Development of an Emergency-Response System

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Introduction

The Hypothetical Electric Company (HECO) is a coastal power company that must deal with emergency power outages from time to time. In the past, HECO has been criticized for its lack of a prioritization scheme in handling emergency outage calls. As a result, our team has been hired to provide HECO with a technical plan for defining what objective criteria should be used in assessing emergency calls and using this information to schedule the required power-restoration work. While data from a particular storm (Hurricane Jane) were provided, we will provide a model broad enough to serve in many emergency situations.

We considered the following criteria:

- immediate response to emergency calls (hospitals and commuter railroads),
- minimization of overtime hours,
- minimization of travel time, and
- minimization of the number of people waiting for service at any time.

We developed a flexible model that uses the first, third, and fourth criteria and processed scenarios with varying overtime limitations. In our judgment, the best scenario for the given data and our assumptions uses each crew for 16 hrs/day. All emergency calls were finished in 8 hrs 10 min of the first call of this type. A total of 595 regular hours and 525 overtime hours were used, and 358 hours were spent driving. The final call was completed after 58 hrs, at a cost of $21,800.

Once all factors have been converted into an equivalent number of people affected, every job becomes quantitatively weighted. Combining this prioritization with localized considerations of distance and repair time results in an optimal dispatching algorithm. This model and the program designed to facilitate its application are adjustable to changing prioritization and to individual company objectives.

Clarification of the Problem

The first issue is the qualitative nature of the information provided by an emergency report. The problem requires a quantification of these data which will allow the dispatcher to weigh objectively, for example, a large number of people affected only a short while against a handful of workers who might wait for a long period of time. Additional data at the time of the report, as well as an understanding of city management, may help in this quantification.

The problem is formidable, because of the number of factors involved at every stage of the scheduling and decision-making process. Crew work times, including overtime considerations, must be weighed. Thus, an efficient utilization of all available crews is required. Distance to and between work sites is a large factor, since driving time consumes potential work time. However, the prioritization of outage sites clearly distinguishes this problem from a basic time-optimization problem. We concluded that an efficient, workable prioritization scheme is the primary goal, with cost vs. time being a secondary consideration to be determined by the company's desire and ability to sacrifice monetary savings for time of completion.

Assumptions Given

- The prioritization scheme required by HECO is for use during emergency situations only; HECO scheduling for routine days is not under consideration.
- By HECO policy, no work may be initiated until the storm leaves the area, with the exception of that required by a hospital or commuter railroad.
- The region serviced by HECO is metropolitan, and an excellent road network is available.
- Dispatch locations are at $(0,0)$ and $(40,40)$ for the HECO service area within $-65 < x < 65$ and $-50 < y < 50$.
- Crews are required to report to dispatch sites only at the beginning and end of each shift.
- Only one crew is scheduled for duty at any time, with the implication that, during an emergency, crews that find themselves not immediately needed may go off duty.

- Each crew consists of three trained workers; six crews are available at each dispatch location.
- Crews work 8-hr shifts, can work only one overtime shift in a work day, and receive time-and-a-half for overtime.

Additional Assumptions

- Crews are available immediately upon request at the dispatch location.
- Crews must return to the same dispatch location from which they started and are uniquely assigned to that dispatch location.
- All distances are measured rectilinearly.
- Crews travel at an average speed of 30 mph between work sites.
- Crew trucks do not break down.
- A power outage maintains its original severity even when fractional parts of the work have been completed.

Assumptions Concerning Parameters

- All estimates given for unknown "# Affected" entries in **Table 1** of the problem statement are taken from averages of calls of a similar type. In the cases of "Government (city hall)" and "Government (traffic lights)," no calls of a similar type were available. Therefore, we specified 0 as the number affected.
- All estimates given for unknown "Estimated Repair Time" entries are taken from the average of all calls recorded from 4:30 A.M. to 11:30 A.M.

Background: Existing Models

The first stage in our analysis of HECO's emergency-response system was a survey of existing networking, minimizing, and prioritizing models. We did not find a precise existing model for such emergency-response networks; however, we outline the following four categories to clarify the pros and cons of applying elements of these models to the problem at hand.

Graph Theory

Graph theory provides a variety of models and optimization algorithms and is most heavily drawn upon in our model. The most relevant models are those beginning with a connected graph (all worksites are connected by roads to other worksites). Notice that the HECO model, as a continuously changing system, will require a graph that is updated continuously (or quasicontinuously, as there is not a decision to be made at every point in time). Distance, time, priority weightings, or a combination of these may be placed as weights upon the edges of the graph. Note that values that are inversely related, such as distance and time, will have to be adjusted to contribute in the same direction to the weight of an edge. Then a variety of minimal-spanning-tree algorithms may be applied to minimize the total time (waiting time, cost, etc.) required.

Prim's algorithm and Kruskal's algorithm [Jackson and Thoro 1990, 191–193], yield minimal spanning *trees*. The crews must return to the dispatch centers at the end of each shift, so a minimal spanning *cycle* would be more appropriate. Dijkstra's algorithm [Skvarcius and Robinson 1986, 231–233] utilizes a weight matrix and, since it provides a minimal path between two vertices, may be used to provide a minimal path from a point back to itself. However, this algorithm requires the consideration of every possible vertex in comparison to all others and would only be capable of calculating one path at a time. The key elements of graph theory minimization which are retained in our HECO model are:

- Weighting of paths on a graph provides a quick reference for minimization.
- Minimal path algorithms utilizing these weights are localized algorithms. In other words, from any vertex the next step in a minimal path may be found by minimizing that step.

The Critical Path Method (CPM)

The critical path method is an algorithm suited to large projects in which some activities may be pursued concurrently while others are dependent upon completion of particular predecessors. It is used primarily when a priority of completion is required and a deadline is set for completion of all activities. Notice that the prioritization required in the HECO response system may be thought of as a system of prerequisites, in which high-priority calls are required to be completed before low-priority calls. Thus, we may have a network as shown in **Figure 1**.

The CPM algorithm then uses this ordering and interdependence, along with time requisites for each task, and produces three variables of importance:

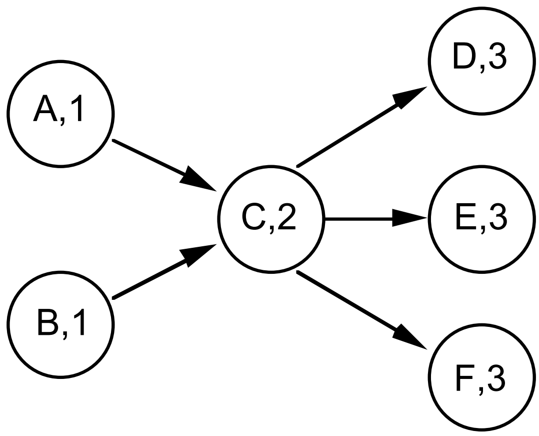

Figure 1. Network of jobs A, ..., F, each of priority 1, 2, or 3.

- The earliest time of completion $e(x)$ for each job x. In the **Figure 1**, if A requires 3 hours and B requires 2 hours, then $e(\text{C}) = 3$, the time when all level-1 jobs are completed so that level-2 jobs may be started.
- The latest event time $l(x)$ for starting job x and still completing the entire project on schedule.
- Float time, $f(x) = l(x) - e(x)$, a range during which a job may be begun.

These three numbers are utilized by CPM to provide an efficient schedule [Minieka 1978, 319–330]. Notice that $l(x)$ requires an explicit deadline. Although it would be feasible to develop a deadline by which all repairs may be expected to be finished, we assume that HECO will wish to complete the entire project in minimal time. The following elements may be applied to the HECO model:

- Tasks of high priority may be considered prerequisites to those of lower priorities.
- A range of time (modeled after float time) may be useful in calculating whether a specific crew should or should not assume a job. Notice that crews themselves have deadlines, specifically the ends of their regular or overtime shifts.

Hypercube Queuing Model (HQM)

The Hypercube Queueing Model [Larson 1978], developed primarily to aid police dispatching, in many ways resembles the HECO model. HQM uses data on time of travel and service times. Mobile response units, whose locations are known at all times, are available to respond to calls. One unit is required per call. However, the model also requires that travel time be insignificant compared to service time, which is highly unrealistic for HECO, as HECO's service area comprises 13,000 square miles. Also, police patrol is essentially different, too, since patrols are required during no-call times. HQM breaks its service areas into small units and groups them into subunits based upon statistics of prediction for calls. Also, HQM cannot remove calls from a queue in any prioritizing manner nor interrupt any en-route or busy crew, and Larson [1978, 6] suggests that "If the system planner wishes to analyze these types of operation ..., he should probably use a simulation model." Thus, for HECO we find the following.

- A useful means of tracking the status of units is with an array $(p_1, \ldots, p_n)$, where p_i encodes the status of unit i. A status of "in transit" may be useful.
- A simulation model may be useful in analyzing a queue in which items are to be removed and assigned based on a preemptive priority system.

Queuing Theory

Queueing theory provides many algorithms for analyzing a queue, based primarily on average rates as calculated, for example, by the Poisson formula for probability of an occurrence over continuous time. An algorithm of this type is (Mi/Gi/1):(NPRP/∞/∞), which calculates expected waiting times for a customer in a system and an individual queue, as well as the expected number of customers in the system or queue at a given time [Taha 1987, 633].

But note that these are algorithms that *predict* solutions that may be useful to HECO should it decide, for example, to relocate a dispatch center or to predict the number of crews that will be needed during a stormy season. What is required at the moment, however, is a more immediate and less statistical system for dispatching calls as they are received.

Analysis of the Problem

In analyzing the need for a prioritization scheme for use by HECO during emergency power restoration, we determined that the following goals are the most important:

- Immediate response to crucial outages (hospital and commuter railroads).
- Minimization of overtime hours, as a cost-saving strategy.
- Minimization of travel time between worksites, as a cost- and time-saving strategy.

- Minimization of the time that facilities must wait for repairs, counted from the time an outage is reported.
- Minimization of the number of people waiting for repairs at any time.

Not all of these goals may be directly optimized within the model, since they conflict (e.g., it is impossible to absolutely minimize both the number of overtime hours used and the waiting time for facilities).

What we desire, then, is a model that optimizes each quantity under the restriction of the others, i.e., uses these criteria to schedule objectively and repair each outage with a balance between cost and time.

Design of Model

General Groupings

The first step in the design of a model for scheduling crews to worksites is a grouping system of those sites. This grouping should primarily satisfy goal of immediate response to crucial outages. Within groups, we assign rankings. [EDITOR'S NOTE: We omit the table of rankings for space reasons.] Following is a general description of each group and its distinguishing characteristics.

- Group I: Facilities of utmost importance. Crews may be assigned to Group I facilities while the storm is in progress as well as after it leaves the area.
- Group II: Facilities needed for public safety. Crews may be assigned to Group II facilities only after the storm leaves the area.
- Group III: Facilities least crucial to general public safety. Crews may be assigned to Group III facilities only after the storm leaves the area.

Constants and Formulas

k (people per hour):

Description: k ensures that (all else held constant) call B (9:00) will be processed before call A (8:00) if and only if

$$\text{(\# of people affected at B)} > \text{(\# of people affected at A)} + k.$$

Rationale: Some constant must relate the relative worth of people affected to the time spent waiting, to provide a balance between the design goals outlined in the section on Analysis of the Problem. We set $k = 15$.

GW (Group Weight, converted to equivalent number of people affected):
Description: GW assures that (all else held constant)

- Worksites from different groups will be processed according to their group.
- Worksites within a group will be processed according to their relative importance. For example, in Group III, a residential area (GW = 0) would be processed before city hall (GW = 300) if and only if

$$\text{(\# of people affected in residential area)} > \text{(\# of people affected by city hall outage)} + 300.$$

Rationale: Some constant must relate the relative importance of within-group worksites while at the same time maintain prioritization by group. Notice that GW allows us to pursue the goal of immediate response to crucial outages from the analysis of the problem.

PV
Description: PV (performance value) establishes a "value" in units of people for each call received by HECO. The considered factors are the time a call was received, the number of people affected, and constants k and GW. Note: The factor $(24 -$ time of call) assumes that all calls come in during the first 24-hr period, and that time is measured in 24-hr time.

$$\text{PV} = (24 - \text{Time of Call}) \times k + \text{(\# of people affected)} + \text{GW}.$$

Rationale: Some cumulative criterion must be available to evaluate the importance of a call and determine its relation to other calls on the queue; PV will allow the model to balance the many desired considerations. Note: A Group I worksite will always have a greater PV than a Group II or III worksite, and a Group II worksite will always have a greater PV than a Group III worksite. This is achieved by setting GW values at appropriate ranges within each group.

SCORE
Description: SCORE is a value that is used when a crew is available to work and a decision must be made regarding where the next assignment should be. SCORE will change for a particular worksite depending upon the location of the crew in question. In simple terms, SCORE is equal to the site's PV times the percentage of the work that the crew would be able to complete.

$$\text{SCORE} = \text{PV} \times \left[\frac{\min \begin{cases} \text{time required to finish job} \\ \text{time left on shift} - \text{time to travel to worksite and back to base} \end{cases}}{\text{time required to finish the job}} \right]$$

Rationale: Some criterion must be available that takes into account not only PV but amount able to be accomplished at a particular worksite. We chose the percentage of work able to be completed as the deciding factor.

Algorithm

[EDITOR'S NOTE: An extended description of the details of the algorithm is omitted for space reasons, as is the computer code itself.]

Determination of an Optimal Priority Scheme

Since all decisions regarding selection of worksites occur in the Crew Finish procedure, this is where we decided to concentrate on manipulation of the model. Five subroutines (based on slightly varying Priority Schemes) were constructed for the Crew Finish procedure, and the five resulting models were compared under the following constant conditions:

- $k = 15$,
- GW as assigned by us, and
- all crews worked two consecutive 8-hr shifts (one regular, one overtime) per work day for the duration of the emergency.

The five Priority Schemes are:

1. The first procedure models the manner in which HECO probably actually operated during Hurricane Jane. Crews are dispatched to sites as calls are received and are placed on a job list once no more crews are available. No consideration is given to criteria other than distance of possible worksites. When a crew becomes free and must decide between two or more jobs on the job list, it simply chooses the closest site.
2. The second procedure is a slight refinement of the first. A priority scheme (using PV) is applied to the list of jobs, ranking them in importance. When a call is received, it is assigned to a crew according to its PV and the distance of each crew from the worksite.
3. Once again, calls are assigned according to PV and crew distance. When a job must be selected for an idle crew, each job on the job list is considered. The percentage of the work which could be completed by the crew is computed, based on considerations of the amount of time left on the crew's shift, the travel time to the site, and back to the crew's base station, and the estimated size of the job. A SCORE value for each site is then calculated. The site with the highest SCORE value is selected.
4. The intent of the fourth procedure is to expedite service to locations on the job list with highest priority. When a crew becomes idle, SCORE values are calculated for each worksite on the job list, as in the third procedure, and the site with the largest value is deemed "first choice." "First choice" sites are then produced for each of the other 11 crews for the times those

crews would next need to make that decision. If any other crew would select the same job and arrive at the location faster, the initial crew must consider another choice (next highest SCORE value) and make another decision. If necessary, third, fourth, etc., choices are made. If no choice is acceptable, the crew returns to its base.

5. In many cases, when the fourth procedure was used, crews were being sent back to their base and left with nothing to do. In an attempt to utilize this time, the procedure was modified so that if all of a crew's possible choices turn out to be better suited to other crews, it returns to its "first choice."

Table 3 presents the data used for determination of the optimal model. The bases for the cost figures in the table are regular hours at $15/hr and overtime hours at $22.50/hr, driving at 30 mph, and truck costs of $0.30/mi. Note that with three members to a crew, the total worker hours spent driving must be divided by 3 to give the time of the truck on the road.

Table 3.
Comparing priority schemes.

Criteria	Priority Scheme				
	1	2	3	4	5
Group I sites done	19:07	14:25	14: 25	14:25	14:25
Group II sites done	41:19	17:07	17:07	17:07	17:07
Group III sites done	53:11	59:04	58:26	65:45	57:50
All sites done	53:11	59:04	58:26	65:45	57:50
Regular hrs	598	676	629	605	613
Total overtime hrs	483	550	498	474	512
Time working	762	762	762	762	762
Time driving	319	464	365	317	363
Cost	$20,800	$23,900	$21,700	$20,700	$21,800

From **Table 1**, we determined that Priority Scheme 5 best met the criteria that we had established at the beginning of the model-building process. For the remaining analysis, this will be the optimal model referred to.

Strengths and Weaknesses of the Model

Our model pursues all of the goals announced in the section on Analysis of the Problem. Every goal corresponds to a summand in the calculation of the Priority Value or in the calculation of SCORE.

There is an intrinsic weakness in the model linked directly to the nature of the problem. Because there is an element of subjectivity to any prioritization scheme, a "true optimal value" does not exist for even one of the variables. For example, brute-force simulation may produce a minimal total travel time by considering every possible combination of assignments; but this is the "optimal value" only if minimum travel time is the sole factor considered. However, directly from this weakness springs this model's primary strength. Recall that we concluded that a balance would be optimal. By varying the parameters in the algorithm, one can compare precisely those values that, in an individual case or to a particular company, represent an "optimal balance."

In addition, a functioning dispatch center will contribute many more variables that may complicate the model but will also facilitate some considerations. For example, many crews in our final model run left sites only 5 min before the job was estimated to have been completed. Most human beings would either finish the job or would have worked a little faster in order to meet a departure deadline.

Suggestions to HECO

We compared the applications of five different prioritization schemes to the established model. These results are based entirely upon tests run on the data provided by HECO concerning Hurricane Jane. Thus, our conclusion that Priority Scheme 5 is optimal would be strengthened by repeated application of the same test to data from different storms. By varying the input, the consistency of the model itself is tested and the prioritization schemes become more finely tuned.

HECO will wish to examine our tables in detail, noting specific company preferences for the results of varying Priority Schemes 1–5 and allowable employee overtime. In response to public dissatisfaction, we recommend that cost not weigh heavily in HECO decisions; however, cost information is provided, as it must certainly be a consideration for any profit-oriented organization.

The model requires an adjustment to enable the anticipation of a crew's departure from an unfinished job. Currently, there is a lag from the time of crew departure and the arrival of the new crew.

During Hurricane Jane, three calls were processed whose locations are outside the HECO service area. As purely additional data with which to fine-tune the developing model and prioritizations, we considered these sites. However, HECO must define its policy in perhaps one of the following ways:

- reject outside calls,
- respond within a predetermined extended perimeter, or

- respond dependent upon changing variables (e.g., proximity to outages within the perimeter, availability of non-overtime crews, etc.).

Any one of these policies may be incorporated into the algorithm and computer program.

Should HECO desire in the future to predict numbers of calls received, areas of heavy call traffic, waiting times on the queue, number of jobs likely to be in the queue, etc., it should pursue a more probabilistic model. These statistics are particularly useful for such tasks as relocating dispatch centers, hiring in anticipation of need, and expanding computer networks or dispatching systems. Queueing theory provides the most highly developed models, particularly when, as in the HECO problem, customers must be handled according to priorities.

Conclusion

Using the available data from HECO, our team defined objective criteria to prioritize emergency power-outage calls and produced a model to schedule the emergency work to available crews. Ideas taken from graph theory, queue theory, and hypercube queuing theory were used in our formulation and assumptions. The chosen optimal model is flexible enough that parameter changes (constants, formulas, amount of overtime allowed) can be easily implemented. HECO will be able to use this model to quantify and assess any number of scenarios, with a wide range of possible variables for future study. In short, service can improve and operation costs can decline if the information in this report is properly applied.

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