

Chapter 4. SCHEDULE ANALYSIS OF TIME TO RECOVERY

Introduction

This chapter investigates the scheduling of the post-hurricane repair process in order to suggest improvements that could reduce the time to recovery following a natural disaster. The schedule analysis incorporates activities including contractor hiring, manufacture of new equipment, installation of permanent repairs, and inspections by VDOT. The repair process is simulated to reveal its critical path, which identifies the activities that determine the overall completion time required by the process. The models and analysis of the post-hurricane process, which have been developed according to a timeline that stretches into the weeks and months following the disaster, are used to formulate an estimation of the time to recovery and assess the efficiency of the schedule of repair activities. An evaluation of the tradeoffs between the time to recovery and pre-hurricane resource investments is used to investigate how costly project delays can be avoided. This chapter includes:

- ~~✍~~ An explanation of project management and network modeling methodology.
- ~~✍~~ A representation of the post-hurricane repair process including the required activities and their relationships using PERT, Program Evaluation and Review Technique.
- ~~✍~~ A demonstration of the methodology using a hypothetical repair process based on data collected through interviews with VDOT personnel.
- ~~✍~~ An investigation of the critical path and near-critical path of the hypothetical repair process.
- ~~✍~~ A cost-benefit tradeoff analysis of the impact that pre-hurricane resources investments have on time to recovery.
- ~~✍~~ A set of recommendations based on the analysis.
- ~~✍~~ A discussion of a simulation system that could be created for further study.

Purpose and Scope

The current procedure for conducting repairs followed by VDOT is to complete them as soon as possible, and then submit applications for reimbursement from FEMA and FHWA (Cogburn, 1998). The efficiency of the procedure can be improved through an understanding and investigation of the repair process and the activities involved.

Mathematical networking and simulation techniques can be used to model a project constituted of separate tasks that observe precedence relationships. Florida and California, two states frequented with natural disasters, have also employed simulation to develop disaster management plans (Della-Giustina, 1994). This chapter models the individual tasks making up the overall repair process following a natural disaster. The model accounts for the demands involved with managing a project and the uncertainties among the dependent relationships of the repair activities. Mathematical algorithms are used to examine the impact the relationships can have on the time to recovery (Krajewski and Ritzman, 1987).

Methods and Materials

Repair Process Management

The series of tasks completed during the post-hurricane repair process is displayed in Figure 4.1.

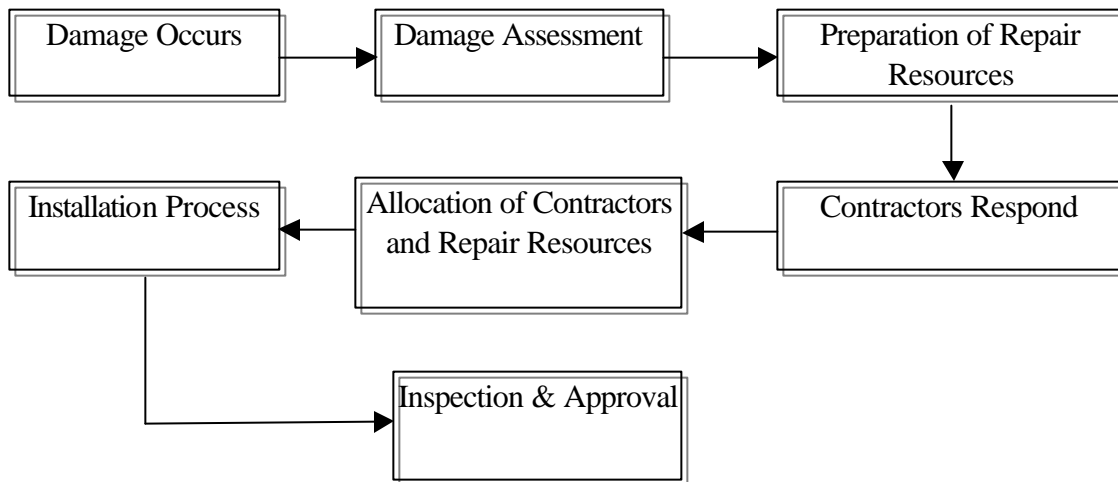


Figure 4.1 Flowchart of the repair process

Using the information gathered from interviews with VDOT personnel and the flowchart in Figure 4.1 as a framework, Table 4.1 lists the typical repair activities that are completed during the post-hurricane process. Each of the activities has an associated letter and list of prerequisite activities called *predecessors* that must be completed before the activity can begin. For example, Activity E, which is the disbursement of plans to contractors and VDOT inventories, cannot begin until Activity C, the definition of damaged equipment, and Activity D, repair plan preparation, have been completed. The repair project is considered complete at the close of Activity K, when payment is made to contractors.

A network diagram demonstrating the relationships among the activities outlined in the Table 4.1 is shown in Figure 4.2. The repair project begins on the left, with the start of Activities A and B, which then lead into Activities C, and D, respectively. Additions of new activities into the process and adjustments to the existing activities can be easily substituted into Table 4.1 and incorporated into the network diagram.

Table 4.1 Descriptions of activities of a hypothetical repair process

| Activity | Description | Immediate Predecessor(s) |
|----------|----------------------------------------------------------------------------------------|--------------------------|
| A | Damage assessment conducted | None |
| B | Requests for resources formulated | None |
| C | Equipment that must be replaced is defined | A |
| D | Final repair plans prepared | B |
| E | Plans and schedules disbursed and responses obtained from VDOT inventories/contractors | C, D |
| F | Resources and contractors assigned to damaged areas | E |
| G | Contractors examine inventory | C, F |
| H | Contractors place order/manufacture equipment | G |
| I | Install equipment | H |
| J | VDOT conducts inspections | I |
| K | Contractors paid | J |

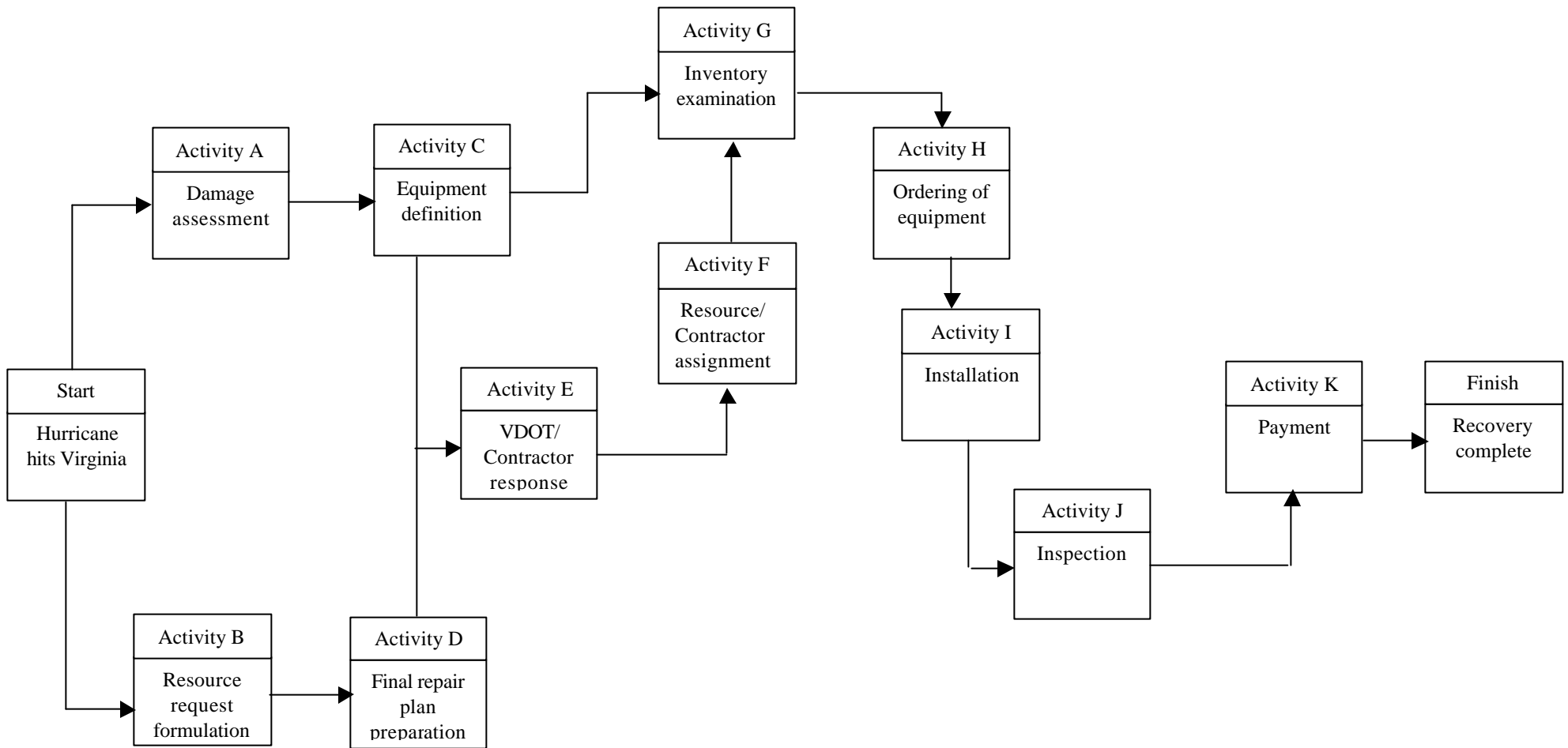


Figure 4.2 Network diagram of the dependencies among post-hurricane repair activities

Repair Process Analysis

The network representation of the post-hurricane repair process displayed in Figure 4.2 can be analyzed using the PERT technique and the CPM method. PERT and CPM provide a visual display of the sequence of necessary activities to complete a project, which can be used to monitor a project throughout its lifecycle. The PERT and CPM methods assume that the activities involved have clearly defined beginning and ending points and that sequential relationships among activities can be identified at the start of the project. The network methods are also used to demonstrate time-cost tradeoffs resulting from the reallocation of resources among activities.

The PERT technique is probabilistic in nature, and is designed for projects where there is little direct experience with the activities involved and thus little certainty associated with the time required for each activity. The CPM technique is more deterministic in nature, and is designed for projects in which activity times are known with certainty. The VDOT repair process is likely to be a combination of the two project types. Because it is unlikely that VDOT's post-hurricane activities always start and finish at defined times, the PERT method, which only requires that the time values be approximations, is more suitable for analyzing the repair process.

Calculations performed in the following sections follow standard project management methodology, and a complete listing of PERT and CPM algorithms are available in *Managing Engineering and Technology* by Daniel Babcock (Babcock, 1999).

Estimating Activity Times

To analyze a project using the PERT technique, three time estimates are required for each activity that must take place:

?? *Most optimistic time, a*: The shortest time in which an activity can be completed.

?? *Most likely time, m*: This is the mode of the distribution of the time required to perform an activity. That is, the activity most often requires m units for completion.

?? *Most pessimistic time, b*: An estimate of the longest possible time needed to complete an activity.

Table 4.2 lists the most optimistic time, most likely time, and most pessimistic time associated with each of the 11 activities given in Table 4.1. The three durations of time have been estimated for a Category II hurricane (95-115mph wind speeds) through interviews with the Richmond EOC, the Suffolk TMS, and the Charlottesville VTRC staff. The time estimates can be updated without affecting the overall project analysis.

Table 4.2 Time estimates of the post-hurricane repair process activities

| Activity | Time estimates (weeks) | | |
|----------------------------------------|--------------------------|----------------------|---------------------------|
| | Most optimistic <i>a</i> | Most likely <i>m</i> | Most pessimistic <i>b</i> |
| A – Damage assessment | 2 | 3 | 4 |
| B – Resource request formulation | 1 | 2 | 3 |
| C – Equipment definition | 1 | 2 | 3 |
| D – Final repair plan preparation | 1.5 | 2 | 3 |
| E – Response from VDOT/contractors | 2 | 3 | 5 |
| F – Resource and contractor assignment | 1 | 2 | 3 |
| G – Inventory examination | 1 | 1.5 | 2 |
| H – Ordering equipment | 2 | 4 | 6 |
| I – Installation | 5 | 6 | 10 |
| J – Inspection | 2 | 3 | 4 |
| K – Payment | 3 | 4 | 5 |

Calculating Time Statistics

Using the three time durations, the mean and standard deviation can be calculated for each activity, which account for uncertainties in the time estimates. The mean and standard deviation are used to calculate the probability distribution of each activity. The distribution, called *beta*, can take on a variety of non-symmetric shapes allowing the mode, which is the most likely time, to fall anywhere between the two end points, which represent the most pessimistic and the most optimistic times.

The mean of the beta distribution, which represents the expected time of an activity, is given by a weighted average of the three time estimates:

$$t_e = \frac{a + 4m + b}{6} \quad \text{(Equation 4.1)}$$

It is important to note that the most likely time is weighted four times greater than the most pessimistic or most optimistic time estimate.

As an example, the expected time for Activity E, the disbursement of plans and schedules to VDOT and its contractors is:

$$t_e = \frac{2 + 4(3) + 5}{6} = \frac{19}{6} = 3.17\text{wks} = 22 \text{ days}$$

This calculation shows that the expected time to completion does not necessarily have to equal the most likely time.

The standard deviation of any activity is given by:

$$\sigma = \frac{b - a}{6} \quad (\text{Equation 4.2})$$

For example, the standard deviation of Activity E is:

$$\sigma = \frac{5 - 2}{6} = 0.5$$

The standard deviation increases as the difference between the most optimistic and the most pessimistic time estimates increases. Therefore, the less certain a person is in estimating the actual time for an activity, the greater the associated deviation is from the expected time.

Table 4.3 lists the expected time and standard deviation associated with each activity. The table reveals that Activity I, the installation process, is the most time consuming task (expected time of 6.5 weeks), and is also associated with the greatest uncertainty (standard deviation of 0.83 weeks).

Table 4.3 Expected time duration and standard deviation associated with each post-hurricane repair process activity

| Activity | Time Estimates (weeks) | | | Activity Statistics | |
|----------------------------------------------------|---------------------------------|-----------------------------|----------------------------------|-------------------------------------------|---------------------------|
| | Most optimistic (<i>a</i>) | Most likely (<i>m</i>) | Most pessimistic (<i>b</i>) | Expected Time (<i>t_e</i>) | Standard Deviation (?) |
| A – Damage assessment | 2 | 3 | 4 | 3 | 0.33 |
| B – Resource request formulation | 1 | 2 | 3 | 2 | 0.33 |
| C – Equipment definition | 1 | 2 | 3 | 2 | 0.33 |
| D – Final repair plan preparation | 1.5 | 2 | 3 | 2.1 | 0.25 |
| E – Response from VDOT inventories and contractors | 2 | 3 | 5 | 3.2 | 0.5 |
| F – Resource and contractor assignment | 1 | 2 | 3 | 2 | 0.33 |
| G – Inventory examination | 1 | 1.5 | 2 | 1.5 | 0.17 |
| H – Ordering equipment | 2 | 4 | 6 | 4 | 0.67 |
| I – Installation | 5 | 6 | 10 | 6.5 | 0.83 |
| J – Inspection | 2 | 3 | 4 | 3 | 0.33 |
| K – Payment | 3 | 4 | 5 | 4 | 0.33 |

Determining the Critical Path

Table 4.4 displays the *Earliest Possible Completion Date (TE)* and the *Latest Allowable Achievement Date (TL)* for each activity. The TE value, which is determined using the expected time and standard deviation calculations of Table 4.3, represents the earliest expected completion date for each activity. The TL represents the last time at which the activity can be completed without delaying the overall completion time of the repair process. By determining the sequence and expected completion times of the activities, the critical path and the overall time to completion of the repair process can be calculated.

The *critical path* of the repair process is the sequence of activities that is associated with the greatest cumulative elapsed amount of time from the point when the hurricane hits to the point when all repair activities have been completed. The critical path is defined by the earliest and latest possible completion

dates of the overall repair process. The activities lying on the critical path are called critical activities. Any delays in the critical activities cause a delay in the overall repair completion time.

Table 4.4 The earliest possible completion date and latest allowable achievement date for each activity in the post-hurricane repair process

| Activity | Activity Statistics | | | |
|----------------------------------------------------|----------------------------|------------------------------------|-------------------------------------------|-------------------------------------------|
| | Expected Time (t_e) | Standard Deviation (σ) | Earliest Possible Completion Date (TE) | Latest Allowable Achievement Date (TL) |
| A – Damage assessment | 3 | 0.33 | 2.67 | 2.67 |
| B – Resource request formulation | 2 | 0.33 | 1.67 | 2.5 |
| C – Equipment definition | 2 | 0.33 | 4.33 | 4.33 |
| D – Final repair plan preparation | 2.08 | 0.25 | 3.5 | 4.33 |
| E – Response from VDOT inventories and contractors | 3.17 | 0.50 | 7 | 7 |
| F – Resource and contractor assignment | 2 | 0.33 | 8.67 | 8.67 |
| G – Inventory examination | 1.5 | 0.17 | 10 | 10 |
| H – Ordering equipment | 4 | 0.67 | 13.33 | 13.33 |
| I – Installation | 6.5 | 0.83 | 19 | 19 |
| J – Inspection | 3 | 0.33 | 21.67 | 21.67 |
| K – Payment | 4 | 0.33 | 25.33 | 25.33 |

Figure 4.3 is used to identify the activities on the critical path. According to the time estimates collected, the critical path in the VDOT repair process is represented by A-C-E-F-G-H-I-J-K. This path is associated with the greatest amount of overall completion time. The only activities not included on the critical path are Activities B and D. The time duration of the path, which represents the overall time to completion of the repair process, is equal to 25.33 weeks, or just over six months.

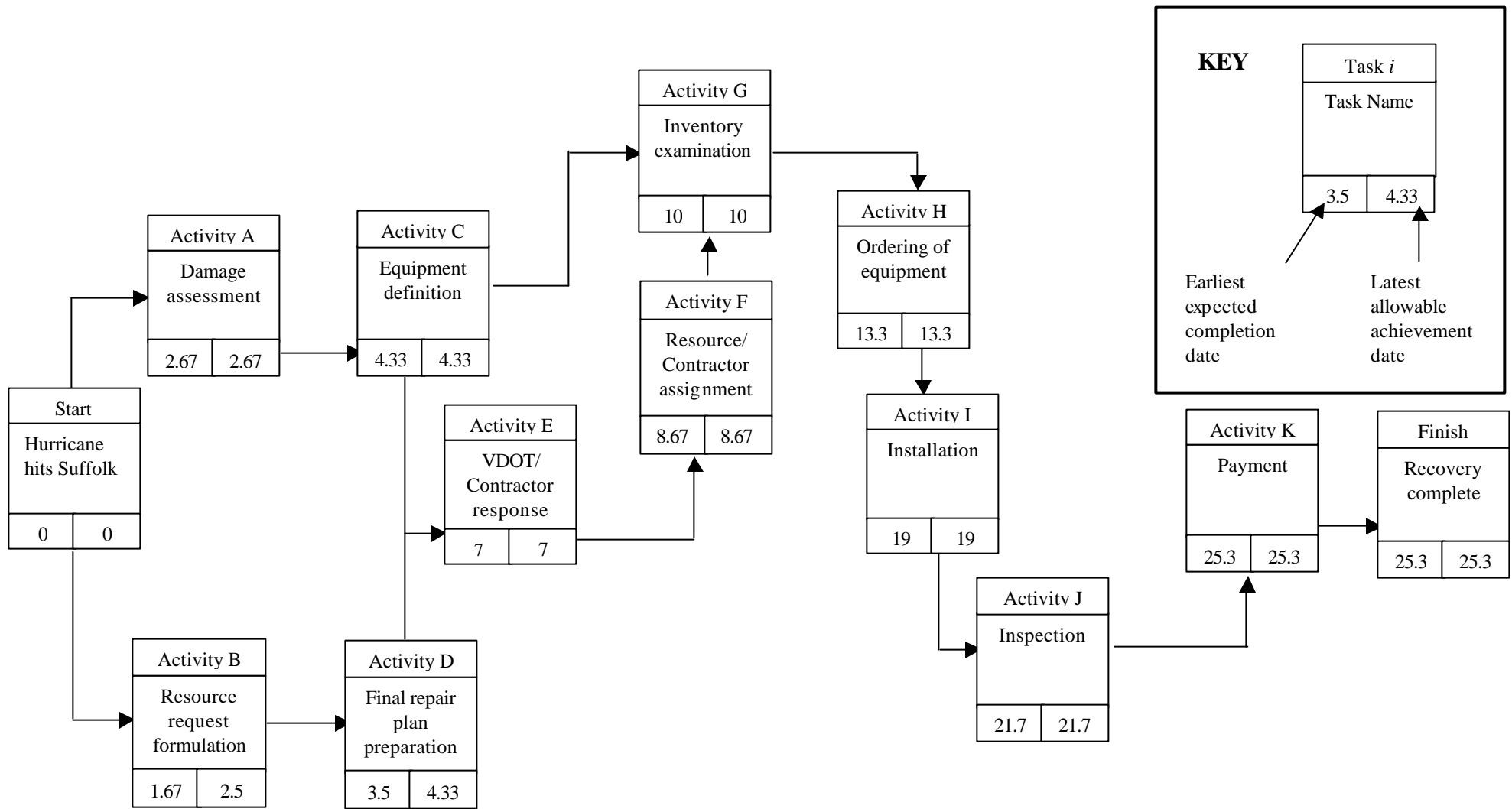


Figure 4.3 Network diagram of the post-hurricane repair process showing the critical path, the earliest expected completion date, and the latest allowable achievement date for each activity

Table 4.5 lists each activity with its associated TL, TE, and *slack* time, which is the difference between the TL and TE values. Slack, which represents the amount of free time allowed among activities, can absorb delays that arise in the post-hurricane repair process. For example, Activity B, the formulation of resource requests, can be delayed for almost a week without lengthening the overall time of the repair process. All activities lying on the critical path have zero slack.

Table 4.5 The amount of slack time associated with each repair activity

| Activity | TL (weeks) | TE (weeks) | Slack (weeks) | Critical Path |
|----------|------------|------------|---------------|---------------|
| A | 2.67 | 2.67 | 0 | Yes |
| B | 2.5 | 1.67 | 0.83 | No |
| C | 4.33 | 4.33 | 0 | Yes |
| D | 4.33 | 3.5 | 0.83 | No |
| E | 7 | 7 | 0 | Yes |
| F | 8.67 | 8.67 | 0 | Yes |
| G | 10 | 10 | 0 | Yes |
| H | 13.33 | 13.33 | 0 | Yes |
| I | 19 | 19 | 0 | Yes |
| J | 21.67 | 21.67 | 0 | Yes |
| K | 25.33 | 25.33 | 0 | Yes |

Analyzing Project Completion Probabilities

Since the time estimates for the activities in a PERT network involve some uncertainty, a measure of the probability that an activity is completed in a specific amount of time has been developed. First, the probability distribution of the completion date for the repair process is determined using mean and variance calculations where the mean is the sum of the individual expected completion times (25.33 weeks) and the variance is the sum of the squares of the individual standard deviations of the critical activities.

Figure 4.4 is a plot of the normal probability curve of completion time for the post-hurricane repair process based on the critical path consisting of A-C-E-F-G-H-I-J-K and the mean and standard deviation calculations from Table 4.3. Using a normal probability plot, the probability that the process exceeds a certain amount of time can be determined. For example, using normal probability tables, the probability that the overall repair process completion time is greater than twenty-seven weeks is 0.12. Therefore, there is a 12% chance that the repair process is delayed.

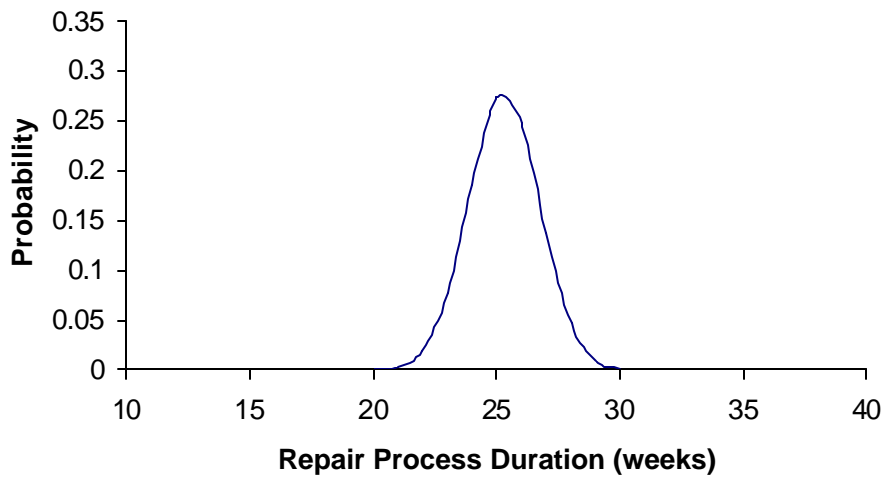


Figure 4.4 Process completion time distribution

It is important to recognize that this analysis hinges on the identification and characteristics of the critical path. If activities are added or removed from the project's activity list, then the critical path and the probabilities of completion change. The critical path could change if one or more critical activities are completed in a shorter time than expected. If the combined expected time duration of Activities A and C is reduced to three weeks, the critical path changes, and the combined time durations of Activities B and D (three and a half weeks) become more significant. For example, Activities A and C could be completed ahead of schedule because the storm damage is concentrated in a small area. The critical path changes to B-D-E-F-G-H-I-J-K because the overall expected time to completion of the path B-D-E-F-G-H-I-J-K is longer than the expected time to completion of the revised path A-C-E-F-G-H-I-J-K. Figure 4.5 is a plot of the normal probability curves of completion time for the two paths.

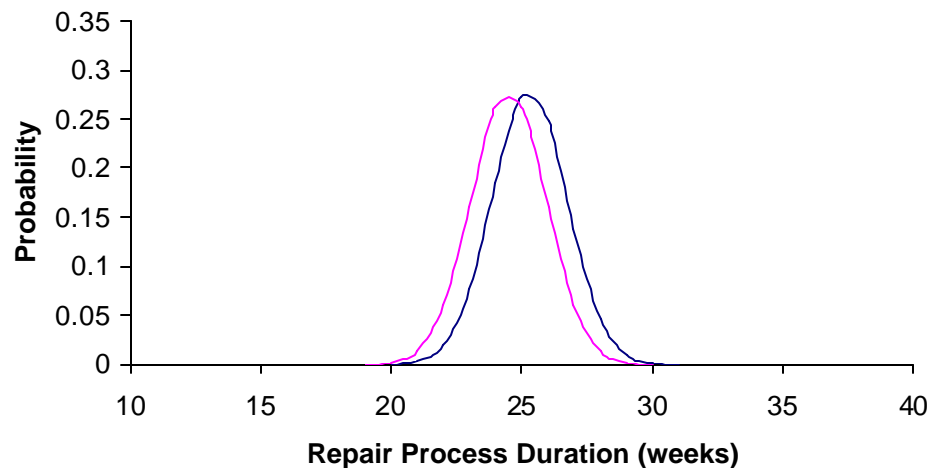


Figure 4.5 Probability distributions for the critical path and near-critical path

The new, lower curve to the left (representing the critical path B-D-E-F-G-H-I-J-K) of the original probability plot (representing the path A-C-E-F-G-H-I-J-K) shows that it is feasible for the repair process to be completed in less time than the current schedule requires. The faster completion time becomes possible when Activities A and C are completed ahead of schedule.

Resource Allocations and Crashing

Allocating additional resources to an activity to reduce its time duration is called *crashing* the activity. The expected time to complete the activity is called the *normal time* (NT), which is equivalent to the expected completion time calculated in section *Calculating Time Statistics*, and the cost of completing the activity in this time is called the *normal cost* (NC). The shortest possible time in which an activity can be completed is called the *crash time* (CT), which is equivalent to the most optimistic completion time of each activity, and its associated cost is called *crash cost* (CC). The per time unit cost of reducing an activity, called the per unit crash cost is:

$$\text{per unit crash cost} = (\text{CC}-\text{NC})/(\text{NT}-\text{CT}) \quad (\text{Equation 4.3})$$

Table 4.6 lists the NT, NC, CT, and CC for each activity, which have been gathered from interviews with VDOT personnel. The cost values listed are based on the damage associated with a Category II (95-115 mph wind speeds) hurricane. Costs for activities such as contractor and VDOT inventory response (Activity E), and payment costs (Activity K) are the administrative costs involved with these activities. The crash cost per week is the difference between the NC and CC values.

Table 4.6 Normal and crash data for the VDOT Hurricane recovery project

| Task | Normal Time (wk) | Crash Time (wk) | Normal Cost (\$) | Crash Cost (\$) | Crash Cost per week |
|------|------------------|-----------------|------------------|-----------------|---------------------|
| A* | 3 | 2 | 35,000 | 50,000 | \$15,000* |
| B | 2 | 1 | 15,000 | 20,000 | \$5,000 |
| C* | 2 | 1 | 5,000 | 7,000 | \$2,000* |
| D | 2.1 | 1.5 | 10,000 | 15,000 | \$8,333 |
| E* | 3.2 | 2 | 5,000 | 10,000 | \$4,167* |
| F* | 2 | 1 | 7,500 | 9,000 | \$1,500* |
| G* | 1.5 | 1 | 5,000 | 6,000 | \$2,000* |
| H* | 4 | 2 | 50,000 | 75,000 | \$12,500* |
| I* | 6.5 | 5 | 2,500,000 | 3,500,000 | \$666,667* |
| J* | 3 | 2 | 30,000 | 40,000 | \$10,000* |
| K* | 4 | 3 | 10,000 | 15,000 | \$5,000* |

*Activity lies on the original critical path.

Because crashing a non-critical activity does not affect the overall project time to completion, only critical activities that can be crashed are considered. The activities to be crashed are chosen in order of increasing expense. Therefore, the activity with the smallest crash cost in Table 4.6 (Activity G) is chosen to be crashed first. Thus, the time required for Activity G decreases from 1.5 to 1 week in length, and the project cost increases by \$1,000. The next activity to be crashed is Activity F, because it has the next highest crash cost. This progression continues until all critical activities have been crashed. Figure 4.6 shows how the cost of the VDOT post-hurricane repair process increases as activities are crashed.

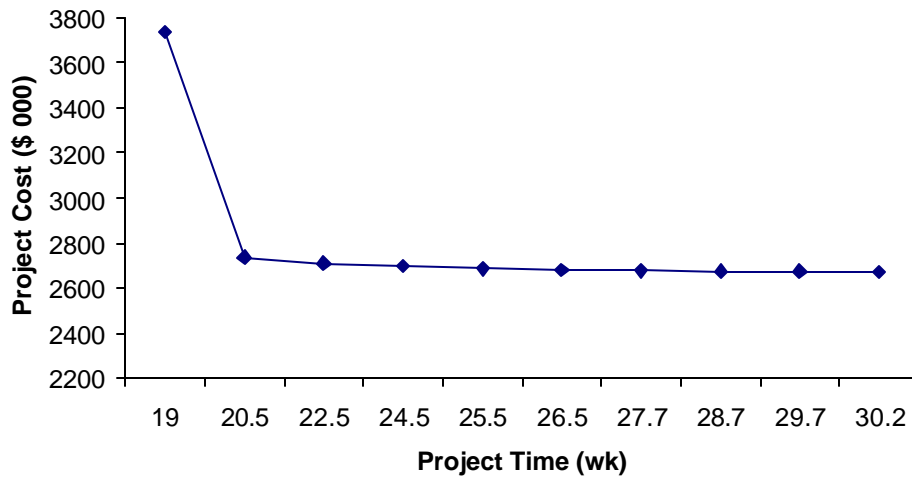


Figure 4.6 Project cost as a function of completion time for the VDOT hurricane recovery project

Though the project costs remain stable across continual reductions in project time, a significant cost change occurs when reducing the project time to less than twenty weeks, which results from the crashing of Activity I, the installation process. Figure 4.6 indicates that VDOT can reduce its overall project completion time by almost ten weeks without significantly increasing costs. Trying to reduce the time to recovery beyond the twentieth week is not recommended unless the equipment installation process is improved to incur lower initial costs, which reduce the rise in total expenditure that results from crashing.

Results

The analysis shows that, because nearly all of the activities lie on the critical path, the current schedule of repair activities is sensitive and highly dependent on a majority of the activities being completed on time. In particular, the *Analyzing Project Completion Probabilities* section demonstrates that a change in the completion times of Activities A, B, C, and D causes the development of a new critical path and a reduction of overall time to completion.

The overall repair process completion time can be reduced if the individual activities lying on the critical path of the repair process are completed in less time. The length of time required by an activity depends on the resources available. For example, if more personnel are assigned to the assessment of damage (Activity A), then A could become a non-critical activity. PERT modeling reveals that, according to the data collected, the installation procedure (Activity I) is the lengthiest and most variable activity. Therefore, pre-hurricane investments should be further investigated in terms of the impact additional resources have on the time to completion of the installation process. Tradeoff analysis reveals that the length of time required to complete the activities lying on the critical path of the repair process can be reduced, or crashed, without a significant increase in cost.

Conclusion

Although the PERT and CPM methods suggest that critical paths should be the focus of analysis, it is also important to examine the near-critical paths, which are paths of activities that *could* likely become critical if certain activities become ahead or behind schedule. It is therefore recommended to perform similar analyses on various near-critical paths and possible scenarios of delay.

Dividing individual activities up into “sub-activities” performed simultaneously can reduce project completion time. The time reduction that results from dividing up tasks can be demonstrated by the fact that if repair activities are completed in a linear sequence, where each activity is completed one after the other, as opposed to the current configuration, the repair process requires additional time for completion. Diversifying activities that follow a linear sequence into parallel sub-activities that occur simultaneously introduces additional paths and creates more slack time, so that if one activity lags behind schedule, the delay can be absorbed by the early completion of an alternate activity.

Reducing the length of completion time for post-hurricane activities, which places greater pressure on the resources employed (for example, equipment and repair crew), may be prudent under extreme situations because of the minimal impact on cost. An example of such a situation could be the aftermath of a moderate hurricane that has left hospitals and emergency services completely inaccessible.

Recommendations

VDOT must now conduct the following activities in keeping with the results of this study:

- ✍ Collect detailed data on the post-hurricane equipment installation process. This requires an analysis of repair crew activities, road clearing activities, and inventory for spare emergency equipment.
- ✍ Use the data to investigate the possibility of dividing up the equipment installation tasks into parallel operations. Examine the impacts of assigning more resources such as personnel and equipment to the installation task.
- ✍ Examine different overall schedule configurations of the activities in the repair process. This chapter has studied the configuration as it currently exists. By diversifying and splitting up the

activities, VDOT can create greater flexibility in the repair process schedule. A reconfiguration of the repair process could provide lower completion times by rearranging critical and non-critical activities. For example, performing Activities G and H (the inventory examination and ordering of equipment, respectively) simultaneously would reduce overall time to recovery.

✍ Investigate possibilities for further time and cost savings. The time-cost tradeoff analysis of section *Resource Allocations and Crashing* shows that costs rise slowly as recovery time is reduced. By conducting a similar analysis for each activity, VDOT can determine the contribution that each activity makes to the rise in cost.

Although the focus of this study is primarily on hurricane effects, the overall template of project management can be applied to blizzard recovery, forest fire recovery, and earthquake recovery. The analysis performed in this chapter is of a general nature, and can be modified to include the study of different highways, communities, repair crews, and geographical locations.

Areas of Further Study

Future study could involve a further investigation of the installation process, which is associated with the most uncertainty and the highest time required for completion. An investigation of the installation process could be performed using computer simulation. A simulation model for the installation process could study the existence of a maintenance crew as it carries out the following activities:

1. Retrieves replacement equipment from inventory. This is the act of the repair crew arriving at the inventory location and accessing the equipment. The crew removes all items needed to substitute for damaged equipment, leaving the inventory depleted by that amount.
2. Travels to the location where the damaged equipment needs to be replaced. Travel times to a location are calculated by taking the distance to the repair site and dividing by the speed of travel for the repair crew.
3. Repairs the equipment and travels to the next site. Repair involves a repair time that depends on the nature of the material being replaced and the complexity of the replacement procedure. Repair time is most accurately modeled using random probability distributions. Traveling to the next site will again involve a travel time based on the speed of travel and the distance to the next repair site.
4. Returns to home base once it runs out of equipment and/or finishes repairing the last site on its agenda.
5. Home base replenishes the equipment installed with inventory. The depletion of inventory and the demand for further material can provide valuable insight for the management of an equipment inventory.

The five-step cycle then begins again. Table 4.7 lists the variables included in the simulation. To set up the installation process simulation, information is required regarding the path the maintenance crew

follows on its repair mission. Impassable roads means that different, and possibly longer, routes are followed. Also, details regarding the nature of the site needing equipment replaced such as the population and surrounding critical facilities are necessary in order to prioritize repairs. For example, if a road is in critical condition and needs a traffic signal to return to a normal traffic flow, the repair crew could replace the signal immediately, while bypassing various other sites where replacements are needed.

Table 4.7 Important variables that will be employed in computer modeling

| Variable name | Nature | Comments |
|------------------------|----------------------------------------------------------------|---------------------------------------------------------|
| Travel time | Time needed to reach destination | Distance to location / speed of repair crew |
| Repair time | Time needed to repair damaged equipment | Random probability depending on complexity of operation |
| Inventory access time | Time spent in accessing the inventory | Dependent on spare availability |
| Delay time | Unforeseen delays (waiting in queue for replacement equipment) | Exponentially distributed |
| Replenishment | Equipment retrieval time | Discrete distribution |
| Total time to recovery | Days/weeks/months | A sum of all the all the model times |
| Total cost | Cost of plan | |
| Equipment status | Most critical in need of repair / not critical | Different models will consider different scenarios |