machines and relief vehicles performing in parallel, to optimally assist the affected communities during response phase. We refer to this problem as the *Humanitarian Road Restoration Problem - Partial Integrated with Post-ROp in Parallel* (HURREP-2P). We introduce and explain our mathematical model in both, its nonlinear and linear version.

4.1 Technical glossary

To model the problem we abstract the scenario to a road network composed of nodes and links, where nodes represent intersections or affected communities and links represent road segments connecting pairs of nodes. Departing from this basis, hereon we will stick to the following glossary for technical purposes:

Region: geographic space affected by a disaster. Due to the fact that demographic, socioeconomic, economic, and other statistical data is often provided for administrative divisions (e.g. for towns, municipalities, cities), it sometimes results convenient to use an administrative division as the region.

Point of Interest (PI): subspace of the region containing a subgroup of the affected population. It should also enclose a school, hospital, shelter area or any central place that could serve to relief purposes. Once again, it could conveniently correspond to an administrative division, but as a subspace of the region, the PI should be in a lower administrative level than the Region. The population, demographic conditions and degree of affectation due to disaster at each PI must be estimated in order to proceed with the restoration and relief planning.

Zone: artificial subspace of a Point of Interest, PI_i, containing a portion of its total demand, D_i. More precisely, each zone has a demand equal to the capacity of a relief vehicle, Q. Thus, each PI has exactly $\lceil D_i/Q \rceil$ zones, all of them geographically located at the same place. In our model, the amount of zones at a given PI, represents the number of times that such PI should be visited in order to assist all the community there.

Restoration tasks: diverse types of restoration activities which are developed in the response phase. These constitute fast ways of roads rehabilitation, allowing the execution of urgent humanitarian operations. Some typical restoration tasks are:

- Displacement of obstacles to the sides of the road
- Removal of structural debris
- Removal of stones and trees
- Dredging of water puddles
- Settlement of military bridges
- Road flattening

These activities are performed by special machines in charge of releasing obstructed roads. For the formulation of the mathematical model, we will treat a restoration task as an damaged link in the network.

Total repair and reconstruction of roads are postponed for the recovery phase, where roads are completely restructured. Total reconstruction activities are not addressed in this thesis.

Resource: any restoration machine or relief vehicle. By the side of machines, resources may represent excavators, bulldozers, loaders, dump trucks, articulated cranes, suction trucks, among others, which release blocked links. Relief vehicles are typically trucks or buses able to transport aid goods or people, respectively.

4.2 Properties of the HURREP-2P

We account for the following properties of the HURREP-2P:

Property 1: Not every restoration machine is able to process every restoration task. Restoration tasks may present specific requirements and restoration machines may possess different capabilities.

Property 2: Processing times of restoration tasks are job-specific and machine dependent.

Property 3: Restoration tasks are links and thus can be accessed by any of its two extreme nodes.

Property 4: Travel times over the network are vehicle-dependent for both, machines and relief vehicles.

Property 5: Travel times at a given moment depend on the jobs previously executed.

Property 6: Routes are not given in advance, they must be defined and updated by the model each time required.

Property 7: At any given moment, links may be available or not, depending on the jobs previously executed.

Property 8: It is not required to perform all restoration tasks.

Property 9: All relief tasks must be performed.

Property 10: Each PI is assigned an priority index. As the priority index, we use the product between: i) the urgency index of the zone, which accounts for the degree of affectation of the population there, and ii) the amount of people in the corresponding PI. Such an index is inherited to all zones belonging to the PI. Then sum of weighted attention times over all zones, works as a measure of the total suffering.

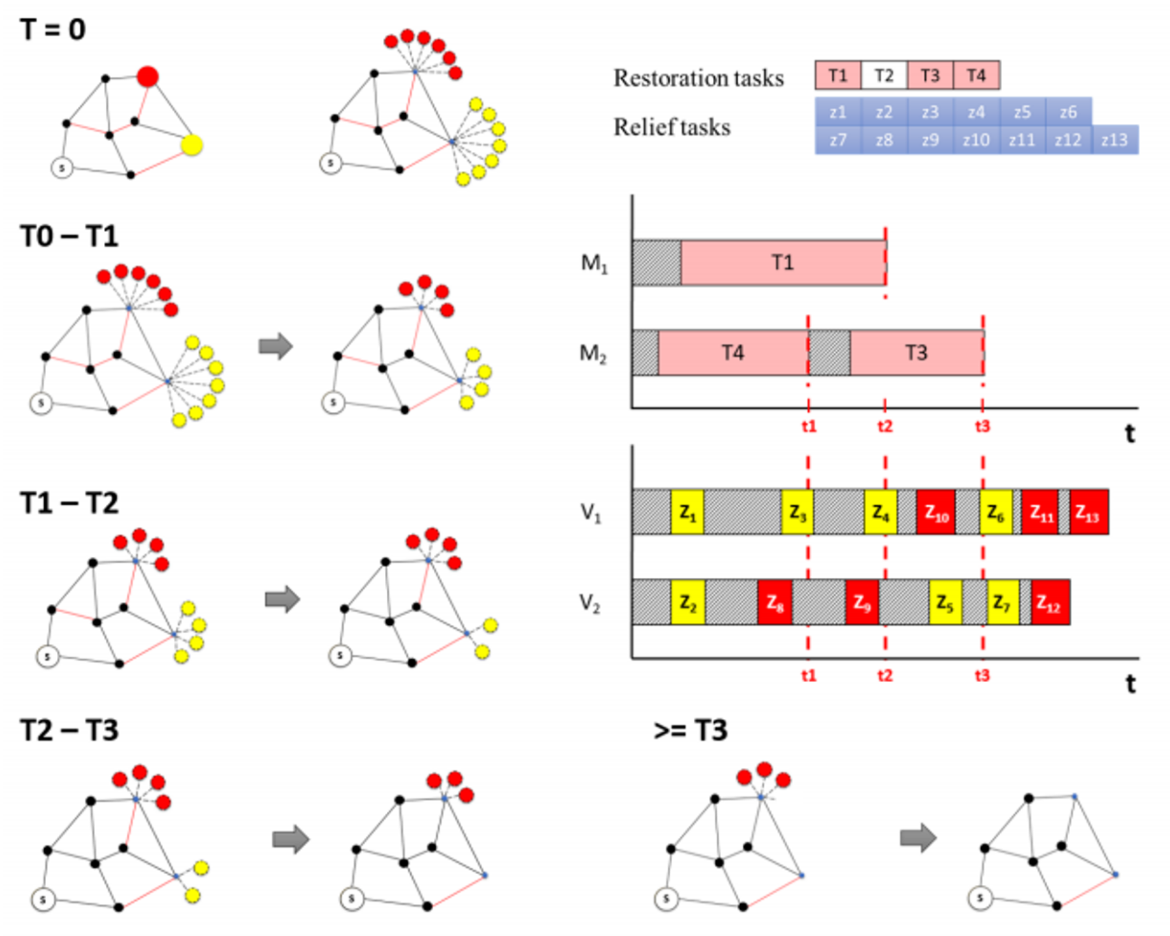

Figure 4.1: Restoration tasks

We illustrate the HURREP-2P in Figure 4.1, which shows a random solution for a toy instance with two restoration machines, two vehicles, four restoration tasks, seven nodes, twelve links and two PI which are split in six (from z_1 to z_6) and seven zones (from z_7 to z_{13}), respectively. For each PI, the priority is denoted by $w_i \in \{0, \ldots, 1\}$. All relief tasks were executed while only 3 out of four restoration tasks were done, as stated in Properties 6 and 7. Moreover, it is important to note, the progressive reduction on travel times for both vehicles and machines as the network is progressively restored. In the right side of Figure 4.1, the solution is illustrated on a machines scheduling fashion, where grey blocks represent displacements between tasks. Completion times of selected restoration tasks are identified with the tags t_1, t_2 and t_3 in the time axis. At the moment t_1, task T_4 was completed. Up to this moment, five trips of relief vehicles to zones had already began: z_1,

z_2, z_3, z_8 and z_9. Note that even though zone z_9 starts being served after moment t_1, the trip underway to that zone started before t_1 and thus at this moment, such attention is a taken decision and the route is built, based on available links previous to the completion of task T_4. Henceforth, task T_4 improves the route to all zones belonging to PI_1 which have not been assigned. This can be seen graphically with a decrease in times between jobs of its remaining zones. At moment t_2 task 1 is execute. From t_1 to t_2 were selected two zones to be assisted belonging to PI_1: z_4 and z_5. From there on, task 1 improves the route to all zones belonging to both PI which have not been assigned. From t_2 to t_3 were assigned three zones to be assisted: z_{10}, z_6 and z_7. From that point on, task 3 improves the routes of zones belonging to PI_2. At this point, it is not necessary to add another restoration tasks because all zones have already been assisted.

4.3 Relation with the Rescue Unit Assignment and Scheduling Problem

Among the different routing and scheduling problems that could present similarities with the HURREP-2P, we found the Rescue Unit Assignment and Scheduling Problem (RUASP), introduced by (Wex, Schryen, Feuerriegel, & Neumann, 2014), to be the one that closely matches with it. This problem consists on scheduling a set of rescue units working in parallel to attend a group of incidents, so that the weighted completion time of incidents is minimized. According to the authors, the RUASP is similar to the parallel-machine scheduling problem with unrelated machines and non-batch sequence-dependent setup times (PMS), except that the times in the RUASP depend of the machine and jobs, while in the PMS, these only depend on the job.

If we map both, restoration machines and relief vehicles to rescue units, and we also map both, restoration and relief tasks to jobs, then the HURREP-2P can be seen as a generalization of the RUASP. More precisely, the HURREP-2P correspond to a RUASP extension where some incidents may be present in paths instead on nodes (Property 3), travel times at a given moment depend on the incidents previously processed (Property 5), routes need to be defined and updated in the run (Property 6) and at any moment, links may be available or not, depending on the incidents previously processed (Property 7). Properties 1, 2, 4, 8, 9 and 10 of the HURREP-2P are explicitly handled by the RUASP. Moreover, in order to prohibit restoration machines assisting zones and relief vehicles processing restoration tasks, the corresponding capability parameters could be set to 0. With regard to Property 7, the corresponding constraints in the RUASP could be omitted. Altogether, this leads to the RUASP with availability of links and travel times depending on the incidents processed at each moment.

However, the adaption of the model proposed by Wex et al. (2014) to account for properties 3, 5, 6 and 7 is not straightforward. It requires building new constraints allowing to control the moment at which an incident has already been processed, embedding a routing model in the formulation for the construction and updating of routes, and adding new variables to the model, determining the availability of links at different moments of the operation.

To the best of our knowledge, there is not a model in the literature, totally matching the structure of the HURREP-2P. Thus, here we provide the first formulation for such problem. In spite of the differences between the HURREP-2P and the RUASP, similarities between both models were exploited in the construction of both, the optimization model and the heuristic algorithm.

4.4 Problem definition

Let us consider a large disaster region, discretized into a collection of sub-regions $\Pi = \{1, \ldots, \rho\}$, so-called Points of Interest (PI). Each PI has associated a nonnegative demand φ_ℓ, determined by the amount of people requiring medical assistance, the amount of people to be evacuated or the number of relief items to be delivered. For the assistance of the people, there is available a fixed fleet of identical relief vehicles $V = \{1, \ldots, u\}$, each of capacity Q, allocated at a relief source node.

In order to reach the PIs, relief vehicles must cover paths over a road network represented by an undirected graph $G(N, \Gamma)$, where $N = \{1, \ldots, d\}$ denotes the set of nodes and $\Gamma = \{(i, j)/i, j \in N\}$ denotes the set of links. Due to disaster effects, a set of links $R = \{0, \ldots, a\}$, with $R \subset \Gamma$, results disabled, implying that those links cannot be used at the beginning of relief operation. Affectations on the links may be of different types, requiring particular types of machines to be processed. In this regard, it is available a set of heterogeneous restoration machines $H = \{1, \ldots, \lambda\}$, each one capable of removing some types of disruptions. As damages vary on type, extension and severity, restoration times r_j^k are link-specific and machine dependent. Travel times t_{ij}^l are also vehicle-dependent for both, relief vehicles and restoration machines. Once a link has been restored, both, relief vehicles and restorations machines become able to pass across it, opening the possibility to reduce travel times between tasks.

We have the following assumptions:

- The discretization is done in such a way that the priority of people within a given PI, ℓ, is approximately homogeneous and the urgency index w_ℓ provides a good description of people's condition there;
- There is a single relief source point;
- A single disrupted link requires only one machine to be repaired;
- There is total knowledge about the condition and transit specifications of the network during the whole operation, i.e.: travel times, location of disrupted links and restoration times;
- Once a link has been repaired, it remains usable until the end of operations;
- Relief vehicles and restoration machines has sufficient resources available (e.g. fuel) for conducting the complete operation;
- Relief vehicles have all the same capacity.
- There is only one type of unit load consistently managed throughout relief operation. It may be composed of a combination of different basic products such as food, water or medicine.

The problem consists on finding: i) the schedule for each relief vehicle (visits to PIs and order); ii) the route for each vehicle along its trips; iii) the schedule for each restoration machine (links to be restored and order); and iv) the route for each machine from an affected link to another. These four products must be elaborated aiming to minimize the suffering of the affected population. Such goal is seek by means of the following objective function:

- Minimization of the sum of visiting times of relief vehicles, weighted by the priority index of the corresponding PI.

This objective prioritizes attention in most affected PIs, which are those with a higher priority index w_ℓ.

A feasible solution for the problem stated above must satisfy the following constraints: (i) each restoration task must be served at most by one restoration machine; (ii) restoration tasks should only be assigned to machines with the required capabilities; (iii) the whole demand at each PI must be satisfied; (iv) relief vehicles must return to the relief source node for replenishment, each time they visit a PI; (v) there should not be traffic on the affected until they get repaired.

4.5 Mixed Integer Nonlinear Program

In this section we propose a MINLP formulation for the HURREP-2P, formally defined Section 4.4. Seeking for a compact illustration of our model, we take advantage of the similarities between restoration machines and relief vehicles, by defining a single set of resources, $\Omega = \{1, \ldots, \lambda, \lambda + 1 \ldots, u + \lambda\}$, containing both of them. In this set, elements from 1 to λ correspond to restoration machines and those from $\lambda+1$ to $u+\lambda$ correspond to relief vehicles. Likewise, we exploit the similarities between restoration tasks and zones, by defining a single group of jobs, $\Omega = \{0, \ldots, a, a + 1 \ldots, \sigma + a + 1\}$, containing both of them. This time, elements from 0 to a correspond to restoration tasks and those fro $a + 1$ to $a + \sigma + 1$ correspond to zones. We also adopt the *zone* concept introduced in Section 4.1, which results convenient for controlled the number of visits that should be conducted at each PI.

The model is a Mixed Integer No-Linear Program, for which notation is given below. A thorough explanation is subsequently made.

Sets

$\boldsymbol{R}$:	Set of restoration tasks $\{0, \ldots, a\}$
$\boldsymbol{Z}$:	Set of affected zones $Z = \{a + 1, \ldots, \sigma + a + 1\}$
$\boldsymbol{\Delta}$:	Set of jobs $R \cup Z$ $\{0, \ldots, a, a + 1 \ldots, \sigma + a + 1\}$
$\boldsymbol{H}$:	Set of restoration machines $\{1, \ldots, \lambda\}$
$\boldsymbol{V}$:	Set of humanitarian vehicles $V = \{\lambda + 1, \ldots, u + \lambda\}$
$\boldsymbol{\Omega}$:	Set of resources $H \cup V$ $\{1, \ldots, \lambda, \lambda + 1 \ldots, u + \lambda\}$
$\boldsymbol{N}$:	Set of nodes in the network $\{1, \ldots, d\}$
$\boldsymbol{C}$:	Set of end nodes 1 of restoration tasks $\{c_0, \ldots, c_a\}$
$\boldsymbol{L}$:	Set of end nodes 2 of restoration tasks $\{l_0, \ldots, l_a\}$
$\boldsymbol{\phi}$:	Set of nodes of affected zones $\{q_{a+1}, \ldots, q_{z+a+1}\}$

Parameters for jobs, resources and network

$\boldsymbol{\mu_j^k}$:	Time required by resource k to execute the job j
$\boldsymbol{\Phi_j^k}$:	1 if resource k is capable of executing the job j
$\boldsymbol{r_{bd}^k}$:	Time required by resource k to restore the link b, d
$\boldsymbol{t_{bd}^k}$:	Time required by resource k to traverse the link b, d
$\boldsymbol{\delta_{bd}}$:	1 if the link b, d is unblocked at the beginning
$\boldsymbol{B_{bdj}}$:	1 if link b, d belongs to job j
$\boldsymbol{\gamma(F_j)}$:	Cost of lack of service in function of the waiting time of the zone j
$\boldsymbol{M}$:	Sufficiently large value of time
$\boldsymbol{W_j}$:	Priority index of job $j \in Z$

Decision variables

$\boldsymbol{X_{ij}^k}$:	1 if job i is processed by resource k immediately before executing job j
$\boldsymbol{Y_{ij}^k}$:	1 if job i is processed by resource k (at any time) before executing job j
$\boldsymbol{S_{ij}^k}$:	Time required by resource k to move from job i to job j
$\boldsymbol{F_j}$:	Completion time of job j
$\boldsymbol{I_j}$:	Start time of job j
$\boldsymbol{P_{bd}^{ijk}}$:	1 if resource k uses link b, d while traversing from job i and j
$\boldsymbol{PV_{bd}^{ijk}}$:	1 if the resource k uses link b, d while going back from job i and j; applicable to $i, j \in Z$
$\boldsymbol{G_{ij}}$:	1 if restoration task $j \in R$ was executed before restoration task $i \in R$
$\boldsymbol{E_{j'j}}$:	1 if restoration task $j \in R$ was executed before visiting zone $j' \in Z$

The mathematical model can be written as follows:

$$Min \sum_{j \in Z} \gamma(F_j) W_j, \tag{O1}$$

s.t.

Scheduling

$$\sum_{j \in R} X_{0j}^k \leq 1, \qquad \forall k \in H \tag{R1}$$

$$\sum_{i\in R}\sum_{k\in H} X_{ij}^k \le 1, \qquad \forall j \in R \tag{R2}$$

$$\sum_{j\in Z} X_{a+1,j}^k \le 1, \qquad \forall k \in V \tag{R3}$$

$$\sum_{i\in Z}\sum_{k\in V} X_{ij}^k = 1, \qquad \forall j \in Z \tag{R4}$$

$$Y_{ij}^k \le \alpha_j^k, \qquad \forall i,j \in \Delta, \forall k \in \Omega \tag{R5}$$

$$Y_{ij}^k \ge X_{ij}^k, \qquad \forall i,j \in \Delta, \forall k \in \Omega \tag{R6}$$

$$\sum_{j\in \Delta}\sum_{k\in \Omega} X_{ij}^k \le 1, \qquad \forall i \in \Delta \tag{R7}$$

$$\sum_{i\in \Delta} X_{ij}^k \ge \sum_{i\in \Delta} X_{ji}^k, \qquad \forall j \in \Delta, \forall k \in \Omega \tag{R8}$$

$$Y_{ii}^k = 0, \qquad \forall i \in \Delta, \forall k \in \Omega \tag{R9}$$

$$Y_{il}^k + Y_{lj}^k - 1 \le Y_{ij}^k, \qquad \forall i,j,l \in \Delta, \forall k \in \Omega \tag{R10}$$

$$\sum_{l\in \Delta} X_{il}^k \ge Y_{ij}^k, \qquad \forall i,j \in \Delta, \forall k \in \Omega \tag{R11}$$

$$\sum_{l\in \Delta} X_{lj}^k \ge Y_{ij}^k, \qquad \forall i,j \in \Delta, \forall k \in \Omega \tag{R12}$$

$$\sum_{i\in R}\sum_{k\in H} Y_{i0}^k = 0, \tag{R13}$$

$$\sum_{i\in Z}\sum_{k\in V} Y_{i,a+1}^k = 0, \tag{R14}$$

$$F_j = \sum_{i\in \Delta}\sum_{k\in \Omega}[\mu_i^k Y_{ij}^k + (\mu_j^k + S_{ij}^k)X_{ij}^k + Y_{ij}^k \sum_{l\in \Delta} X_{li}^k S_{li}^k] \qquad \forall j \in \Delta \tag{R15}$$

$$I_j \ge F_j - (\mu_j^k + S_{ij}^k) - M(1 - X_{ij}^k) \qquad \forall i,j \in \Delta, \forall k \in \Omega \tag{R16}$$

$$F_j \le M(\sum_{i\in \Delta}\sum_{j\in \Delta}\sum_{k\in \Omega} X_{ij}^k) \qquad \forall j \in \Delta \tag{R17}$$

Restoration machine routing

$$\sum_{d\in N} P_{c_i d}^{ijk} + \sum_{d\in N} P_{l_i d}^{ijk} = X_{ij}^k, \qquad \forall i,j \in R, \forall k \in H \tag{R18}$$

$$-\sum_{d\in N} P_{dc_j}^{ijk} - \sum_{d\in N} P_{dl_j}^{ijk} = -X_{ij}^k, \qquad \forall i,j \in R, \forall k \in H \tag{R19}$$

$$\sum_{d\in N} P_{bd}^{ijk} - \sum_{d\in N} P_{db}^{ijk} = 0, \qquad \forall i,j \in R, \forall k \in H, \forall b \in N, b \ne c_i, l_i, c_j, l_j \tag{R20}$$

$$\sum_{b\in N}\sum_{d\in N} P_{bd}^{ijk} \le \mid N \mid\mid N \mid X_{ij}^k, \qquad \forall i,j \in R, \forall k \in H, \tag{R21}$$

$$S_{ij}^k \ge \sum_{b\in N}\sum_{d\in N} P_{bd}^{ijk} t_{bd}^k, \qquad \forall i,j \in R, \forall k \in H \tag{R22}$$

Network updating for machines

$$-(I_j - F_i) \le M(1 - G_{ji}), \qquad \forall i,j \in R \tag{R23}$$

$$\sum_{k\in H} X_{0j}^k + G_{ji} \le 1, \qquad \forall i,j \in R \tag{R24}$$

$$G_{hj} \le \sum_{k\in H}\sum_{i\in R} X_{ij}^k, \qquad \forall h,j \in R \tag{R25}$$

$$R_{bd}^{ijk} \leq Q_{bd} + \sum_{h \in R} B_{bdh} G_{jh}, \qquad \forall i,j \in R, \forall k \in H, \forall b,d \in D \tag{R26}$$

RVs backward routing

$$\sum_{d \in N} PV_{q_i d}^{ijk} - \sum_{d \in N} PV_{d q_i}^{ijk} = X_{ij}^k, \qquad \forall i,j \in Z, \forall k \in V \tag{R27}$$

$$\sum_{d \in N} PV_{q_{a+1} d}^{ijk} - \sum_{d \in N} PV_{d q_{a+1}}^{ijk} = -X_{ij}^k, \qquad \forall j,i \in Z, \forall k \in V \tag{R28}$$

$$\sum_{d \in N} PV_{bd}^{ijk} - \sum_{d \in N} PV_{db}^{ijk} = 0, \qquad \forall j \in Z, \forall k \in V, \forall b \in N, b \neq q_{a+1}, q_i \tag{R29}$$

$$\sum_{b \in N} \sum_{d \in N} PV_{bd}^{ijk} \leq \mid N \mid\mid N \mid X_{ij}^k, \qquad \forall i,j \in Z, \forall k \in V, \tag{R30}$$

RVs forward routing

$$\sum_{d \in N} P_{q_{a+1} d}^{ijk} - \sum_{d \in N} P_{d q_{a+1}}^{ijk} = X_{ij}^k, \qquad \forall i,j \in Z, \forall k \in V \tag{R31}$$

$$\sum_{d \in N} P_{q_j d}^{ijk} - \sum_{d \in N} P_{d q_j}^{ijk} = -X_{ij}^k, \qquad \forall i,j \in Z, \forall k \in V \tag{R32}$$

$$\sum_{d \in N} P_{bd}^{ijk} - \sum_{d \in N} P_{db}^{ijk} = 0, \qquad \forall j \in Z, \forall k \in V, \forall b \in N, b \neq q_{a+1}, q_j \tag{R33}$$

$$\sum_{b \in N} \sum_{d \in N} P_{bd}^{ijk} \leq \mid N \mid\mid N \mid X_{ij}^k, \qquad \forall i,j \in Z, \forall k \in V, \tag{R34}$$

$$S_{ij}^k = \sum_{b \in N} \sum_{d \in N} P_{bd}^{ijk} t_{bd}^k + \sum_{b \in N} \sum_{d \in N} PV_{bd}^{ijk} t_{bd}^k, \qquad \forall i,j \in Z, \forall k \in V \tag{R35}$$

Network updating for RVs

$$-(I_{r'} - F_r) \leq M(1 - E_{r'r}), \qquad \forall r' \in Z, \forall r \in R \tag{R36}$$

$$E_{hj} \leq \sum_{k \in H} \sum_{i \in R} X_{ij}^k, \qquad \forall h \in Z, \forall j \in R \tag{R37}$$

$$\sum_{k \in V} X_{0j}^k + E_{ji} \leq 1, \qquad \forall i \in R, \forall j \in Z, \forall k \in H \tag{R38}$$

$$R_{bd}^{ijk} \leq Q_{bd} + \sum_{h \in R} B_{bdh} E_{jh}, \qquad \forall i,j \in Z, \forall k \in V, \forall b,d \in N \tag{R39}$$

$$RV_{bd}^{ijk} \leq Q_{bd} + \sum_{h \in R} B_{bdh} E_{jh}, \qquad \forall i,j \in Z, \forall k \in V, \forall b,d \in N \tag{R40}$$

Having defined our mathematical model, we proceed to explain its functioning.

Objective Function In the objective function, $\gamma(f_i)$ is a non-decreasing linear function that assigns a cost penalty to the time it takes to serve zone i, which is represented by F_i. Then, equation (O1) minimizes such a cost weighted by priority index W_i.

Constraints The first set of constraints, (R1) - (R17), controls the scheduling of jobs to resources. Specifically, Constraints (R1) and (R2) are concerned about scheduling of restoration tasks (i.e., jobs $\in R$), while Constraints (R3) and (R4) are focused on the scheduling of visits to zones (i.e., jobs $\in Z$). Constraint (R1) ensures that at most one task in the schedule of each restoration machine, is immediately preceded by the dummy task 0. Similarly, Constraint (R3) ensures that at most one zone in the schedule of each relief vehicle, is immediately preceded by the dummy zone $a + 1$. Constraint (R2) ensures that each restoration task has at most one immediate predecessor. By its side, Constraint (R4) warranties that there is exactly one immediate predecessor for every affected zone. As evident, Constraint (R2) do not enforces the execution of all restoration tasks, allowing the model to determine which tasks are convenient for the performance of relief operations. In contrast, Constraint (R4) enforces the attention of each single zone, warrantying the satisfaction of the whole demand.

Given the similarities between restoration scheduling and relief scheduling, all constraints from (R5) to (R17) are used to control assignments of both, restoration tasks to machines and zones to relief vehicles. Constraint (R5) ensures resource k is not assigned to job j if k has not the capability to process j. In this way, the following three issues are controlled: (1) the assignment of restoration machines to zones; (2) the assignment of relief vehicles to restoration tasks; and (3) the assignment of restoration machines to disruptions that they are not able to process by functionality.

Constraint (R6) states that every immediate predecessor job should also be a non-immediate predecessor. Inversely, Constraint (R11) states that every non-immediate predecessor must also be an immediate predecessor. By its side, Constraint (R12) states that every non-immediate successor must also be an immediate successor. Constraint (R7) ensures that each job has at most one immediate successor. Constraint (R8) states that a job must have an immediate successor in order to become an immediate predecessor. Constraint (R9) prohibits reflexive precedence relationships while the transitivity relationship among predecessor jobs is ensured by Constraint (R10) ensures. Constraints (R13) and (R14) prohibit any precedence relationship where the dummy job 0 is the successor.

Constraint (R15) is an adaptation of the objective function implemented in Wex et al. (2014) for the RUASP formulation. Such a Constraint accounts for the computation of the completion time of each job. It operates as follows:

- The first term, $\sum_{i\in\Delta}\sum_{k\in\Omega}\mu_i^k Y_{ij}$, computes the sum of processing times for all jobs preceding job j.

- The second term, $\sum_{i\in\Delta}\sum_{k\in\Omega}(\mu_j^k + S_{ij}^k)X_{ij}^k$, computes the total time required to execute job j, which is not only composed by its processing time, but also by the time required to get in j, coming from its immediate predecessor i.

- The third term, $\sum_{i\in\Delta}\sum_{k\in\Omega} Y_{ij}^k \sum_{l\in\Delta} X_{li}^k S_{li}^k$, computes the sum of travel times between all pairs of jobs preceding job j.

On the other side, Constraint (R16) determines the starting time of job j. It is computed as its completion time minus its total processing time, which is in turn composed by its processing time plus the time required to move from its immediate predecessor i to its location. Finally, Constraint (R17) enforces non-scheduled jobs to have a completion time equal to zero.

The second set of constraints, (R18) to (R22), builds a route for each resource $\in H$ (i.e., restoration machines). Constraints ((R18), (R19) and (R20) determine the route of machine k between every pair of consecutive restoration tasks. If job j is performed immediately after i, Constraint (R18) ensures the constitution of a link departing from one of the two extreme nodes of job i. In that same scenario, Constraint (R19) ensures that there is a link arriving at one of the two extreme nodes of job j. This mechanism allows restoration machines to enter on a damaged road in the most convenient direction. Constraint (R20) accounts for the specification of the remaining links on the path between i and j, by flow ensuring conservation. Constraint (R21) prohibits the construction of routes between pairs of restoration tasks that are not consecutive in the sequence of machine k. The travel time between tasks i and j is computed in Constraint (R22).

Our model allows both, relief vehicles and also restoration machines to take advantage of those links that have already been repaired at any moment, in order to improve their travel times. In the case of restoration machines, the dynamic updating of road network is provided by constraints (R23) to (R27). Constraint (R23) allows a machine to use links belonging to task i, along its trip to task j, only if the completion time of task i is lower or equal than the starting time of task j. By its side, Constraint (R25) prohibits any machine to take advantage of any restoration task if it is not assigned to be executed. Constraint (R26) allows machine k to use a link in its trip to a given task, if those links were unblocked from the beginning of operations or became repaired before such a trip takes place.

Constraints (R27) - (R35) are responsible for the routing of relief vehicles, which requires a special treatment. In contrast to restoration machines, which can move directly from a task to another, relief vehicles must return to the relief source node for replenishment, each time they visit a PI. In this regard, Constraints (R27)-(R30) are designated to build the route back from the last assigned zone to the relief source node, and Constraints (R31) - (R34) work on the construction of route onward to the next assigned zones. By its side, Constraint (R35) computes the travel time between two zones as the sum of the times backward from previous zone and onward to next zone. In the case of the first zone visited by a vehicle, the travel time only it includes the route from relief source node to the designated zone. This set of constraints works as follows:

If zone j is visited by vehicle k immediately after zone i, Constraint (R27) ensures that there is a link leaving node i; Constraint (R28) ensures that there is a link arriving at node j; and finally, Constraint (R29) determines the remaining links on the path from i to j. Constraints (R31)-(R34) are very similar to constraints (R27)-(R30), but the former construct the path from relief source point to next assigned zone instead of defining it from the last assigned zone to the source node.

The last set of constraints, (R36) - (R40), enables links to be exploited by relief vehicles, each time a restoration task is completed. Constraint (R36) merges machines schedules with relief vehicles schedule. Constraint (R23) allows a relief vehicle to use links belonging to task r, along its trip to zone r', only if the completion time of task r is lower or equal than the starting time of zone r'. Constraint (R37) prohibits any relief vehicle to take advantage of any restoration task if it is not assigned to be executed. Finally, Constraints (R39) and (R40) allow relief vehicle k to use a link in its trip to a given zone, if those links were unblocked from the beginning of operations or became repaired before such a trip takes place.

4.6 Enhanced model

In this section, our MINLP formulation is revised in two main aspects. At first, we resolve the nonlinearities present in Constraint (R15). This adjustment leads us to a Mixed Integer Linear Program (MILP) formulation, which results convenient in terms of computational efficiency. Secondly, we derive a framework to manage decreasing priorities of zones based on the amount of people that remains unassisted at each PI.

4.6.1 Linearization

As stated in previous section, Constraint (R15) is an adaptation of the objective function proposed in Wex et al. (2014) for the RUASP, which computes the weighted sum of completion times of tasks. Unfortunately, both expressions are non-linear and most part of the efficient solution method available today work only for linear formulations. In order to facilitate the solution of the problem, we linearize the model. For this purpose, we introduce new elements in the notation as follows:

Sets

$\boldsymbol{\Pi}$:	Set of Points of Interest $\{1, \ldots, \rho\}$
$\boldsymbol{\Theta}$:	Set of greatest zone indexes per PI $\{1, \ldots, g_\rho\}$

Parameters for jobs, resources and network

$\boldsymbol{W_j}$:	Pre-computed importance of the job $j \in Z$

Decision variables

$\boldsymbol{SS_j}$:	Sum of restoration time of job j and the travel time from previous job
$\boldsymbol{T^k_{lij}}$:	Time required by resource k to move between job l and i, given than job j is executed by resource k at any time after job i

The following set of linear constraints is also added to the formulation:

$$SS_j \geq (\mu^k_j + S^k_{ij}) - M(1 - X^k_{ij}) \qquad \forall j, i \in \Delta, \forall k \in \Omega \quad \text{(R41)}$$

$$T^k_{lij} \geq S^k_{li} - M(2 - X^k_{li} - Y^k_{ij}) \qquad \forall i, j, l \in \Delta, \forall k \in \Omega \quad \text{(R42)}$$

$$F_j \geq \sum_{i \in \Delta} \sum_{k \in \Omega} (\mu^k_i Y^k_{ij} + SS_j + \sum_{l \in \Delta} T^k_{lij}) \qquad \forall j \in \Delta \quad \text{(R15a)}$$

$$I_j = F_j - SS_j \qquad \forall j \in \Delta \quad \text{(R16a)}$$

Constraint (R41) computes the time required to execute job j, as the sum of the travel time from previous job i and the processing time of job j. Constraint (R42) computes the travel time between jobs l and i if job i is executed at any time before job j is executed. Results from Constraints (R41) and (R42), are then implemented in Constraint (R15a), which results a linear version of Constraint (R15). Both expressions determine the completion time of job j as the sum of: i) processing times for all jobs preceding j; ii) the total time required to execute job j (processing time plus travel time from previous job); and iii) the travel times between all pairs of jobs preceding job j. The main difference is that terms two and three in Constraint (R15) where revised to linear expressions by means of Big-M equations in Constraints (R41) and (R42). This change also leaded to the transformation of Constraint (R16) into (R16a), which both compute the starting time of job j.

To summarize, the MINLP introduced in Section 4.5 can be mapped to a MILP by adding Constraints (R41) and (R42), and replacing Constraints (R15) and (R16) with Constraints (R15a) and (R16a), respectively. This linearization scheme results also a valid approach to obtain a linear version of the formulation proposed in Wex et al. (2014) for the RUASP.

4.6.2 Managing decreasing priorities

Objective Function (O1) computes the priority of the zone as the product between the urgency index of the zone and the amount of people in the corresponding PI. The weakness with such an approach is that it gives the same priority for two zones with the same urgency index, belonging to different PIs with the same number of initial people affected, but different amount of people remaining unassisted. Under such formulation, the only fact that would determine which one of those two zones will be attended first is the time required to reach each zone. To synthesize, if two zones have the same priority index, Objective Function (O1) will lead the model to attend first all the demand at the PI with the shortest travel time. Seeking for a more equitable way of scheduling visits to PIs, we modified the computation of priorities of zones in our model. Instead of multiplying the urgency index of the zone by the amount of people in the corresponding PI, we decided to multiply the urgency index by the amount of people **remaining unassisted** at the PI. One approach to do so may be to introduce a control variable corresponding to the amount of unassisted people at a given PI at the moment when each zone is visited. However, such an approach would make the Objective Function (O1) nonlinear, and thus, the model would become nonlinear again. Seeking to keep the advantages of a linear formulation, we opted for an alternative approach, which in fact does not require any additional variable, but just an additional constraint. It consists on forcing the model to schedule visits to zones of the same PI, from the one with the lowest index to the one with the highest one. Such an imposition is illustrated in Constraint R43

$$F_i \leq F_{i+1}, \qquad \forall i \notin \Theta \quad \text{(R43)}$$

Given that the amount of demand covered at each visit to a PI is known, a pre-defined order of attendance for zones of the same PI allows us to relate each individual zone with an amount of unassisted population. As well as the old priority index, the new one can be pre-computed and the formulation remains linear. For a better compression of our approach, consider the following example: There is a PI with urgency index $u = 0.5$ and a required number of visits of 5. A contrast between two approaches is offered in Table 4.1.

Table 4.1: Fixed vs decreasing priority

Zones	Visits left	Priority (w)	
		Old approach	New approach
z1	5	5 x 0.5 = 2.5	5 x 0.5 = 2.5
z2	4	5 x 0.5 = 2.5	4 x 0.5 = 2.0
z3	3	5 x 0.5 = 2.5	3 x 0.5 = 1.5
z4	2	5 x 0.5 = 2.5	2 x 0.5 = 1.0
z5	1	5 x 0.5 = 2.5	1 x 0.5 = 0.5

4.7 Solution of a test instance

Now that we have modeled the problem, we illustrate the solution provided by CPLEX 12.6.2 for a small test instance, with the purpose of validating its consistency and offering the reader a clear idea of the information delivered by our model. Parameters for the instance are presented in Figure 4.2 and Table 4.2.

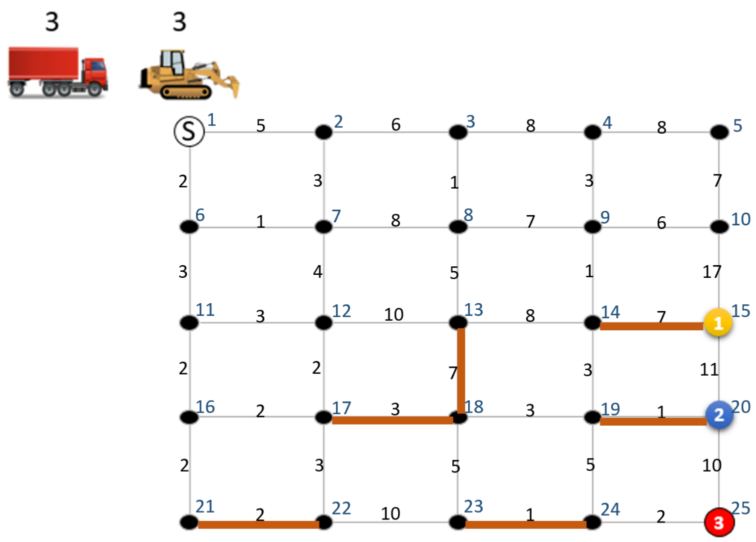

Figure 4.2: Test instance

The solution provided by the model for this instance is presented in Table 4.3. From there, it can be appreciated that the execution of restoration task 1 was exploited by machine 2, which used links belonging to such task for moving between tasks 6 and 5. On the other hand, vehicle 1 took advantage not only of the execution of one task, but of the execution of two of them. This vehicle used links belonging to tasks 4 and 1 to reach zone 3. Moreover, vehicle 2 exploited the execution of task 3 to reach zones 4 and 1.

It should be noted that once a restoration machine reaches one extreme of its next restoration task, the machine is able to perform the task and then appear in any of the two extremes of such task, with no difference in the corresponding restoration time. This feature can be appreciated in the sequence of machines 3, which enters in task 6 through the node 18, and then appears in the same node for its trip from task 6 to task 5. We modeled the behavior of machines in this way, based on interviews with members of the

Table 4.2: Test instance

Restoration			Relief operation		
Restoration task	Extreme nodes	Restoration time	Zones	Nodes	Attention time
1	17, 18	80	1	15	20
2	23, 24	90	2	20	10
3	14, 15	60	3	20	10
4	19, 20	80	4	25	15
5	21, 22	80	5	25	15
6	18, 13	70	-	-	-

Table 4.3: Solution for a test instance

Restoration plan				
Restoration machine	Restoration task	[O - D]	Route	Exploited tasks
1	3, 2	[0 - 3]	1, 6, 7, 8, 9, 14	–
		[3 - 2]	14, 19, 24	–
2	1, 6, 5	[0 - 1]	1, 6, 7, 12, 17	–
		[1 - 6]	18	–
		[6 - 5]	18, 17, 22	1
3	4	[0 - 4]	1, 6, 7, 8, 9, 14, 19	–
Relief plan				
Vehicles	Zones	[O - D]	Route	Exploited tasks
1	2, 3	[0 - 2]	1, 6, 7, 8, 9, 10, 15, 20	–
		[2 - 3]	20, 19, 18, 17, 12, 7, 6, 1, 6, 7, 12, 17, 18, 19, 20	4, 1
2	4, 1	[0 - 4]	1, 6, 7, 8, 9, 10, 15, 20, 25	–
		[4 - 1]	25, 24, 19, 14, 9, 8, 7, 6, 1, 6, 7, 8, 9, 14, 15	3
3	5	[0 - 5]	1, 6, 7, 8, 9, 10, 15, 20, 25	–

Administrative Department for Prevention, Attention, and Recovery from Disasters in Antioquia, Colombia (DAPARD). According to them, a restoration task typically does not consist of a single pass of the machine over the roads from extreme to extreme of the restoration task, but it usually involves multiple passes over the road and stops at different angles. Thus, it results more realistic to assume that machines are able to appear in any of the two extremes of the task once it has been completed, and such decision is previously considered in the restoration time by planners.

Another interesting fact in the solution is that not all restoration tasks that were completed, were also exploited. Specifically, in this solution, tasks 2, 5 and 6 are not exploited by anyone. This happens because the objective function of the model is the minimization of weighted attention times of zones, which is not explicitly affected by the number or extent of restoration tasks that are executed. Moreover, there is no budget constraint in the formulation, which may prohibit the execution of some tasks. In other words, the solution presented in Table 4.3, and the same solution without tasks 2, 5 and 6, are alternative solutions for this instance, based on our formulation. A variation of our formulation, which accounts for the elimination of unnecessary tasks from the plan, and also for a budget is proposed later in Section 6.4.

This small instance leads to another interesting result, which becomes evident with the inspection of Table 4.4, which presents the starting and completion times for each restoration task and visit to zone in the solution. From there, it can be appreciated that the model is able to make some vehicle or machine to wait at some point until a given restoration task is delivered, as a strategy to exploit the benefits that such a task will generate for the next trip of the vehicle/machine. This kind of decision occurred when vehicle 1 reached zone 2. The vehicle became vacant at time 62, but the model decided to make it wait until restoration task 4 was completed in time 102. As can be seen in Table 4.3, next trip of vehicle 1 was from zone 2 to zone 3, taking advantage of restoration tasks 4 and 1.

Table 4.4: Starting and completion times in test solution

Restoration		
Restoration task	Starting time	Completion time
1	0	89
2	79	173
3	0	79
4	0	102
5	159	245
6	89	159
Relief operation		
Zones	Start time	Completion time
1	79	150
2	0	62
3	102	144
4	0	77
5	0	77

4.8 Screening experiments with CPLEX

In order to evaluate the resolution speed of our model using an exact solution method, we performed a series of computational experiments, where we varied the number of restoration tasks and zones among experiences, as illustrated in Table 4.5.

All experiences were performed over a network with 25 nodes and 40 links, where 3 restoration machines, 3 relief vehicles were operating to serve 3 PIs. Such a basis condition is presented in Figure 4.3. In all experiences, the urgency indexes of PIs 1, 2 and 3 were fixed on 0.2, 0.3 and 0.5, respectively. Travel times were sampled only once at the beginning of the experiment and remained constant throughout all experiences. These were sampled from $\mathrm{U}(5, 20)$ min, which assuming a travel speed of 30 mph equals to working on a network with distances uniformly distributed on the range 2.5 - 10 miles. Restoration times were sampled from $\mathrm{U}(80, 320)$ min, which corresponds to an average

Table 4.5: Screening instances

Scenario	Restoration Tasks	Relief Tasks	Zones		
			P1	P2	P3
S1	4	5	1	2	2
S2	4	7	1	2	4
S3	6	5	1	2	2
S4	6	7	1	2	4

restoration time 16 times bigger than the average travel time. This order of scale is a typical condition for HURREP-2P instances, where restoration times are sufficiently large to allow some relief operations to take place in parallel. The range of restoration times was also relatively large with respect to the range of travel times. This feature accounts for the fact that road damages could be of diverse types, and may require very different times to be removed.

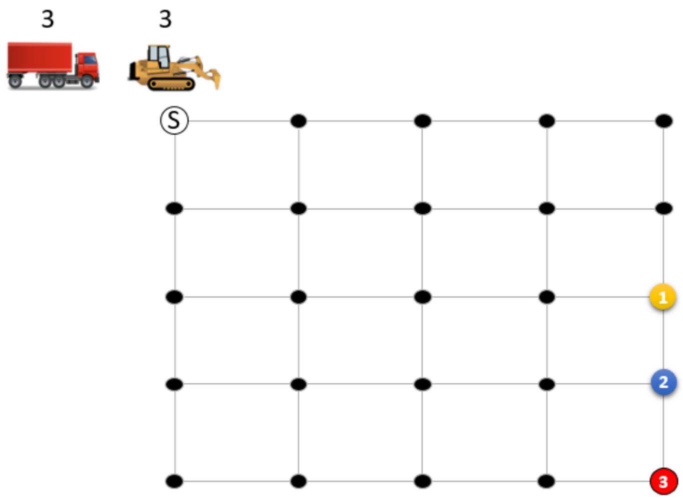

Figure 4.3: Instance for screening with CPLEX

During our first tests with the model, we realized that the solution time for the same instance (same number of damaged arcs) may vary depending on the location of damaged links at each simulation. Therefore, in our screening tests, we solved the problem for each scenario three times, all with the same number of affected links, but each with a randomly generated location of damaged links. All experiences were run on an Intel Core i5-6300U with 2.5GHz and 8GB RAM. Results from this experiment are presented in Table 4.6.

In regard to practical processing times for the HURREP-2P, decision support must be provided in less than 12 hours, as confirmed in interviews with members of DAPARD [1]. Thus, we also set a runtime of 12 hours as an alternative terminating condition. In all instances, the model was solved optimally, except in the condition 3 from scenario 2 and all conditions from scenario 4 in which the solution method stopped by terminating condition of 12 hours.

[1]Administrative Department for Prevention, Attention, and Recovery from Disasters in Antioquia, Colombia (DAPARD)

Table 4.6: CPLEX times - screening

Scenario	Condition	ResT	RelT	CPLEX Time (sec)
1	1	4	5	191
	2	4	5	98
	3	4	5	263
2	1	4	7	10642
	2	4	7	11223
	3	4	7	43200*
3	1	6	5	1673
	2	6	5	674
	3	6	5	936
4	1	6	7	43200*
	2	6	7	43200*
	3	6	7	43200*

* Time limit of 12 h exceeded

A first thing that becomes evident from results in that the location of damaged links may cause important changes in the solution time. For instance, in conditions 1 and 2 from scenario 2, the problem was solved in less than 11300 seconds, but in condition 3 from the same scenario, the model stopped at the time limit of 43200 seconds. This happens because restoration tasks located at different places cause different benefits to Post-ROp and thus, depending on the location of damages, decisions of the model are easier or harder to be taken. It can also be seen that results from the smallest instances (scenario 1), present a lower variability than largest scenarios.

On the other hand, it can be perceived that the effect of increasing the number of relief tasks (visits of affected zones) is greater than the effect of increasing in the same amount, the number of restoration tasks. The increment in solution times from scenario 1 to scenario 2 and also from scenario 3 to scenario 4, were much more drastic than the changes perceived from scenario 1 to scenario 3 and from scenario 2 to scenario 4. In other words, the solution time of our model seems to be more susceptible to changes in the number of relief tasks than in the number of restoration tasks.

For relatively small instances (4 restoration tasks and 5 relief tasks) the solution times reported by CPLEX were highly satisfactory. Moreover, solution times for medium-size instances (combinations of 4 restoration tasks with 7 relief tasks, and 6 restoration tasks with 7 relief tasks) remained far from the time limit of 12 hours in the majority of cases, instead for the third condition of scenario 2. In all the largest conditions (scenario 4), the time limit of 12 hours was reached, pointing out a boundary of applicability of the formulation proposed here. Although a larger experiment should be necessary to properly establish usage policies for our model, these results suggest the need for a methodology able to solve large instances of our problem in relatively short time. In the next section we address such a need by introducing a hybrid heuristic which combines Ant Colony Optimization with GRASP to efficiently solve the HURREP-2P. Upgrading computational power technology through faster hardware, the application of alternative solution methods for MILP optimization, future enhancements of the model and augmented parallel processing might further extend the size limit for solvable instances. The adoption of disjunctive constraint pairs in our formulation seems a promising avenue in this regard.

Chapter 5

ACO-GRASP heuristic for the HURREP-2P

Our optimization problem, *HURREP-2P* (P1), is a generalization of the machine scheduling problem: *Identical parallel machine non-preemptive scheduling with minimization of sum of completion times* (P2), which is NP-hard (Blazewicz, Dror, & Weglarz, 1991).

To test this, we consider an instance with a finite number of relief vehicles with the same capabilities, all affected zones requiring the same amount of time until being attended, and distances between zones equal to zero. In the transformation, each machine corresponds to one of the relief vehicles, and each non-preemptive job corresponds to an affected zone. The execution time of a job corresponds to the attention time of a zone.

If we map affected zones on jobs and relief vehicles on machines, then the generalization refers to the fact that our problem provides for set-up times (travel times between jobs), non-identical machines and constraints on the assignment of relief vehicles to affected zones, all these, in addition to the parameters of the restoration problem. Given an instance of P2, we can map this instance onto an instance P1 (in polynomial time) by setting $\lambda = 0$ (number of restoration machines), a=0 (number of restoration tasks), $t_{ij}^{k} = 0$ (travel time in link i,j by relief Vehicle k), $\mu_i^{k_1} = \mu_i^{k_2}$ (attention time), $\Phi_i^k = 1$(capability). Based on our proof, the problem of scheduling non-preemptive jobs on identical parallel machines can be solved by solving an instance of the HURREP-2P. Thus, our problem is at least NP-hard, which means that no efficient solution techniques for the problem at hand exists.

In this section, we present *Humanitarian Restoration and Relief Algorithm* (HURRA); a new hybrid ACO-GRASP algorithm able to deal with the trade off between solution quality and processing time in large instances of the HURREP-2P. The algorithm has the structure of ACO algorithm and implements the GRASP algorithm to solve the relief operation. The ACO part of the HURRA smartly allocates restoration resources to a subset of the affected links on the road network. By its side, the GRASP part, which we will call ROp-GRASP, provides efficient relief plans based on the ratio of zones weights to at-the-moment sum of corresponding travel and processing times. The HURRA algorithm is described in depth on the following subsections.

5.1 Ant Colony Optimization for restoration plan

ACO is a constructive meta-heuristic inspired in the natural ability of ants to find short paths from a source to their nest, using their pheromone trail as a communication mechanism to share information on the best known paths. ACO was introduced in the early 1990s by M. Dorigo and his colleagues as a novel heuristic able to deal with combinatorial optimization problems (Dorigo, Maniezzo, Colorni, & Maniezzo, 1991; Dorigo, 1992; Dorigo, Maniezzo, & Colorni, 1996; Dorigo & Blum, 2005). Since then, it has been consistently proven as an efficient solution method for a wide variety of routing and scheduling problems. For very good reviews on ACO, reader is referred to (Dorigo & Stützle, 2010), and (Mohan & Baskaran, 2012).

In this study, ACO was chosen to deal with the construction of the restoration plan for the HURREP-2P. The rationale behind our selection is the following: it is well known that the k-best paths for a given instance of a routing problem, may often have high overlap (low diversity, since may share a large number of links), instead of being spread all over the network (Yongtaek & Hyunmyung, 2005; Van der Zijpp & Catalano, 2005). As a fusion of scheduling and routing problems, the HURREP-2P is not the exception to the rule. Thus, a natural approach to efficiently solve this problem may be to first perform a screening of the solution space by exploring solutions in diverse directions, and then condense the efforts exploring the neighborhood of best known solutions. ACO indeed behaves exactly this way, by means of its exploration and exploitation mechanisms (i.e. local and global pheromone update, respectively). In the first few iterations, ACO explores the solution space in very diverse directions. As the algorithm advances, the exploration is progressively reduced due to the learning mechanism which reinforces the attractiveness of links in the best known solutions. As the exploration is decreased, the exploitation is increased, and the algorithm starts testing slight modifications of those best known solutions. These characteristics make ACO not only a very fast alternative for obtaining good solutions in relatively short time, but also an ideal solution method for the HURREP-2P.

Irrespective of the objective function, our approach departs from the ACO algorithm proposed by (Lin, Hsieh, & Hsieh, 2012) for the problem of scheduling unrelated parallel machines to minimize total weighted tardiness, which we call ACO-UPM (Ant Colony Optimization for Unrelated Parallel Machine). That algorithm presents a good departing point for our algorithm since it considers the case where a single ant provides the schedule for multiple machines working in parallel, as required in the HURREP-2P. Before introducing our algorithm, we will briefly describe the ACO-UPM. Then, we will delve into the adaptation and extensions introduced by us.

ACO-UPM steps:

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1. Initialization: a colony is generated and each ant is localized on a dummy node (job). Additionally, each link on the network is assigned an initial pheromone value.
2. Construction: each ant applies different decision rules to select the links composing a feasible tour for each machine starting at the dummy node and ending up when all nodes (jobs) have been visited by one machine. For this purpose, two main sources of information are used: the heuristic information and pheromone information.
3. Local pheromone update: each time a node is added to the sequence of a given machine, pheromone values are locally updated. It means that their values are modified only considering the last decision of the corresponding ant, which is going from job i to job j with machine k. Local update has the purpose of reducing the probability of selection of the link (i, j, k) by other ant. This mechanism helps to enforce the exploration of other solutions.

4. Local search: each time an ant becomes complete (all jobs have been scheduled), a local search procedure is applied to improve the solution.
5. Global pheromone update: each time a colony is completed, pheromones are globally updated. It means that their values are modified considering information gathered by the whole colony about the quality of different schedules. Global update increases the probability of selection of links composing the best known solutions. This mechanism promotes the exploitation of available information about the solution space in order to condense search efforts in hot zones where the best schedules tend to be.

* Repeat until stopping conditions are meet.

5.2 Extending the ACO-UPM to HURRA

We provided an overview of the ACO-UPM in the previous section. Now we describe the adaptations that we performed in the algorithm in order to make it suitable for the HURREP-2P.

A fundamental step on the constitution of our algorithm was the redefinition of the concept of *restoration task*. We made such a redefinition, because we found it useful for identifying and avoiding a kind of solution where restoration machines could be assigned to jobs that are clearly not going to improve relief operations. These kind of solution, called here *doomed from start* (ds), appear when there are some restoration tasks assigned in the schedule, that will not enable new routes. For a very simple example of these kind of solution, reader is referred to Figure 5.1, where we show a disrupted network with four damaged roads (Figure 5.1a) and three potential ds solutions (Figures 5.1b - 5.1d). All these solutions are likely to be sub-optimal, since machines spend their time processing useless jobs instead of restoring roads that could improve relief times.

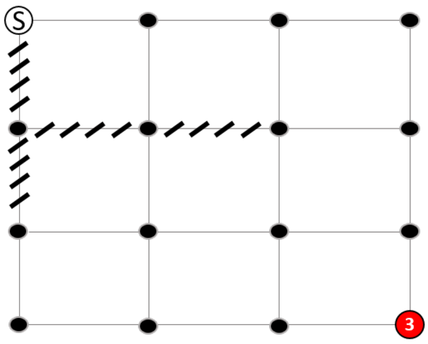
The major issue with the original definition of *restoration task* is that as soon as a random decision rule is embedded in the algorithm, ds solutions become very likely to appear. The problem tends to be worst as the network size is increased and damaged links are distributed sparsely. In that cases, it could become a challenge to work with the original definition of *restoration task* and reach a single non-ds solution.

Now that rationale behind our redefinition of *restoration task* has been provided, we formally present the new definition.

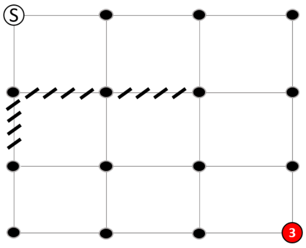
Restoration task: Set of interconnected damaged links, presenting the following two properties:

- Property 1: a restoration task must be connected at each extreme with at least one operable (unblocked) link.
- Property 2: a restoration task may not be partially composed of other restoration tasks.

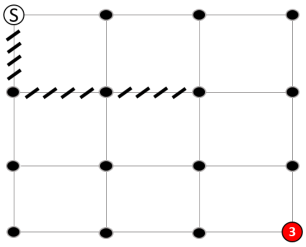
In order to illustrate how new restoration tasks look like, we implemented the definition in the dummy network used for the example above. Results are illustrated in Figure 5.2.



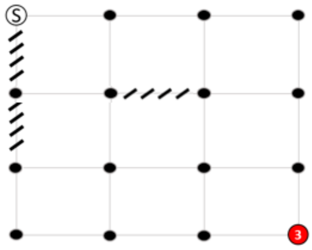
(a) Original restoration tasks



(b) ds 1



(c) ds 2



(d) ds 3

Figure 5.1: Issue with original restoration tasks

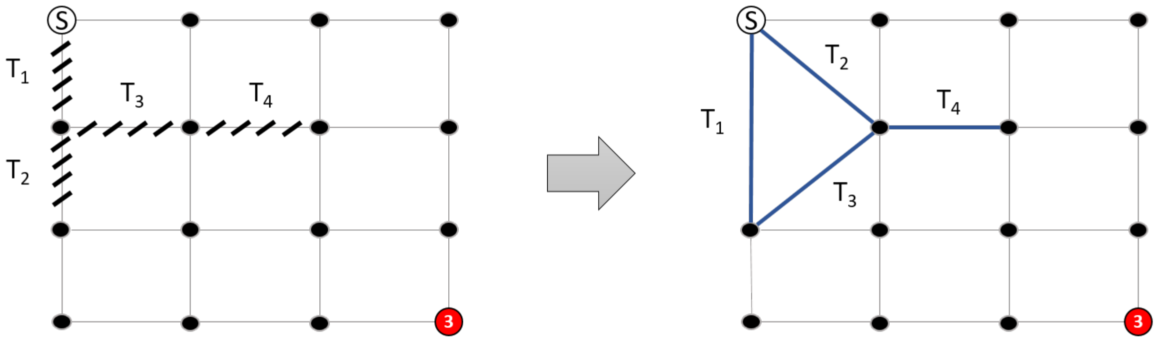


Figure 5.2: Link-based vs path-based restoration tasks

Reader may note that each time a restoration task in the new framework is performed, new routes become available. Reader may also note that in this example, the number of restoration tasks is 4 for both frameworks, which not always happens. In fact, the majority of times, the number of tasks in the new framework overpasses that in the old framework. This is why it is still convenient to work with the old *restoration task definition* in the optimization model.

Now that the concept of *restoration task* has been redefined, we are able to detail the main aspects in which the ACO proposed here generalizes the algorithm presented in (Lin et al., 2012). These are:

1. In ACO-UPM, an ant represents a solution, which corresponds to a job processing schedule. In HURRA an ant represents a solution for the HURREP-2P, involving both, the restoration plan and also the relief plan.

2. In ACO-UPM, setup times are fixed. In contrast, travel times in HURRA depend on the path used to go from one job to another, which is updated each time a

restoration task has been completed and links got repaired. Therefore, HURRA accounts for variable travel times depending on previously executed jobs.

3. ACO-UPM assumes that any machine is able to process any job. In HURRA, heterogeneous machines / jobs are considered, which means that some machines are specialized in and only able to process specific types of jobs.

4. ACO-UPM assumes that all connections between jobs are available at any time. In HURRA some connections will not be available until the corresponding tasks get executed.

5. In ACO-UPM, processing times of jobs are fixed. In contrast, HURRA employs the new definition of restoration task, introduced in 5.2, which states that a restoration task may be composed of multiple damaged links. Under this definition, restoration tasks could partially overlap (share links) and once a link (b, d) has been restored on a given task (i, j), it no longer needs to be restored at other tasks. Thus, the processing time of link (b, d) shall be removed from any other task containing it. As a result, processing times depend on previously executed jobs.

6. ACO-UPM works with node-like jobs, which means that they can only be accessed on one way. HURRA considers link-like jobs, which can be accessed in two ways, corresponding to entering on a damaged road by either of its two extremes. This feature makes necessary not only to determine if a job is processed by a machine, but also from which extreme is it accessed.

7. In ACO-UPM, an ant becomes completed when all jobs have been assigned to machines. In HURRA, not all jobs must be done, but only those that result convenient for the optimization. In other to determine if the ant is already completed, it is required to run a surrogate algorithm for relief planning, each time a task is assigned, and verify if either the demand has already been meet or there is still place for other restoration tasks to be scheduled.

The pseudo-code for the HURRA is presented in Algorithm 1. It could be noted that the HURRA has a similar structure than ACO-UPM. In fact, HURRA includes all steps involved in ACO-UPM, except for the local search procedure, which was not addressed in this study. By the other side, HURRA accounts for two additional steps which are: i) the construction of shortest paths between tasks (line 13), and ii) a call to the ROp-GRASP algorithm (line 19), which returns an efficient relief plan considering the restoration schedule available at the moment. The following is a detailed description of main steps in our algorithm.

1. **Initialization:** as in classic ACO, the initialization in HURRA consists on creating new colony containing a set of solutions called ants. Here an ant represents a solution for the HURREP-2P and thus, it manages both, restoration and relief plan.

2. **Construction:** here, the ant makes a step forward in the completion of a new solution. In the HURRA, each time an ant performs the construction step, it assigns a new restoration task to a machine and validates if there is place for a further restoration to be assigned.

Algorithm 1 HURRA for the HURREP-2P

```
while Stopping conditions remain unsatisfied do
    Create a new colony Col of size Psize
    ColonyState := partial
    for <f=1:Psize> do
        Locate each machine at its initial position
        Tag each machine as Partial
        Tag Ant as partial
    end for
    while <ColonyState == partial> do
        for <each ant in Col> do
            if (ant f remains partial) then
                Randomly select a partial machine k from f
                Determine shortest paths to feasible tasks
                Select a feasible task j for machine k
                Update schedule of machine k
                Check for consistency
                Perform local pheromone update on used links
                Check which agents remain partial
            end if
            Solve relief plan with ROp-GRASP
            Check if ant remains partial
        end for
        Check if colony remains partial
    end while
    Perform global pheromone update
end while
```

Output: Efficient road restoration and relief plan

(a) ***Select a partial ant:*** an ant is considered partial when the restoration plan is not complete, that is, when there is place for other tasks in the schedule that could improve the relief plan. At every iteration of the construction step, we assign a new restoration task to one machine belonging to each partial ants.

(b) ***Select a feasible machine:*** a machine is said to be feasible if: i) is able to perform at least one restoration task that has not been assigned yet; and ii) is able to reach at least one of those tasks from its current location. The restoration machine to be updated is randomly selected among all feasible machines.

(c) ***Build shortest paths:*** in order to chose the next task in the schedule of selected machine, it is necessary to find the shortest path from the current location of that machine to each feasible task. A task is said to be feasible if: i) it has not been executed before; ii) the selected machine has the capability for processing it; and iii) the selected machine can reach it. Here we perform multiple calls to Dijkstra's algorithm for such purpose (Dijkstra, 1959).

(d) ***Select a feasible task:*** once a restoration machine k has been selected, we proceed to assign the next feasible task in its sequence. In order to choose next job in the sequence of machine k, the following sources of information are taken into account:

Pheromones the pheromone level τ_{ij}^k gives information about the potential benefit of including the link (i, j, k) on the solution, based on the best known solutions at each moment. It is typically fixed at a starting level τ_0 and then continuously updated throughout the execution of the algorithm.

Visibility the visibility of a task j, coming from a task i with machine k, here denoted as η_{ij}^k, indicates the potential benefit of including the link (i, j, k) on the solution, based on the parameters and variables specific of the instance been solved. Following the notation for the HRRP-PP declared in Section 4.5, visibility of link (i, j, k) can be computed as follows:

$$\eta_{ij}^k = \frac{1}{tv_{ij}^k + r_j^k} \tag{5.1}$$

where tv_{ij}^k is the travel time between jobs i and k using the machine k and r_j^k is the restoration time of job j by machine k.

In most ACO algorithms, the visibility is only computed once at the beginning of the algorithm and remains constant during the whole run. In contrast, the HURRA updates the visibility each time a machine is going to chose a task, since travel and restoration times are dependent on previous decisions.

Taking both, pheromones and visibility into account, next task in the sequence of machine k is chosen as follows. Let i be the last restoration task assigned to k and also let Ω_i^k be the set of feasible restoration tasks for machine k, given that it is located at task i. The decision is taken by applying one the following three decision rules:

Rule 1: choose the task with the greatest attractiveness, defined as the product between pheromone level and visibility. This rule can be mathematically expressed as:

$$j* = \text{argmax}\{\eta_{ij}^k \tau_{ij}^k\}, \qquad j \in \Omega_i^k \tag{5.2}$$

where j^* represents the chosen task.

Rule 2: randomly select one task based on a probability pie resulting from the standardized attractiveness of feasible tasks. This second rule can be mathematically expressed as:

$$P_{ij}^k = \frac{\eta_{ij}^{k^\alpha} * \tau_{ij}^{k^\beta}}{\sum_{l \in \zeta} \eta_{il}^{k^\alpha} * \tau_{il}^{k^\beta}} \tag{5.3}$$

where P_{ij}^k is probability of selection for link i, j to be added in the sequence of machine k, α is a coefficient of exploration and β is a coefficient of exploitation.

Rule 3: randomly select one task among feasible ones, all with same probability of selection.

$$P_{ij}^k = \frac{1}{|\Omega_i^k|} \tag{5.4}$$

where P_{ij}^k can be interpreted the same as in rule 2.

The rule to follow is in turn chosen according to the following distribution function:

$$Decision = \begin{cases} rule\ 1, & \text{if } q \leq q_0 \\ rule\ 2, & \text{if } q_0 < q \leq q_1 \\ rule\ 3, & \text{otherwise} \end{cases}$$

where q is a uniformly distributed number in [0, 1], while q_0 and q_1 are parameters specified by the user in the range $0 - 1$.

(e) ***Check for consistency:*** each time a task is matched with a machine, the schedule may require a correction process. Such a process consists on deleting all previously selected tasks whose starting time is greater or equal to the completion time of the task that has just been added to the schedule. This procedure is necessary because both, restoration and processing times of previously assigned tasks are subject to changes in the schedule at any time before their starting time, and thus, the decision criteria adopted for their selection losses validity.

3. ***Local pheromone update:*** each time a task is matched with a machine, a reduction in the pheromone's level of those links that have already been selected by a given ant takes place. This procedure promotes the diversification of solutions within a given colony, seeking for the exploration of unknown regions of the solution space. Local pheromone update is performed based on Equation 5.5, where ρ is a parameter that simulates the evaporation rate ($0 \leq \rho \leq 1$).

$$\tau_{ij}^{k} = (1-\rho)\tau_{ij}^{k} + \rho\tau_{0} \tag{5.5}$$

4. ***Solve relief plan with ROp-GRASP:*** each time a restoration task is added to the sequence of some machine, ROp-GRASP is called to build an efficient relief plan, considering the updated restoration plan. ROp-GRASP not only delivers the relief plan, but also determines when the restoration plan is complete. A full description of ROp-GRASP is further provided in Section 5.3.

5. ***Global pheromone update:*** each time a colony gets complete, an increment in the pheromone's level of those links included in the best known solutions takes place, helping the algorithm to converge around them. Global pheromone update is performed according to Equation 5.6.

$$\tau_{ij}^{k} = \tau_{ij}^{k} + \Delta\tau_{ij}^{k} \tag{5.6}$$

   In this study, the value of $\Delta\tau_{ij}^{k}$ was fixed in τ_0 based on (Schilde, Doerner, Hartl, & Kiechle, 2009).

5.3 ROp-GRASP: custom-made heuristic for relief planning

In this section we introduce our heuristic algorithm for structuring the relief plan in the HURREP-2P. This algorithm, called *Relief Operation - Greedy Randomized Adaptive Search Procedure* (ROp - GRASP), was built based on scheduling heuristics proposed in (Wex et al., 2014) for the RUASP, which in turn can be seen as adaptions of Smith's rule for parallel machines (Smith, 1956). The algorithm proceeds as follows.

The ROp-GRASP receives as parameters, the set of restoration tasks that have already been scheduled, as well as their respective completion times. Each completion time indicates a moment of improving in the network. We call periods between subsequent completion times, *Restoration Windows.*

---

1. Select a vehicle: there are two rules for selecting a vehicle: i) select the vehicle with the lowest make-span; and ii) randomly select the vehicle. The first rule seeks to balance the load among vehicles, which contributes to schedules with lower end time. By its side, the second rule keeps the solution space unbiased, allowing the algorithm to produce any feasible solution.

2. Sort zones: at each restoration window, routes from depot to each unvisited zone are determined, taking into account which links have already been repaired. Let i be the current position of selected vehicle k. Then, zones are sorted as follows:

$$\frac{w_1}{TP_{i1}} \geq \frac{w_2}{TP_{i2}} \geq \ldots \geq \frac{w_n}{TP_{in}} \qquad \text{with} \qquad TP_{ij} \leftarrow tv_{ij}^k + P_j^k$$

   The resulting rates are organized in a descending order for each window. This way, zones with shorter processing times (travel plus attention) and a higher priority become most likely to be selected in the next assignment.

3. Window selection: once a vehicle has been selected, the window in which it will attended the next zone is also selected. Let i be the last zone visited by the selected vehicle k, then the algorithm randomly decides between: i) selecting the window where visit i is completed; or ii) postpone the allocation of next visit to a subsequent iteration and update the makespan of vehicle k to the end of the window where visit i is completed, so that any further visit is performed from this point on. This mechanism allows a better exploration of the solution space.

4. Zone selection: after selecting the processing window, next zone to visit is also selected by means of one of the following two rules: i) randomly select a zone from a percentage of the best feasible destinations in terms of the ratios computed in step 1; ii) randomly pick a zone.

   Once the zone has been selected, it is allocated on either: i) the window corresponding to the current makespan of the vehicle; or ii) the next window. To decide between the two solutions, the algorithm computes the completion time of the task for both alternatives, and assigns the task to the alternative that gives the lowest completion time. This procedure is useful when a visit is going to be added to a vehicle whose makespan is close to the end of a restoration window. In that case, instead of adding the visit just at the current makespan of the vehicle, it could be preferable to wait until the next restoration window starts and take advantage of repaired roads for processing such visit.

5. Check demand satisfaction: Each time the ROp-GRASP is executed, it verifies if either: i) all restoration tasks have already been scheduled; or ii) the whole demand can be meet without exploiting the roads released by the last restoration task. In any of these two scenarios, the algorithm concludes that the restoration plan is complete since there is no place for any further restoration. In any other case, the ROp-GRASP sends back a message to HURRA indicating that another restoration task may be required.

* Repeat until stopping conditions are meet.

Main differences with respect to scheduling heuristics proposed in (Wex et al., 2014):

1. Our ratio uses not only the processing time but also the processing time to compute the ratio in step 1.

2. Total processing times are not fixed, but may vary among restoration windows.

The GOp-GRASP presents an alternative for fast construction of relief plans, keeping unbiased the solution space. Processing speed was a very desirable characteristic in this algorithm, since it is called by the HURRA multiple times. More specifically, HURRA calls the GOp-GRASP each time a new restoration task is added to any machine on any ant of any colony. Another advantage of the GOp-GRASP is that it is able to produce high quality solutions, driven by the greedy ratio computed in step 1.

5.4 Screening experiments with HURRA

In this section we test the ability of our heuristic to find high quality solutions in a relatively sort processing time. For that purpose, we solved the same instances than those solved in Section 4.8 via CPLEX, and we compared the progress of both algorithms during run. Ten replications were used to compute the average of the best found solutions until each moment by HURRA.

Simulation results are compiled in Table 5.1, where we compare the performance of HURRA vs CPLEX. In this case, we are not only interested about the runtime of each algorithm, but also about their rate of convergence and the solution quality reachable by the heuristic. Thus, in Table 5.1, we provide an overview of the progress of both algorithms solving each instance. Each column of the Table 5.1 corresponds to a moment (in seconds) at which either CPLEX or HURRA improved the value of the objective function.

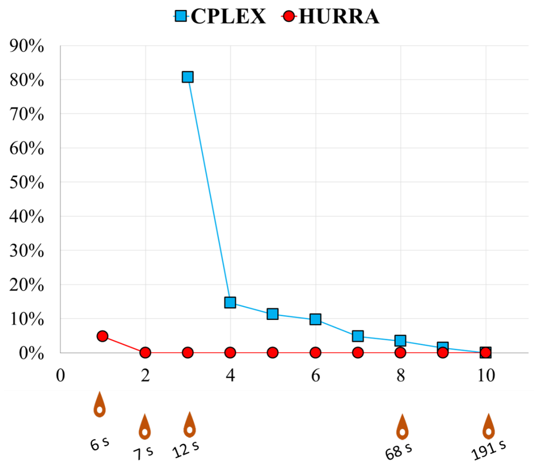
As explained in Section 4.8, CPLEX was run and stopped at a time limit of 12 hours (in case this did not solve optimally before 12 hours). By the side of HURRA, the algorithm was set on an infinite loop generating colonies, and the following terminating conditions were adopted: i) stop if there have been five subsequent colonies without improvement in the objective; ii) stop if CPLEX terminating time was reached; and iii) stop if the time limit of 12 hours was reached.

For an easier interpretation of results, data from Condition 1 of each Scenario was also plotted in Figure 5.3a. The y-axis corresponds to the optimality gap (%) and the x-axis to the solution time in seconds.

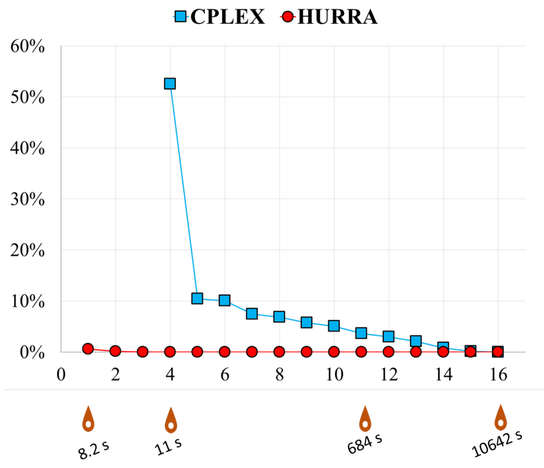
Table 5.1: Cplex vs HURRA - Progress comparison

Scenario 1																		
Condition 1	Moment	1	2	3	4	5	6	7	8	9	10	11						
	Time (sec)	6	7	12	15	24	38	47	49	68	70	191						
	CPLEX	-	-	80,7%	14,6%	11,3%	9,7%	4,8%	3,4%	1,4%	0,0%	0,0%						
	HURRA	4,8%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%						
Condition 2	Moment	1	2	3	4	5	6											
	Time (sec)	9	10	11	16	22	98											
	CPLEX	42,1%	2,4%	2,4%	2,0%	0,0%	0,0%											
	HURRA	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%											
Condition 3	Moment	1	2	3	4	5	6	7										
	Time (sec)	8	10	11	12	16	178	263										
	CPLEX	55%	55%	55%	3%	1%	0%	0%										
	HURRA	-	2%	1%	0%	0%	0%	0%										
Scenario 2																		
Condition 1	Moment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Time (sec)	8,2	8,3	8,4	11	19	24	91	99	196	207	684	1030	1086	1271	1923	3705	10642
	CPLEX	-	-	-	52,5%	10,4%	10,1%	7,4%	6,8%	5,7%	5,1%	3,6%	2,9%	2,0%	0,8%	0,1%	0,0%	0,0%
	HURRA	0,6%	0,1%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Condition 2	Moment	1	2	3	4	5	6	7	8	9	10	11	12	13				
	Time (sec)	10	12	13	14	15	17	143	164	174	1473	1723	2555	11223				
	CPLEX	56,6%	56,6%	56,6%	9,5%	9,4%	2,5%	2,3%	2,3%	1,2%	0,8%	0,0%	0,0%	0,0%				
	HURRA	1,5%	0,7%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%				
Condition 3	Moment	1	2	3	4	5	6	7	8	9	10	11	12	13				
	Time (sec)	13	18	19	22	26	38	82	244	274	1545	7506	26982	43200*				
	CPLEX	38,8%	38,8%	38,8%	11,2%	6,9%	4,4%	3,6%	1,7%	1,5%	1,2%	0,1%	0,0%	0,0%				
	HURRA	-	5,9%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%				
Scenario 3																		
Condition 1	Moment	1	2	3	4	5	6	7	8	9								
	Time (sec)	10	11	12	16	18	19	55	113	1673								
	CPLEX	80,3%	80,3%	26,8%	18,2%	16,3%	10,0%	3,9%	0,0%	0,0%								
	HURRA	1,8%	0,9%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%								
Condition 2	Moment	1	2	3	4	5	6	7	8	9	10	11	12	13	14			
	Time (sec)	9	10	11	13	16	23	25	30	46	49	138	212	360	674			
	CPLEX	-	80,5%	80,5%	20,0%	17,3%	15,6%	6,7%	3,1%	2,9%	0,9%	0,8%	0,2%	0,0%	0,0%			
	HURRA	3,9%	2,0%	0,9%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%			
Condition 3	Moment	1	2	3	4	5	6	7	8	9	10	11						
	Time (sec)	11	13	14	15	16	17	20	22	119	445	936						
	CPLEX	70,9%	70,9%	70,9%	15,9%	15,5%	9,7%	6,4%	1,7%	0,2%	0,0%	0,0%						
	HURRA	42,3%	1,8%	0,9%	0,9%	21,6%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%						
Scenario 4																		
Condition 1	Moment	1	2	3	4	5	6	7	8	9	10	11	12	13				
	Time (sec)	14	15	19	21	23	24	259	273	906	1310	7251	11947	43200*				
	CPLEX	74,0%	66,5%	34,9%	34,9%	34,9%	13,8%	4,2%	4,1%	2,1%	0,4%	0,2%	0,0%	0,0%				
	HURRA	-	-	13,8%	5,9%	0,4%	0,4%	0,4%	0,4%	0,4%	0,4%	0,4%	0,4%	0,4%				
Condition 2	Moment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Time (sec)	17	21	28	29	351	813	854	1033	1088	1730	5738	7411	7904	9403	9578	22903	43200*
	CPLEX	51,4%	7,1%	7,1%	6,9%	6,4%	6,0%	5,5%	5,3%	4,6%	3,6%	2,6%	2,5%	1,7%	0,6%	0,1%	0,0%	0,0%
	HURRA	-	6,0%	5,3%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%	0,6%
Condition 3	Moment	1	2	3	4	5	6	7	8	9								
	Time (sec)	17	18	23	356	1833	2862	3369	3622	24813								
	CPLEX	76,1%	76,1%	7,1%	3,6%	0,5%	0,2%	0,1%	0,0%	0,0%								
	HURRA	-	6,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%								

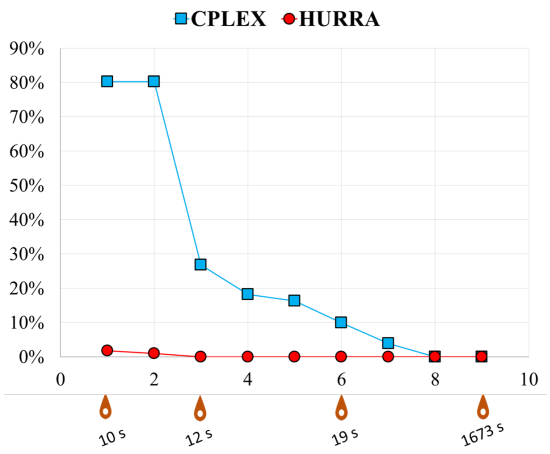
* Time limit of 12 h exceeded



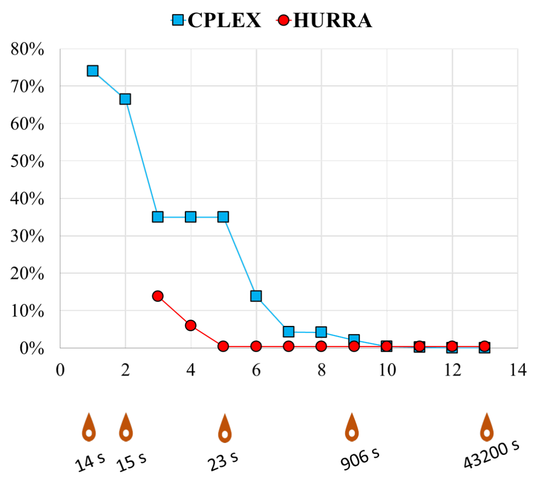
(a) Scenario 1 - Cond. 1



(b) Scenario 2 - Cond. 1



(c) Scenario 3 - Cond. 1



(d) Scenario 4 - Cond. 1

Figure 5.3: CPLEX vs HURRA performance

There are four main facts that stand out from results:

1. The first solution found by HURRA in all cases was better than the first solution found by CPLEX. This result comes from the fact that HURRA exploits information about the instance to guide the search to hot spots of the solution space from the first moment of run.

2. HURRA was able to find the best known solution in all instances except for Conditions 1 and 2 of Scenario 4. In all the remaining cases, except for Condition 3 of Scenario 2, we are sure that the solution found by HURRA was the optimum solution. In that particular exception, we could not guarantee that the solution found by HURRA was the optimum, but it was the best solution found by CPLEX until the time limit of 12 hours.

3. HURRA converged faster than CPLEX to the best known solution. In all the ten cases where HURRA got 0% gap, it converged to that value in less than the 9.2% of the time required by CPLEX to reach a terminating condition. In fact, in 7 of this

ten, HURRA reached 0% gap in less than the 2% of the time required by CPLEX to reach a terminating condition.

4. HURRA always stopped by convergence. As mentioned before, HURRA got 0% gap in 10 of the 12 experiences. In the remaining 2, the gap remained under 7%, which evidences that the algorithm is not only fast, but also provides high quality solutions.

5. All runs HURRA converge in less than 29 seconds, which is a very promising result in comparison with the time limit of 12 hours suggested by DAPARD.

Chapter 6

Managing special features and extensions

The mathematical model and the heuristic provided in Chapters 4 and 5 offer the possibility of modeling some special cases of the HURRE-2P that may appear in some real scenarios. Some of these features can be managed through the original formulation, proposed in Chapter 4. Others can be introduced in the model by slight modifications in the formulation. Our study case evidences how such possibility contributes to a more accurate modeling of reality. Those special features are described bellow.

6.1 Multiple relief modes

Our products(the model and heuristic) are able to manage different types of transport modes. This can be done by specifying vehicle-dependent travel times and vehicle-dependent adjacency matrices. The great utility of this possibility will be evidenced later in our case study, where the fleet of relief vehicles is constituted by trucks and boats. It is important to clarify that this functionality does not make the model a muti-modal formulation, since it does not allow transference of loads among modes.

6.2 Natural road release

Our products also make it possible to simulate a special kind of disruption, which do not require the action of a restoration machine to be removed. We refer to disruptions that naturally disappear from the network after some time lapse. For instance, in our case study, a road segment of 42 km length remained flooded for the first seven days of relief operation and then, the road became passable again due to evaporation and drainage. These kinds of disruptions can be modeled following the procedure below:

1. Create an artificial restoration task, a*.
2. Create an artificial restoration machine capable of restoring only the task a*.
3. Match the artificial task a* with corresponding links that are affected by the special disruption.
4. Assign a restoration time of 0 time units to restoration task a*, $r_{a*}^{k*} = 0$.

5. Assign task a*, a starting time equal to the expected natural release time of the road. This can be achieved by adding the following constraint to the formulation:

$$I_{a*} \geq T_{est} \tag{R44}$$

6. Assign routing times for the special machine equal to zero, $tv_{ij}^{k*} = 0 \; \forall i, j \in$ to the path from source node to one extreme of the artificial task a*.

As the artificial restoration task has a starting time equal to the expected natural release moment of the road, and a processing time equal to zero, the task will be instantaneously enabled in the model at the desired moment.

6.3 Vehicle-dependent starting times

In real world scenarios, restoration machines and relief vehicles may not be all available at the same moment. In order to model vehicle-dependent starting times, it can be adopted a similar procedure than that used for modeling cases of natural road release. In that case, we may add an artificial restoration task to the network of each vehicle that has a starting time greater than 0. Such a task may only be manageable by an artificial machine, whose travel times are equal to zero. The processing time should also be equal to zero and the right side of Constraint R44 should be fixed on the expected release time of each vehicle.

6.4 Restoration cost

Our mathematical model minimizes the weighted cost for lack of service (WCLS), which is treated in this thesis as a linear function of the waiting time of affected people for humanitarian aids. At this point, the model does not consider the existence of a limited budget for the restoration plan. This feature can be incorporated to the model by means of the following constraint:

$$\sum_{i \in R} \sum_{j \in R} \sum_{k \in H} \sum_{b \in N} \sum_{d \in N} X_{ij}^{k} B_{bdj} co_{bd}^{k} \leq \Upsilon, \tag{R45}$$

where Υ is the budget for the restoration operation and co_{bd}^{k} is the cost for restoring the link (b, d) using machine k.

This way, we could ensure that the available budget for restoration is not exceeded. We also propose a lexicographic solution approach, seeking for the lowest possible restoration cost, subject to the minimum WCLS. This approach consists on solving the problem in two steps:

1. Solve the mathematical model proposed in Chapter 4, adding Constraint R45 to the formulation.

2. Solve the mathematical model using the minimization of the restoration cost as the objective function and forcing the WCLS to be equal to the objective function obtained in step 1. The objective function and constraint to be used in the second step are illustrated in expressions O2 and R46, respectively.

$$Min \sum_{i \in R} \sum_{j \in R} \sum_{k \in H} \sum_{b \in N} \sum_{d \in N} X_{ij}^{k} B_{bdj} co_{bd}^{k}, \tag{O2}$$

$$\sum_{j \in Z} \gamma(f_j) W_j \leq S^*, \tag{R46}$$

where S^* is the optimal value of WCLS obtained in step 1.

Although restoration cost is minimized in the second step of this methodology, it should not be understood that the original model has become a multi-objective formulation. Even under this approach, the objective function of the formulation is primarily the WCLS. We emphasize on this point because it has important conceptual implications. In a multi-objective formulation, the objective functions compete with each other. In the humanitarian context, the WCLS represents human suffering while restoration cost represent money. Thus, WCLS should be the primary objective function and the restoration cost should not compete with it. This extension was not yet developed for the heuristic, only for the mathematical model.

This procedure was validated with the toy instance presented in Section 4.7. The solution of this instance using the original methodology is rewritten in table 6.1 for convenience of the reader.

Table 6.1: Solution obtain with the original methodology

		Restoration plan	
Restoration Machine	Restoration task	Route	Exploited tasks
1	3, 2	[0 - 3] ->1, 6, 7, 8, 9, 14	–
		[3 - 2] ->14, 19, 24	–
2	1, 6, 5	[0 - 1] ->1, 6, 7, 12, 17	–
		[1 - 6] ->18	–
		[6 - 5] ->18, 17, 22	1
3	4	[0 - 4] ->1, 6, 7, 8, 9, 14, 19	–
		Relief plan	
Vehicles	Zones	Route	Exploited tasks
1	2, 3	[0 -2] ->1, 6, 7, 8, 9, 10, 15, 20	–
		[2 -3] ->20, 19, 18, 17, 12, 7, 6, 1, 6, 7, 12, 17, 18, 19, 20	4, 1
2	4, 1	[0 -4] ->1, 6, 7, 8, 9, 10, 15, 20, 25	–
		[4 -1] ->25, 24, 19, 14, 9, 8, 7, 6, 1, 6, 7, 8, 9, 14, 15	3
3	5	[0 -5] ->1, 6, 7, 8, 9, 10, 15, 20, 25	–

By applying the lexicographic approach, we obtained the same WCLS that we obtained with the original methodology, but we also avoided the selection of tasks 2, 5 and 6, which are not exploited by any vehicle. This solution evidences how the lexicographic approach allows to keep the restoration cost as low as possible, while the WCLS is maintained in its minimum possible value.

Chapter 7

Study Case: 2010 - 2011 Mojana's Floods

To test the application of our products on data relevant to real world scenarios, we built a study case based on data from the Mojana's floods occurred in northern Colombia duri

Regional background

According to interviews with members of DAPARD, the processes carried out by restoration and relief organizations in Colombia for fast restoration of roads and relief, conducted just after the hit of a disaster, can be summarized in the following steps:

1. Collection of information: in this first step, two types of information are collected; i) general information, which is compiled by *Fuerza Area Colombiana* and member of *Police Department* and then is complemented by data captured from social networks; and ii) technical information, which is recollected by engineers and experts, most of them members of *Secretaría de Planeación*. For restoration purposes, the most part of information correspond to the state of the roads. In regard to the relief operation, the information is majorly oriented to features describing the state of the affected communities, such as the amount of population affected, critical victims, missing people and the degree of affectation of the community.

2. Damage assessment: once general and technical information has been collected, it is evaluated and debugged by experts, which determine the degree of affectation of roads. These experts also determine potential restoration times and the type of machinery required. Information about the condition of community is used to prioritize attention and establish the type of goods (food, medicines, clothes) required by the affected people. All this process is called *Evaluación De Daños y Análisis De Necesidades* (EDAN)

3. Decision-making: once the information has been collected and evaluated by experts, the resulting information is delivered to *Consejo Municipal para la Gestión de Desastre* (CMGD), which is the highest authority of each municipality in issues related to disaster management. This entity is responsible for decision making and coordination of all humanitarian logistics operations. If the situation is beyond the control of the municipality, the emergency is declared public calamity. By means of

this declaration, higher governmental authorities help to speed up the contracting process of organizations to be involved in restoration and relief operations. If the emergency is manageable by the CMGD, this entity makes the connections and establishes the contracts by itself.

4. Implementation of the rehabilitation process: in this step, the rehabilitation of roads is performed. Recall, the procedure described here is related to fast reestablishment of roads functionality. It does not correspond by no means with a total recovery process, where roads are restructured to a top functionality level.

Currently, according to the director of DAPARD, decisions on restoration are made empirically or based on experience. No formal methodologies or models are adopted in decision making by cited organizations in regard to road restoration of relief operations.

General context

Mojana is a geographic region belonging to Momposina depression in the northern Colombia. As a region surrounded by three major rivers (Cauca, San Jorge and Magdalena) and allocating more than 20 swamps, Mojana can be considered one of the major wet regions in Colombia. Unfortunately, this condition makes Mojana a highly vulnerable region to strong winter seasons experienced in tropical zones. Between the end of 2010 and the beginning of 2011, a streak of heavy rains stroke Mojana, causing Cauca river to overflow. As a result, the region became flooded, leaving more than a hundred thousand people in 8 municipalities literally living between water (see Figure 7.1).

Figure 7.1: Mojana's floods

To make matters worse, a total of 6 bridges located over the major road connecting all municipalities got partially or totally damaged, and multiple roads became damaged or flooded, causing major difficulties in the execution of relief operations. During the first part of response operations, a brigade of Red Cross Colombia used boats to reach the affected communities. As the water on roads started to drain and restoration tasks were completed, relief trucks were enabled to access some primarily isolated areas. The whole operation was coordinated from a port located a San-Marcos, a municipality located at western Mojana, which remained unaffected and connected by road to the outside of Mojana. More details and specific data is provided below.

Restoration process

Blocked roads: main road damages occurred in the inter-municipal road going from San Marcos to Majagual. Other important disruptions were placed in the entrances to some municipalities, leaving them deprived of access by road. Disruptions where mainly caused by fallen bridges, water puddles and large amount of debris carried on by the water and accumulated over segments of the road. Blocked sections are listed in Table 7.1. The Figure 7.2 shows the blocked roads, marked with a red tag.

Table 7.1: Road blockages in Mojana's floods

Section	Type of disruption
El azulito	Db
Los mosquitos	Db
Las pozas	Db
Limoncito	Db
Muddy section 1	Wpmd
Entrance to El Cauchal and Pacifueres	Wpmd
Caño rabón	Db
Entrance to La Sierpe	Wpmd
San Roque	Db

Db: Damaged bridge
Fr: Flooded road
Wpmd: Water puddles / mud / debris

Restoration machines: at the time of the flood, there was a set of machines working on a section of San Marcos-Majagual road. These restoration machines were used for the purpose of road restoration in the response phase. The team was composed of one bulldozer, one backhoe loader and one loader. All three machines were located at a point near las Palmitas, marked with an orange dot in Figure 7.2. Machines were allowed to overpass some blockages in the following ways: i) damaged bridges could be evaded by machines using ferries which carried them from extreme to extreme of the blockage; and ii) flooded roads were passable for machines due to their size and stability. These two alternatives allowed machines to move among some blockages with no restrictions on other damages that could be present in the way. Entrances to municipalities were only passable by repairing the road due to the great impediments to transit imposed by the large extent of mud.

Relief operation process

Affected population: as illustrated in Figure 7.2 all the affected municipalities were located on the surroundings of the San Marcos - Majagual road. The main humanitarian activity carried on during the response phase was the distribution of relief goods, including foods, toilet goods, water and medicines. As mentioned before, the port located in San Marcos was used as a depot and coordination center for this activity. From there,

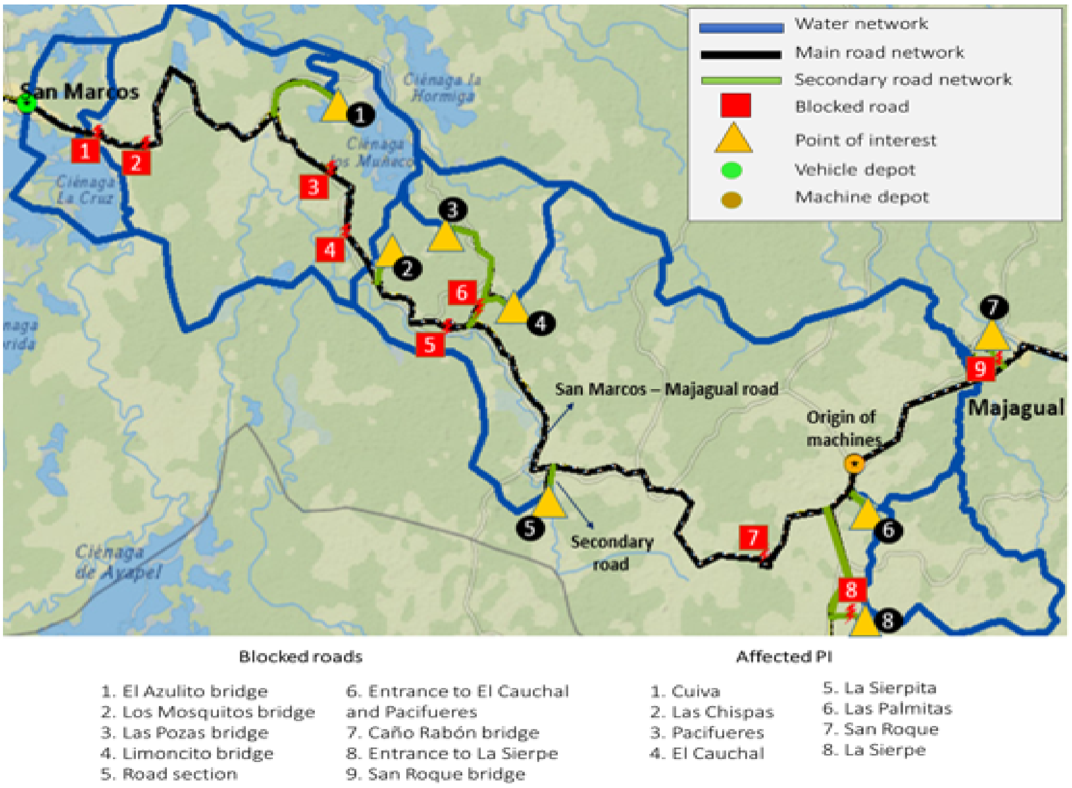


Figure 7.2: Mojana

resources were delivered to Cuiva, Las Chispas, Pacifueres, El Cauchal, Sierpita, Las Palmitas, San Roque, and La Sierpe. Each of these municipalities was mapped to a point of interest in our model.

In this study, the urgency index of all PIs was equally set on 1, due to the scarcity of information required for a proper estimation of custom urgency indexes. However, according to DAPARD, all municipalities were affected with a similar severity and thus, our assumption may not have drastic implications on results. In spite of the wide extension of response phase, which rounded six months, in this study case, we only consider operations performed in a first distribution stage, which accounted for 3 rounds of 2.902 emergency kits distributed among municipalities as follows: 450 kits to El Cauchal, 450 to Las chispas, 450 to Cuiva, 450 to Pasifueres, 201 to La sierpita, 201 to Las Palmitas, 201 to San Roque and 500 La sierpe. This accounts for a total of 8.706 kits considered in our study case. Instead of managing different types of kits, we assume a single unit load representing some combination of relief items.

Relief vehicles: products were carried to San Marcos Port by means of trucking rigs. Then, products were reshipped to PIs in smaller trucks and boats provided by Red Cross Colombia. Both, trucks and boats were used as relief vehicles in our study case. Naturally, we considered two independent networks for both types of vehicles. Details on the manage of networks are discussed later. Each time a boat released a load at a PI, it returned to San Marcos Port for replenishment and then departed to another PI. In spite of the small variations among trucks, capacity of each vehicle rounded 4.7 tons. By its side, boats had a capacity of 5.1 tons. Due to the structure of our model, we assumed a standard capacity of 5 tons for every vehicle.

We fixed the weight of each relief kit on 23 kg, based on standards provided by International Red Cross (Secretaría de Gestión de Riesgos y Organización Internacional para las Migraciones, 2009). Knowing this, the number of visits required by each PI was computed based on the following equation:

$$nv_i = \left\lceil \frac{nk_i * 23kg}{5000kg} \right\rceil \tag{7.1}$$

This operation resulted in a total of 54 visits to PIs distributed as follows: 9 visits to El Cauchal, 9 to Las chispas, 9 to Cuiva, 9 to Pasifueres, 3 to La sierpita, 3 to Las Palmitas, 3 to San Roque and 9 La sierpe. Each one of these 54 visits correspond to a single zone in our model.

Transit network

In order to represent possible displacements of each type of vehicle, we built a transit network composed o three sub-networks, each one for a specific type of vehicle; restoration machines, relief vehicles, and relief boats. Each sub-network presents particular travel times and adjacency matrices, based on the characteristics of each type of vehicle.

Networks were built based on the system of roads and waterways illustrated in Figure 7.2, in addition to an alternative road which offered a access to the most distant zones from the Port, implying a detour with an extension up to 6 times the length of San Marcos - Majagual major road. The whole network including the alternative road is presented in Figure 7.3. All three sub-networks are described below.

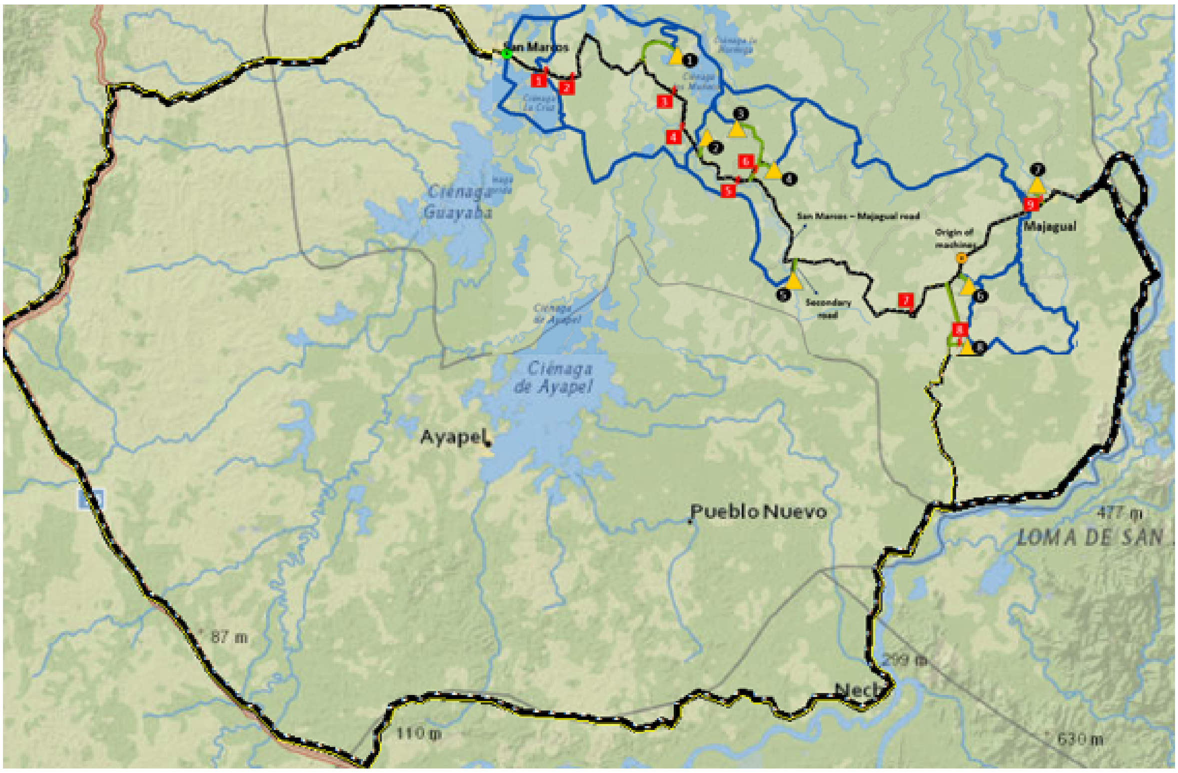


Figure 7.3: Mojana

Restoration network: as mentioned before, restoration machines are able to overpass damaged bridges by means of transfers in ferries. We represent a transfer on ferry as two links. The abstracted restoration network is illustrated in Figure 7.4.

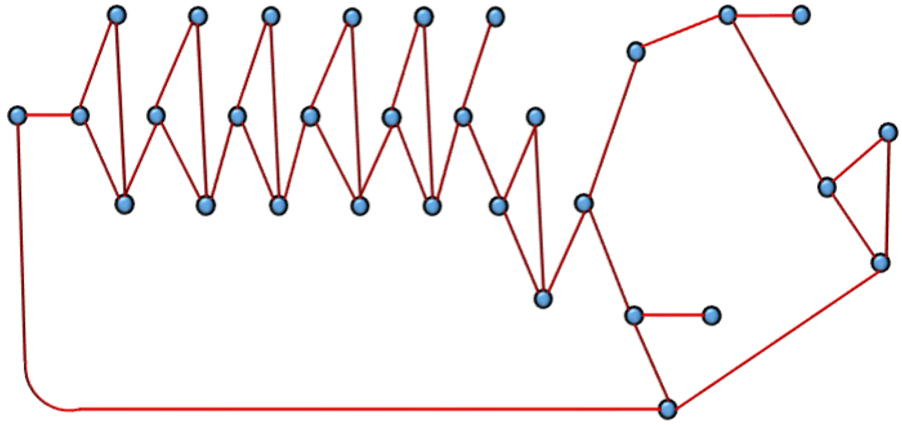


Figure 7.4: Restoration network

Trucks network: this network is naturally very similar to the restoration network, but they present two main differences: i) trucks are not able to overpass damaged bridges by ferry; and ii) restoration machines are never required to reach the PIs, and the entrance roads can be omitted for them. The abstracted trucks network is illustrated in Figure 7.5.

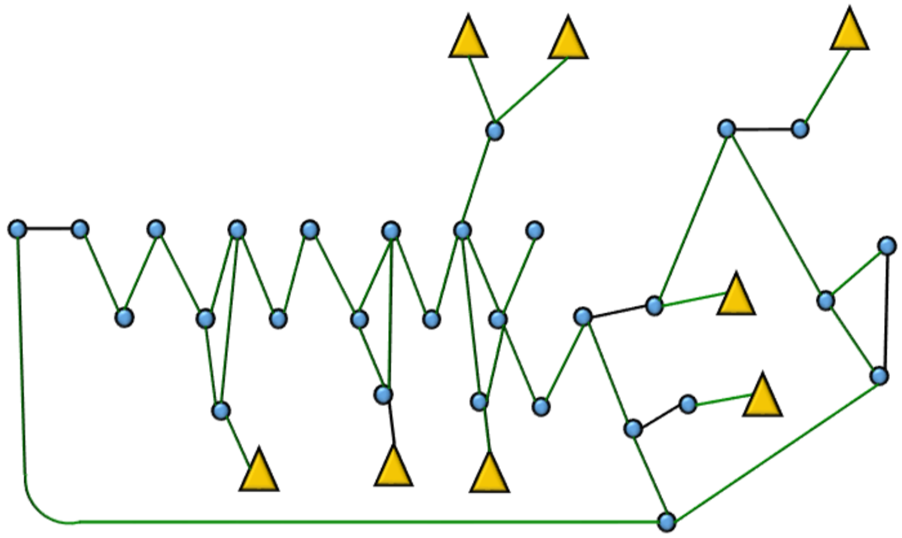


Figure 7.5: Trucks network

Boats network: boats are able to reach any PI. Nonetheless, travel times for boats are larger than for trucks with the network in regular functioning. The abstracted boats network is illustrated in Figure 7.6.

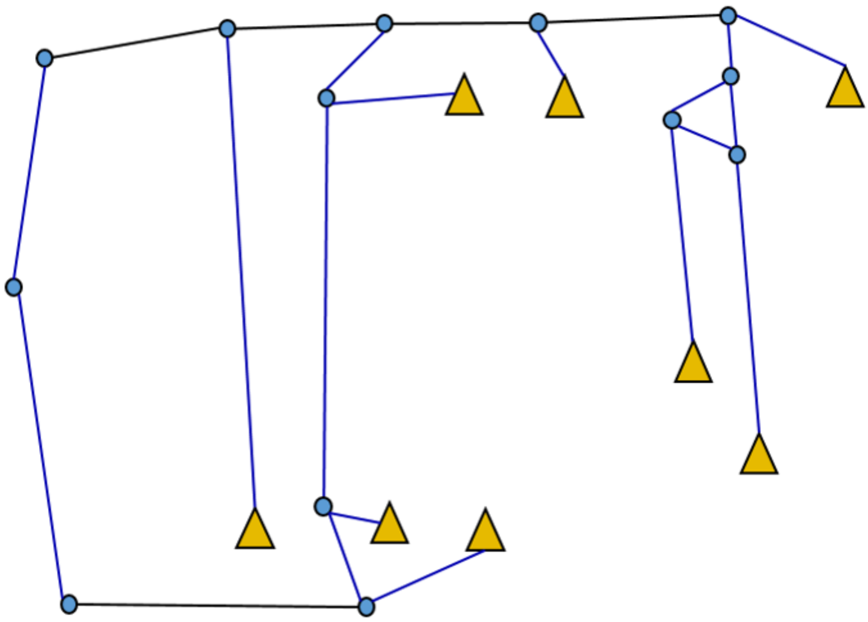


Figure 7.6: Boats network

Integrated network: all three networks are integrated in the whole transit network as shown in Figure 7.7.

Summary

The data set adopted for the Mojana study case is summarized in Table 7.2. Restoration times were sampled from a Gaussian distribution $N(6, 2)$, which corresponds to a reference time for building a provisional military bridge in Colombia. In order to compute travel times, all distances over the network were determined using ArcGIS 10.3. Then, those distances were divided by the speed corresponding to each type of vehicle, which in our study case were fixed on 19, 31 and 16 mph for machines, trucks and boats respectively.

Table 7.2: Parameters of study case

Parameter	Value	Parameter	Value
Restoration tasks	9	Boats	3
Points of Interest	8	Relief vehicles	5
Affected zones	54	Nodes	55
Restoration macines	3	Machine depot	Node 30
Trucks	2	Vehicle depot	Node 0

Results

The dataset provided above was used to perform two types of experiment: i) a comparison between CPLEX and HURRA on solution quality and processing time; and ii) the solution of the complete study case by means of our heuristic algorithm, HURRA. In the former experiment, we solved multiple instances derived from the study case, but considering

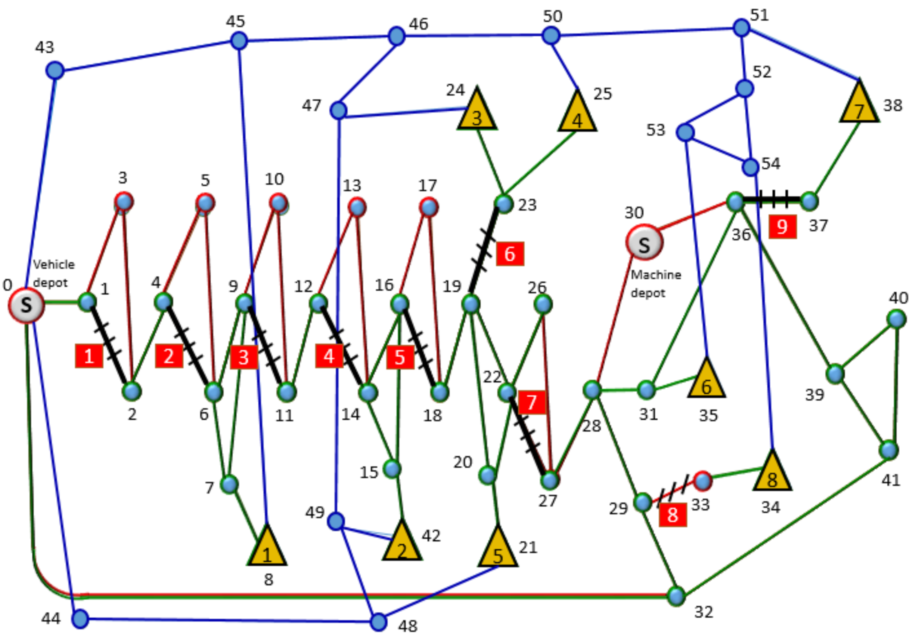


Figure 7.7: All networks

only a subset of the original pull of restoration tasks and zones. Specifically, we started the experiment with 6 and fixed the amount of restoration tasks in 4. The amount of zones was upgraded until CPLEX exceeded the runtime limit of 12 hours. For the second experiment, we validated the usability of HURRA for real world scenarios.

CPLEX vs HURRA In addition to comparing the performance of both methods, this experiment was performed to provide some insights on potential politics that could be implemented to decide when to use each solution method. In this first type of experiment, HURRA was solved using 20 ants and as stopping conditions we used: i) a runtime of 12 hours; ii) a runtime equal to CPLEX runtime; and ii) maximum 5 colonies without improvement.

Table 7.3: Results on small versions of Mojana

n	z	CPLEX		HURRA	
		Objective	Runtime	Objective	Runtime
4	6	1759	30	1759	28
4	7	1685	660	1685	60
4	8	1821	5700	1826	102
4	9	2560	420	2560	222
4	10	2891	43200 *	2888	235

* Time limit of 12 h exceeded
Runtime in seconds

Results from this experiment are provided in Table 7.3. In all the five instances, HURRA was able to reach convergence before CPLEX did. In fact, the stopping condition activated for HURRA was always the maximum number of colonies without improvement.

These results coincide with results from Chapter 5. By the side of solution quality, it can be concluded that both solution methods are able to deliver pretty similar results within the runtime limit of 12 hours. In 3 of the 5 instances, both algorithms found the optimum. On the other 2 instances results differed for less than 0.3%.

With regard to possible politics that could be adopted, we may conclude that keeping all the other factors constant, the application of the model when solved to optimality is limited to 9 zones. Thereon, HURRA would provide relatively high quality results in much less processing time.

HURRA solving complete study case For this second experiment, we only used the HURRA to solve the complete study case as specified in Table 7.2. In this case, we run HURRA with 25 ants and generated colonies until one of the following stopping conditions was meet: i) the runtime limit of 12 hours was reached; and ii) maximum 10 colonies without improvement.

In this experiment, HURRA converged and stopped after 19 minutes running and 10 colonies without improvement. The tasks proposed to be restored were 1, 2, 3, 4, 5 and 8. At the beginning of the operation, major road was blocked to trucks due to floods. As a consequence, the model assigned boats to assist the closer PIs (1, 2, 3) and sent the trucks by the alternative road to assist PI 5. PIs 4 and 8 were totally attended by boats in restoration windows 2, 4, 6, 7. The heuristic noted that vehicles were unable were very limited at the beginning to access other zones than the sixth, which was not blocked, and decided to meet the whole demand of such PI with vehicles. By their side, restoration machines persistently worked on the restoration of tasks 1, 2, 3, 4 and 5, providing access to PIs 1, 2 and 5. Once the water drained from the major road, trucks started assisting PIs 1, 2 and 5. An interesting fact is that the heuristic decided to execute those restoration tasks, closest to the port, allowing vehicles to exploit those roads immediately after the road became drained. Results are illustrated in Figures 7.8 - 7.15., where we marked those links that supported flow from each type of vehicle on each time window. The full solution is provided in Tables 7.4 - 7.9. From these results, we can conclude that proposed methodology allows to deliver a complete schedule for both types of relief vehicles and effectively coordinates them with restoration machines for a fast assistance of communities during disaster response phase. This study case, which may be hard to solve for a human without decision support, was solved by HURRA in only 19 minutes, corresponding to less than 2.6% of the time limit suggested by DAPARD.

Table 7.4: Case study - solution for machines

Restoration machine	Restoration task	[O - D]	Route	Exploited tasks
1	3, 4	[0 - 3]	[30, 28, 27, 26, 22, 19, 18, 17, 16, 14, 13, 12, 11, 10, 9]	–
		[3 - 4]	[11, 12]	–
2	5, 8	[0 - 5]	[30, 28, 27, 26, 22, 19, 18, 17, 16]	–
		[5 -8]	[18, 19,,22, 26, 27, 28, 29]	–
3	2, 1	[0 -2]	[30, 28,,27, 26, 22, 19, 18, 17, 16, 14, 13, 12, 11, 10, 9, 6]	–
		[2 -1]	[4, 2, 3,,1]	–
4*	10*	[0 -5]	[30, 0]	–

* Fictitious machine

Table 7.5: Case study - Solution for Truck 1

PI	Rutas	Tareas Aprovechadas
6, 6, 8	[0 - 6] → [0, 32, 29, 28, 31, 35]	–
	[6 - 6] → [35, 31, 28, 29, 32, 0, 0, 32, 29, 28, 31, 35]	–
	[6 - 8] → [35, 31, 28, 29, 32, 0, 0, 32, 29, 33, 34]	8

In order to evaluate the restoration plan in consistency and quality, we condensed the shortest paths from source to each PI, on each restoration window, using any of the two types of restoration vehicles (trucks or boats). This data is shown in Table 7.10. As can be seen, tree up to eight shortest paths were released by the restoration plan delivered by HURRA. At a first glance, results might not seem great, since 3 up to 8 is only the 37.5% of the shortest paths, and they were released just in the last restoration window. However, the explanation of this result underlies on the existence of the special disruption which became naturally removed at the end of window 6. This fact not only explains why the routes were not improved before, but also evidences a smart restoration plan, since those three PIs whose shortest path was repaired, are all located near the port and

Table 7.6: Case study - Solution for Truck 2

PI	Rutas	Tareas Aprovechadas
6, 2, 2, 5, 5, 1	[0 - 6] → [0, 32, 29, 28, 31, 35]	–
	[6 - 2] → [35, 31, 28, 29, 32, 0, 0, 1, 2, 4, 6, 7, 9, 11, 12, 14, 15, 42]	**1, 2, 3, 4, 10**
	[2 - 2] → [42, 15, 14, 12, 11, 9, 7, 6, 4, 2, 1, 0, 0, 1, 2, 4, 6, 7, 9, 11, 12, 14, 15, 42]	**1, 2, 3, 4, 10**
	[2 - 5] → [42, 15, 14, 12, 11, 9, 7, 6, 4, 2, 1, 0, 0, 1, 2, 4, 6, 7, 9, 11, 12, 14, 15, 16, 18, 19, 20, 21]	**1, 2, 3, 4, 10**
	[5 - 5] → [21, 20, 19, 18, 16, 15, 14, 12, 11, 9, 7, 6, 4, 2, 1, 0, 0, 1, 2, 4, 6, 7, 9, 11, 12, 14, 15, 16, 18, 19, 20, 21]	**1, 2, 3, 4, 10**
	[5 - 1] → [21, 20, 19, 18, 16, 15, 14, 12, 11, 9, 7, 6, 4, 2, 1, 0, 0, 1, 2, 4, 6, 7, 8]	**1, 2, 3, 4, 10**

Table 7.7: Case study - Solution for Boat 1

PI	Rutas	Tareas Aprovechadas
3, 3, 1, 3, 2, 3, 2, 1, 4, 8, 1, 2, 3, 1, 8, 3, 7	[0 - 3] → [0, 44, 48, 49, 47, 24]	NA
	[3 - 3] → [24, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 1] → [24, 47, 49, 48, 44, 0, 0, 43, 45, 8]	NA
	[1 - 3] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 2] → [24, 47, 49, 48, 44, 0, 0, 44, 48, 49, 42]	NA
	[2 -3] → [42, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[3- 2] → [24, 47, 49, 48, 44, 0, 0, 44, 48, 49, 42]	NA
	[2 - 1] → [42, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[1 - 4] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 8] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 1] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 43, 45, 8]	NA
	[1 - 2] → [8, 45, 43, 0, 0, 44, 48, 49, 42]	NA
	[2 - 3] → [42, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 1] → [24, 47, 49, 48, 44, 0, 0, 43, 45, 8]	NA
	[1 - 8] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 3] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 7] → [24, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 38]	NA

Table 7.8: Case study - Solution for Boat 2

PI	Rutas	Tareas Aprovechadas
2, 2, 2, 1, 4, 8, 4, 8, 3, 1, 8, 7, 7, 4	[0 - 2] → [0, 44, 48, 49, 42]	NA
	[2 - 2] → [42, 49, 48, 44, 0, 0, 44, 48, 49, 42]	NA
	[2 - 2] → [42, 49, 48, 44, 0, 0, 44, 48, 49, 42]	NA
	[2 - 1] → [42, 49, 48, 44, 0, 0, 43, 45, 8]	NA
	[1 - 4] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 8] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 4] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 8] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 3] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 1] → [24, 47, 49, 48, 44, 0, 0, 43, 45, 8]	NA
	[1 - 8] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 7] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 38]	NA
	[7 - 7] → [38, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 38]	NA
	[7 - 4] → [38, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA

thus, such restorations were exploited by the trucks immediately after water got drained from roads.

Table 7.9: Case study - Solution for Boat 3

PI	Rutas	Tareas Aprovechadas
1, 3, 4, 4, 1, 8, 3, 2, 4, 8, 4, 5, 4, 8	[0 - 1] → [0, 43, 45, 8]	NA
	[1 - 3] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 4] → [24, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 4] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 1] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 43, 45, 8]	NA
	[1 - 8] → [8, 45, 43, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 3] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 24]	NA
	[3 - 2] → [24, 47, 49, 48, 44, 0, 0, 44, 48, 49, 42]	NA
	[2 - 4] → [42, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 8] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA
	[8 - 4] → [34, 54, 53, 52, 51, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 5] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 21]	NA
	[5 - 4] → [21, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 25]	NA
	[4 - 8] → [25, 50, 46, 47, 49, 48, 44, 0, 0, 44, 48, 49, 47, 46, 50, 51, 52, 53, 54, 34]	NA

Table 7.10: Shortest paths by window

PI	Pre-disaster	Post-disaster W1	Post-disaster W2	Post-disaster W3	Post-disaster W4	Post-disaster W5	Post-disaster W6	Post-disaster W7
1	23,15	146,03	146,03	146,03	146,03	146,03	146,03	23,15
2	29,68	194,48	194,48	194,48	194,48	194,48	194,48	29,68
3	42,18	235,90	235,90	235,90	235,90	235,90	235,90	235,90
4	38,70	324,20	324,20	324,20	324,20	324,20	324,20	324,20
5	47,51	275,60	275,60	275,60	275,60	275,60	275,60	47,51
6	67,39	527,56	527,56	527,56	527,56	527,56	527,56	527,56
7	77,51	456,86	456,86	456,86	456,86	456,86	456,86	456,86
8	73,41	567,00	567,00	567,00	567,00	567,00	567,00	567,00

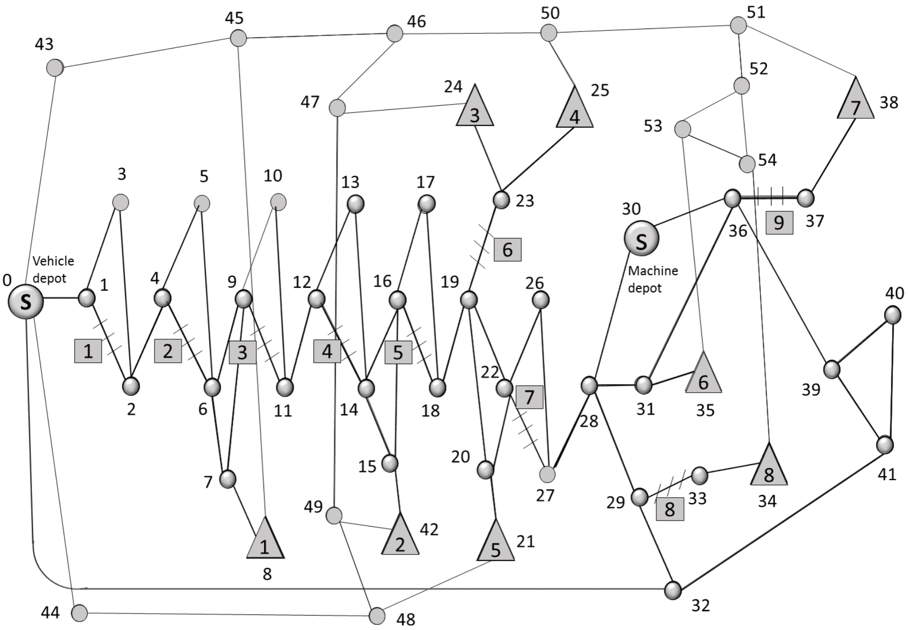


Figure 7.8: Original network

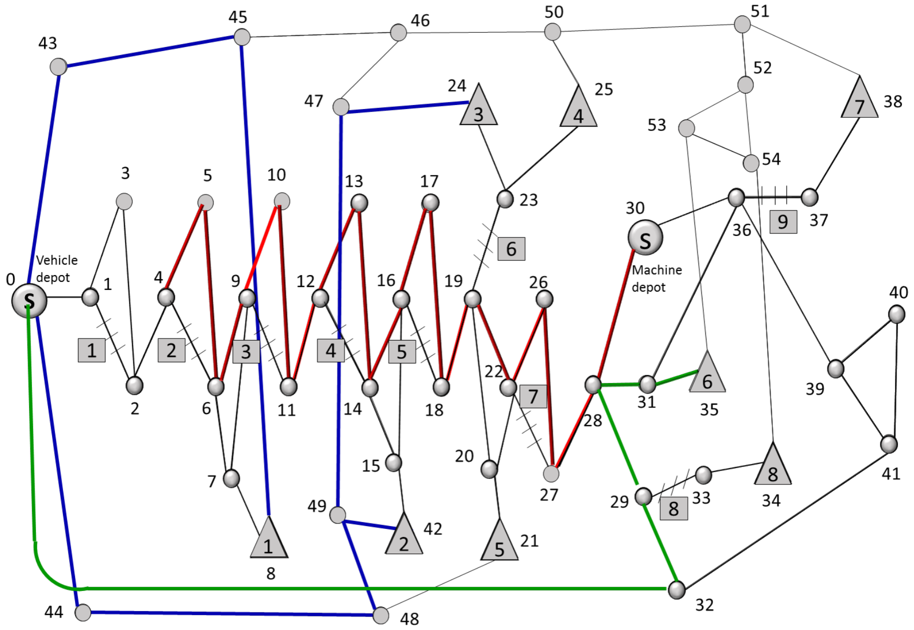


Figure 7.9: Restoration window 1

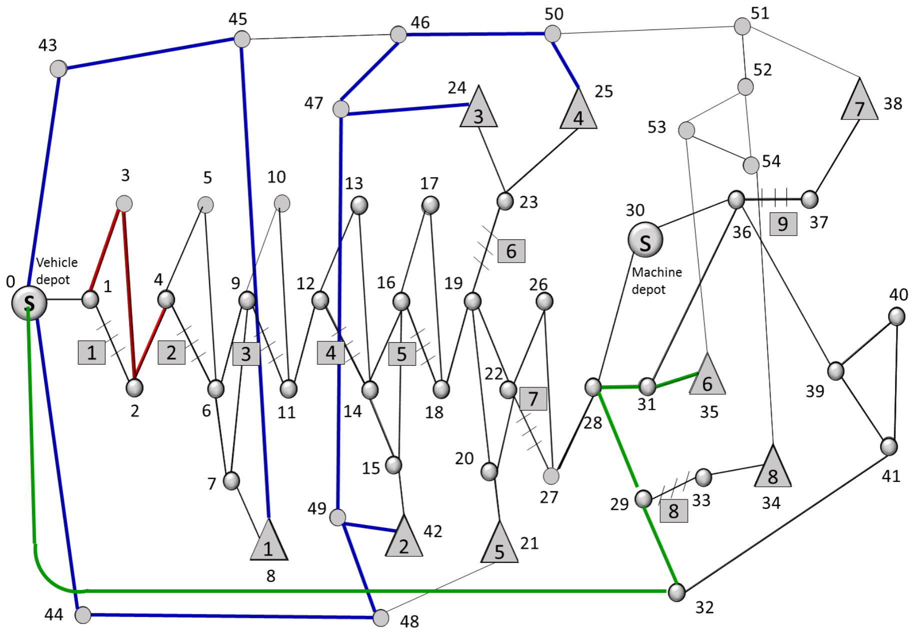


Figure 7.10: Restoration window 2

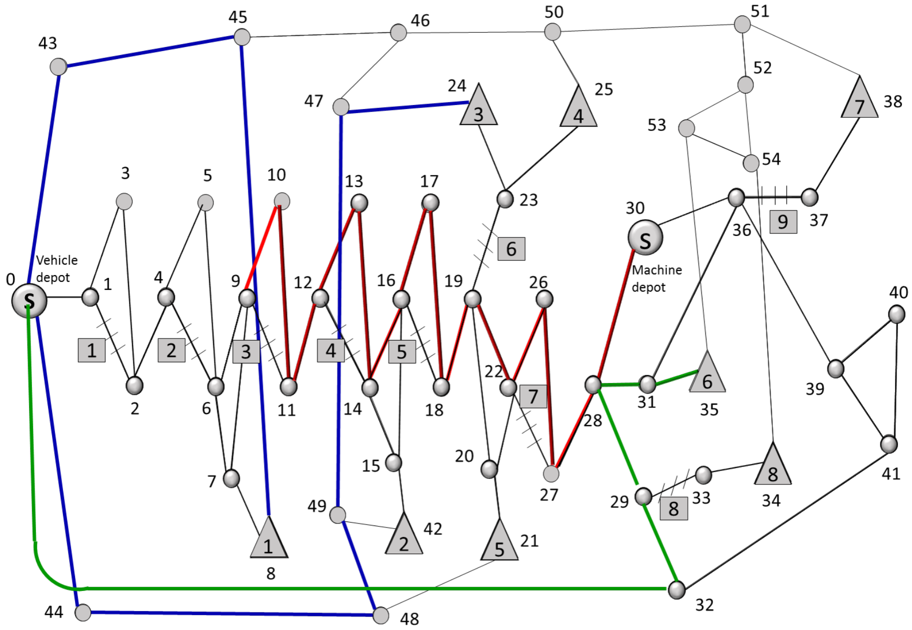


Figure 7.11: Restoration window 3

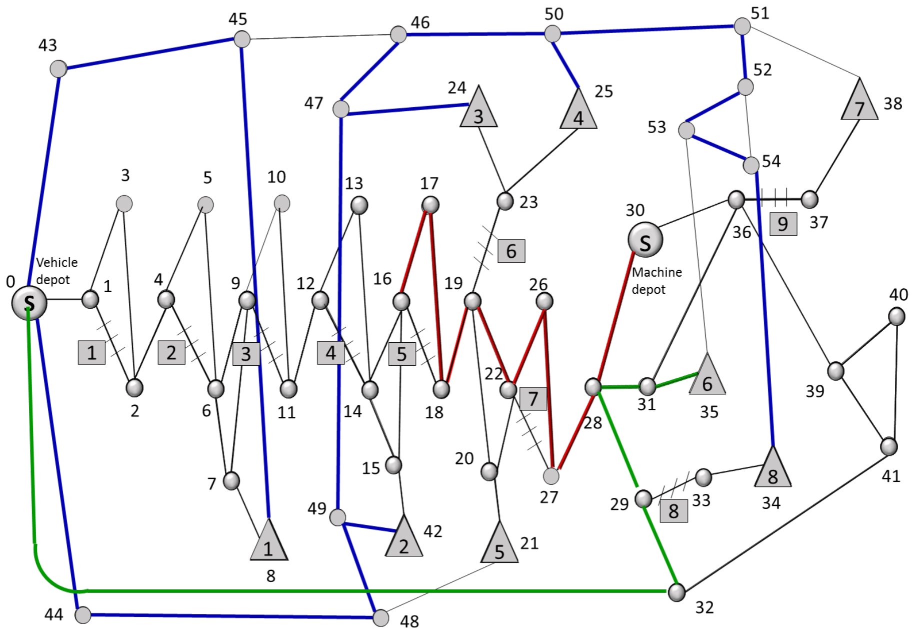


Figure 7.12: Restoration window 4

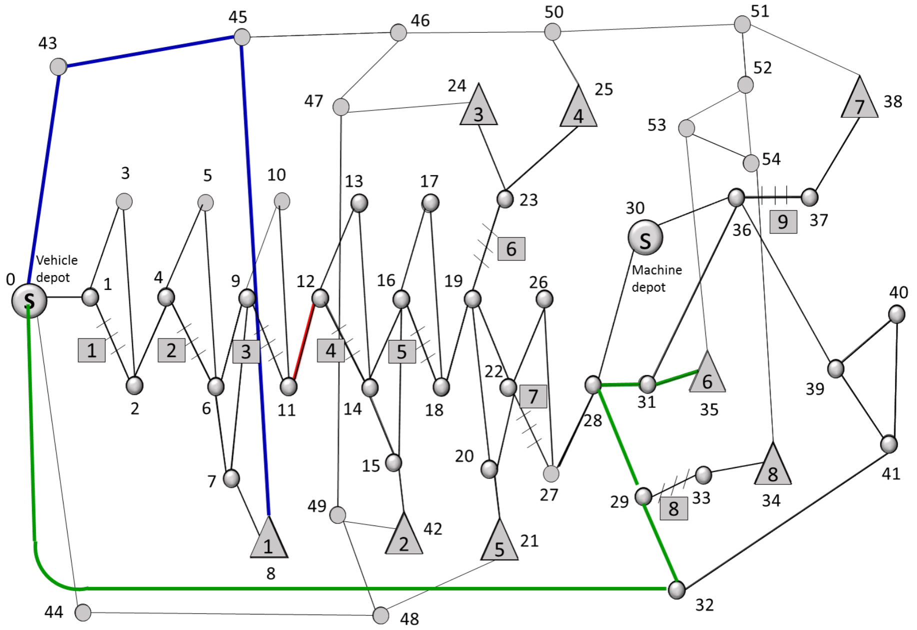


Figure 7.13: Restoration window 5

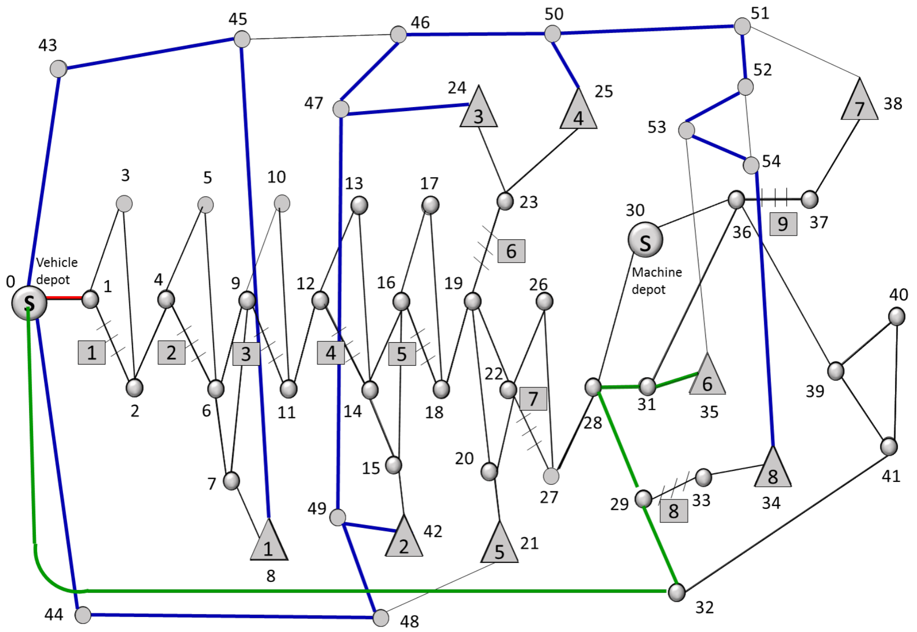


Figure 7.14: Restoration window 6

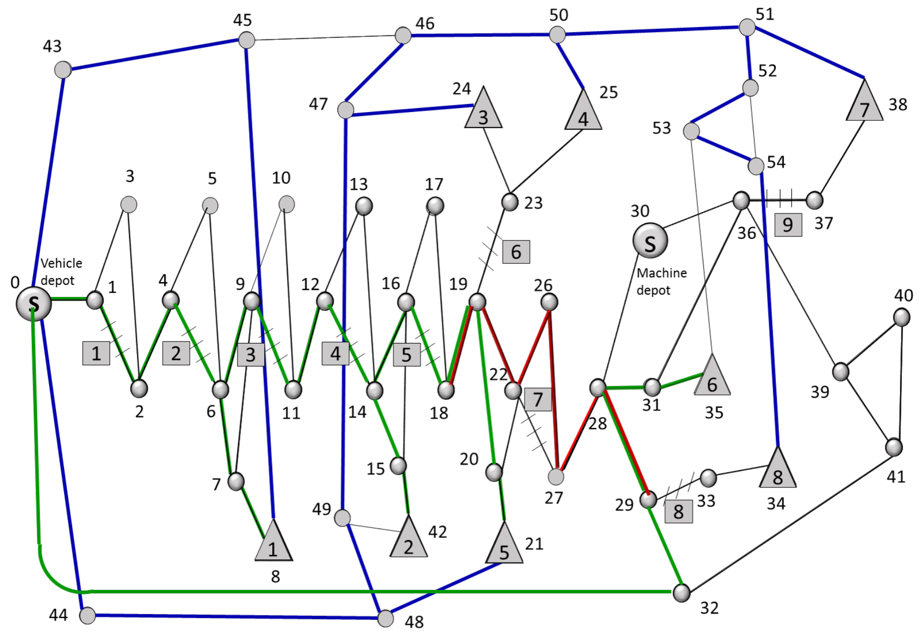


Figure 7.15: Restoration window 7

Chapter 8

Conclusions and Future Research

In this study we tackled the *Humanitarian Road Restoration Problem - Partial integrated in Parallel* (HURREP-2P) under a mathematical approach. We provided a mathematical optimization model and an heuristic algorithm, as alternative methods for solving the problem under study. Both methods are able to provide a combined road network restoration and relief plan oriented to the response phase of disaster management. Such a plan includes the schedule for restoration activities and visits to affected communities as well as the routing plan for restoration machines and relief vehicles.

Multiple gaps in the HURREP-2P literature were fulfilled in this thesis: 1. our model is one of the few that provide the routing plan for the restoration machines; 2. it is also one of the few that provide the schedule for restoration machines; 3. our model is the first in the literature dealing with heterogeneous disruptions/machines; and 4. our model is the first one in the literature working on a continuous framework with no impositions on the time horizon for operations.

Moreover, our model contributes to the development of HURREP-2P, which is one of the less studies problems in the HURREP literature.

Both, our model and heuristic were validated on diverse scenarios in order to prove their consistency, get insights about usage policies and validate their usability on real world cases. Based on results, we conclude that both methods provide solutions for the HURREP-2P which smartly coordinate restoration and relief operations to opportunely assist the affected communities. We found limitations on the mathematical model for solving moderately large size instances. An expected result, based on the complexity of the problem and the integer structure of the formulation. However, in the disaster management context, any effort for ensuring a better result, translates on saved lives and justifies further work on the improvement of the formulation and its exact solution method to ensure its usability on larger instances. For this purpose, the adoption of disjunctive constraints and the pre-computation of heuristically fixed gaps that could speed up the cutting process in CPLEX, are some interesting alternatives to test.

The validation of our methods using the real world study case of Mojana's floods (2010-11) allowed us to identify special features which our model and algorithm are able to consider: first of all, our model is able to deal with multiple modes of transport working in parallel for relief operation. In spite of the great advantage of modeling multiple modes, our model does not allow multimodal transactions. Such an extension is proposed for further development. Secondly, our model is able to simulate disruptions that naturally get removed such as water puddles that get drained or evaporated in a period of hours to days. Thirdly our model is able to consider vehicle-dependent starting times. This feature is very common in reality and thus, represents an strength of our model. None of those three special features were considered by any other study on HURREP-2P literature. Moreover, first two features (multiple modes of transport and disruptions that naturally get removed) are not considered in any previous study in the broad HURREP literature.

Currently in Colombia, restoration decisions are made empirically and based on experience that could have good results in some cases and poor results in others. Our methodology provides a formal criterion for deciding how to proceed in the road restoration process during response phase. Our methods were proved to be easily extendable to different peculiarities that may arise in real life.

Far from theoretically, the problem addressed here arises on thousands of unfortunate events that occur each year. In this thesis, we validated the applicability of our methods for real world cases with the regional case study of Mojana's Floods. The development of this study case was consistently supported by members of the Administrative Department for Prevention, Attention and Recovery from Disasters in Antioquia Colombia (DAPARD). Their advisory allowed us to keep a continuous path of improvement during the execution of this thesis, which ended on a mathematical model with very realistic assumptions. It is our sincere hope that our developments will contribute to the improvement of Disaster Management and will inspire other researchers and newcomers to the field, to develop work in order to fill research gaps that may still be present in the literature.

Achieved Results and Products

Research articles:

- *Integrating road network restoration and disaster relief operations during response phase.* Academic article exposing our methodology and results.

Conference speeches:

- *Evacuación de una Población Considerando Interrupciones en la Red Vehicular.* Conferencia en Logistica Social LS 2016 - Universidad del Norte, Barranquilla, Colombia.

- *Evacuation of a Population Considering Network Disruptions.* INFORMS International Conference 2016 - Hawaii, USA.

- *Integrating road network restoration and disaster relief operations during response phase.* POMS 28th Annual Conference 2017 - Seattle, USA.

Future Research Lines

For near future development, we propose the following research avenues:

On the problem setting and assumptions

Limited capacity on roads In real life, roads are able to allocate a fixed number of vehicles per unit of time. Our formulation assumed that such a number is infinity. In order to prevent excessive congestion on the network, that could have a negative impact on the execution of relief operations, we propose the incorporation of capacity constraints on the formulation as a further extension of this research.

Restoration tasks requiring multiple machines In many practical cases, restoration tasks may require the joint action of multiple machines working as a team. Such a feature should be integrated to the model in order to enhance its potential application in real life.

Programmed delays between visits to zones In real operations, visits to zones are not necessarily performed once after the other. In fact, operations such as distribution of relief goods are often performed on a periodic fashion, adopting programmed delays between deliveries. Future research may consider enforcing programmed delays in the formulation.

Multiple humanitarian operations performing in parallel The attention of disasters often involve multiple relief operations which are conducted simultaneously. This is the case of search and rescue, evacuations, relief goods distribution and sheltering. In the present study, we do not explicitly account for multiple operations occurring simultaneously. Such an extension is proposed as future research.

Exponential deprivation cost In this thesis, our purpose was to improve the way of coordinating road restoration and relief operation so that the restoration plan generates the best possible results to relief plan. With this in mind, we worked with a linear deprivation function as our objective function, which is simpler to manage than the exponential function suggested by Pérez-Rodríguez and Holguín-Veras (2015). However, the exponential function tends to describe well the effect of deprivation on peoples condition as a function of time, based on the discussion offered in the cited study. As a natural future development, we suggest the extension of our methods to account for exponential deprivation costs.

On the heuristic

Budget constraint and restoration costs In Section 6, we described a methodology to incorporate budget limitations and restoration costs in our mathematical model. The adoption of such extensions into our heuristic, requires a deeper study, which is proposed as a future research avenue.

On the solution methods

Local improvement in heuristic Local improvement methods such as K-opt have been proved to be promising alternatives to enhance the solution of heuristic algorithms or speed up the convergence in various combinatorial optimization problems. Our heuristic performed quite well during our experiments, being able to solve a real world case in less than 20 minutes. However, we are not able to warranty if such solution was optimum. As long as we have such uncertainty, it could be worth it to make efforts in enhanced the power of our algorithm (i.e., making it faster or capable of reaching better solutions). In this regard, we propose the incorporation of local improvement heuristics to our algorithm as a future research line.

On the model

Adoption of disjunctive constraint pairs The MILP developed in Chapter 4 was effectively solved during our experiments. Nonetheless, the processing time was clearly prohibitive for big instances of our problem. It is well known that the number of integer variables in a mathematical programming model has a great impact on the processing time. The adoption of disjunctive constraint pairs would help to reduce the number of integer variables of our formulation, enabling its application on larger instances than those tested here.

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