

Air Force Institute of Technology

AFIT Scholar

Theses and Dissertations

Student Graduate Works

3-2007

Critical Infrastructure Rebuild Prioritization Using Simulation Optimization

Namsuk Cho

Follow this and additional works at: <https://scholar.afit.edu/etd>



Part of the [Infrastructure Commons](#), and the [Operational Research Commons](#)

Recommended Citation

Cho, Namsuk, "Critical Infrastructure Rebuild Prioritization Using Simulation Optimization" (2007). *Theses and Dissertations*. 3077.

<https://scholar.afit.edu/etd/3077>

This Thesis is brought to you for free and open access by the Student Graduate Works at AFIT Scholar. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of AFIT Scholar. For more information, please contact richard.mansfield@afit.edu.



**CRITICAL INFRASTRUCTURE REBUILD PRIORITIZATION USING
SIMULATION OPTIMIZATION**

THESIS

Namsuk Cho, Captain, ROK Army

AFIT/GOR/ENS/07-04

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

AFIT/GOR/ENS/07-04

**CRITICAL INFRASTRUCTURE REBUILD PRIORITIZATION USING
SIMULATION OPTIMIZATION**

THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Operations Research

Namsuk Cho, B.S. Computer Science

Captain, ROK Army

March 2007

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT/GOR/ENS/07-04

**CRITICAL INFRASTRUCTURE REBUILD PRIORITIZATION USING
SIMULATION OPTIMIZATION**

Namsuk Cho, B.S. Computer Science

Captain, ROK Army

Approved:

Dr. Sharif Melouk, PhD (Chairman)

Date

Dr. Marcus Perry, PhD (Member)

Date

Acknowledgments

I would like to express my great appreciation to my advisor, Dr. Sharif Melouk and Dr. Marcus Perry, for their support and guidance. I also would like to give my appreciation to my wife.

Capt. Namsuk Cho

Table of Contents

	Page
Acknowledgments.....	v
Table of Contents.....	vi
List of Figures.....	viii
List of Tables.....	xi
Abstract.....	xii
I. Introduction.....	1
1.1 Background.....	1
1.2 Problem Statement.....	3
1.3 Methodology.....	6
1.4 Research Objectives.....	7
1.5 Overview of thesis outline.....	8
II. Literature Review.....	9
2.1 Introduction.....	9
2.2 Rebuilding after disaster.....	9
2.3 Critical infrastructure interdependency.....	11
2.4 Introduction to critical infrastructure.....	17
2.5 Dynamic system.....	26
2.6 Design of experiment.....	28
2.7 Simulation optimization.....	33
III. Methodology.....	37
3.1 Introduction.....	37
3.2 Data collection.....	37

3.3 Global rebuilding model.....	38
3.4 Physical network	40
3.5 Information layer	52
3.6 Spatial layer.....	66
3.7 Heuristic optimization	69
3.8 Conclusion.....	75
IV. Analysis and Results.....	77
4.1 introduction.....	77
4.2 Rebuild model results	77
4.3 Heuristic optimization	98
4.4 Summary.....	108
V. Recommendations and Further research.....	110
5.1 Introduction	110
5.2 Restrictions on model and future research	110
5.3 Conclusion / Summary	119
Appendix A. MATLAB code for spatial model	120
Appendix B. MATLAB code for rebuild simulation model.....	127
Appendix C. MATLAB code for optimization model.....	157
Appendix D. Incident matrix of infrastructure interdependency	159
Appendix E. Experiment results to find temperature setting (SA)	160
Bibliography	162

List of Figures

	Page
Figure 1.1 Critical Infrastructures.....	4
Figure 2.1 Infrastructure interdependencies (Rinaldi <i>et al</i> , 2001:15).....	12
Figure 2.2 Key component of typical drinking water system (GAO, 2003:15)	18
Figure 2.3 Waste water system	19
Figure 2.4 Classification of electrical power plant	20
Figure 2.6 Thermal power plant (americanhistory.si.edu).....	21
Figure 2.7 Nuclear power plant (www.nucleartourist.com)	22
Figure 2.8 Fossil fuel power plant (Wikipedia encyclopedia)	23
Figure 2.9 Production by temperature and production made from a crude oil (EIA.com)24	
Figure 2.10 Natural gas industry.....	25
Figure 2.11 Stock and flow diagram (Business dynamics, 2000:193)	27
Figure 2.12 2^2 and 2^3 Factorial Design (Sanchez, 2005:74).....	28
Figure 2.13 Response surface example.....	30
Figure 2.14 Black box approach (April <i>et al</i> , 2003:73).....	31
Figure 2.15 Black box approach example (Based on Averill, M. Law, 2000:663)	32
Figure 2.16 SA pseudo code (Kinney. Class handout, OPER623, winter 2006).....	35
Figure 3.1 Three inter-acting sub-models.....	39
Figure 3.2 Power infrastructure physical layer	40
Figure 3.3 Drinking water physical layer	43
Figure 3.4 Waste water physical layer	45

Figure 3.5 Oil infrastructure physical layer	45
Figure 3.6 Natural gas infrastructure physical layer.....	47
Figure 3.7 Transportation infrastructure physical layer.....	48
Figure 3.8 Telecommunication physical layer.....	51
Figure 3.9 Power infrastructure information layer	52
Figure 3.10 Water infrastructure information layer.....	55
Figure 3.11 Oil infrastructure information layer.....	57
Figure 3.12 Natural gas infrastructure information layer	59
Figure 3.13 Transportation infrastructure information layer	60
Figure 3.14 Telecommunication infrastructure information layer.....	61
Figure 3.15 Relationship of score and priority	63
Figure 3.16 Mapped Louisiana road systems in spatial layer.....	67
Figure 3.17 Interaction between simulation model and optimization model.....	71
Figure 3.18 Flow diagram of simulated annealing	75
Figure 4.1 Water infrastructure: water wells initialization	80
Figure 4.2 Power infrastructure: transmission line initialization.....	80
Figure 4.3 Oil infrastructure: port and pipeline initialization.....	81
Figure 4.4 Natural gas infrastructure: pipeline initialization	81
Figure 4.5 Transportation infrastructure: road initialization.....	82
Figure 4.6 Transportation infrastructure: rail initialization	82
Figure 4.7 Infrastructure dynamic (Initial Priority: 123456).....	84
Figure 4.8 Infrastructure dynamic (Initial Priority: 654321).....	84

Figure 4.9 Priority and score dynamic (Initial Priority: 134265)	90
Figure 4.10 Rebuild rate dynamic (Initial Priority: 134265)	90
Figure 4.11 Water infrastructure demand / supply (Initial Priority: 215436).....	93
Figure 4.12 Power infrastructure demand / supply (Initial Priority: 215436)	93
Figure 4.13 Oil infrastructure demand / supply (Initial Priority: 215436)	93
Figure 4.14 Natural gas infrastructure demand / supply (Initial Priority: 215436)	94
Figure 4.15 Telecommunication infrastructure demand / supply (Initial Priority: 215436)	94
Figure 4.16 Transportation infrastructure demand / supply (Initial Priority: 215436).....	94
Figure 4.17 Global Optimum Search (Scenario #1)	100
Figure 4.18 Global Optimum Search (Scenario #2)	102
Figure 4.19 Global Optimum Search (Scenario #3)	104
Figure 5.1 Power allocation to Telecommunication	116
Figure 5.2 Possible extensions in terms of priority.....	118

List of Tables

	Page
Table 3.1 Example on refinery rebuilding	49
Table 3.2 Transportation unit of oil infrastructure.....	50
Table 3.3 Example of resource allocation.....	63
Table 3.4 Example of resource allocation function	65
Table 3.5 Road coordinates and weighted capacity.....	68
Table 4.1 Estimation of final sample size.....	96
Table 4.2 Estimation of sample variance.....	97
Table 4.3 Three Scenarios.....	98
Table 4.4 Initial condition (Scenario #1)	99
Table 4.5 Optimization results on scenario #1.....	99
Table 4.6 Initial condition (Scenario #2)	101
Table 4.7 Optimization results on scenario #2.....	101
Table 4.8 Initial condition (Scenario #3)	103
Table 4.9 Optimization results on scenario #3.....	103
Table 5.1 Estimate of parameters (1).....	111
Table 5.2 Estimate of parameters (2).....	112

Abstract

This thesis examines the importance of a critical infrastructure rebuild strategy following a terrorist attack or natural disaster such as Hurricane Katrina. Critical infrastructures are very complex and dependent systems in which their re-establishment is an essential part of the rebuilding process. A rebuild simulation model consisting of three layers (physical, information, and spatial) captures the dependency between the six critical infrastructures modeled. We employ a simulation optimization approach to evaluate rebuild prioritization combinations with a goal of minimizing the time needed to achieve an acceptable rebuild level. We use a simulated annealing heuristic as an optimization technique that works in concert with the rebuild simulation model. We test our approach with three disaster scenarios and find that the initial rebuild strategy greatly impacts the time to recover. With respect to the scenarios tested, we recommend a rebuild strategy and areas for further investigation that may be of use to disaster and emergency management organizations.

CRITICAL INFRASTRUCTURE REBUILD PRIORITIZATION USING SIMULATION OPTIMIZATION

I. Introduction

1.1 Background

Hurricane Katrina was the one of the biggest storm catastrophe in the American history. From the formative period that was August 23, 2005 to the dissipated period that was August 31, 2005, it destructed haphazardly the whole things whatever it was a house, a livestock or people unless those are stand at the way of the hurricane passing through. Hurricane strokes the northern Gulf Coast and mostly New Orleans, Louisiana was badly damaged. The estimated damage is amount to \$81.2 billion dollars. About 1,800 people are confirmed to be death and about 700 people were missing. Also, critical infrastructures in those areas were deadly damaged by storm effect. A huge part of highway was destructed and it makes prompt recovery harder. Drinking water and waste water treat system were destroyed and by the destruction of electricity infrastructure three million people should have kept awake all night without light. Moreover, break down of oil industry affects not the New Orleans itself but the other neighborhood states. According to the report of Burton Mark L *et al* the total estimated economy effect may be above \$150 billion dollars.(Hurricane Katrina: Preliminary Estimates of commercial and Public Sector Damages, 2005) In summary, economies of New Orleans were gone and restoration and recovery problem were come into the spotlight.

In the sense of recovery phase, there are various elements which should be recovered by the first priority. One panel may insist that preventing the people from the infection is the most important while others assert that house was the first priority should focused on. Actually, The Urban Land Institute played host to discuss this problem in December 10, 2005 at the Washington, DC and the panels who participated to that discussion addressed five critical areas that are government effectiveness, economic development, culture, urban and city planning, housing and infrastructure. (A strategy for rebuilding New Orleans, ULI, 2005:5) But, the real issue is not the discussion between those but seeing through what makes all those possible. For example, in the case of housing rebuilding, in order to make a house raw materials such as concrete and brick should be delivered to the area and crews also should be get there by using transportation. Even though the house was built by all means, people can not reside without electricity and water. Now, think about the electricity. To generate electric power, certain amount of waters is needed for cooling the system and source materials are must be transported to the electric plant which also possible only the transportation system is well repaired. The whole things by connecting each other like chain and I mentioned just before are named as critical infrastructure. In short, we can not say anything without considering infrastructures in the process of restoration. And, infrastructures are strongly correlated with each others. In other words, critical infrastructures have interdependency.

Infrastructure and its interdependency are the topics which are researched and be studying now by a lot of laboratories and university. Including Steven M. Rinaldi who is one of the eminent people in this area, many researchers and a various government paper

dealt with critical infrastructure and interdependency. Some of those would be introduced at the following chapter hence it would not be mentioned detailed now. But, I need to describe common characteristics which those studies have for scoping out my research. Most of infrastructure articles or models were studied and developed with the object of preventing the critical infrastructure from the consecutive disruption. In other words, main goal of their study are enhancing the reliability of infrastructures and preparing the emergency response by detecting the relations among the critical infrastructures. For instance, let's assume the case of attack by terrorist who has a goal of making the certain region into disorder or panic state by destroying the critical infrastructure. In this case, protect-oriented research will be helpful in terms of re-distribution plan to the attack area by assistance of neighborhood areas because the interdependencies between critical infrastructure themselves or region to region are already researched so that response promptly.

1.2 Problem Statement

As I mentioned before, critical infrastructure is essential part of rebuilding phase after disaster. I would simulate the model which depicts the rebuilding process in terms of some critical infrastructures. Since each infrastructure is not independent but they are strongly dependent to each others, mostly I would focus on the interdependency between critical infrastructures. Critical infrastructures which I would simulate were decided as following figure.



Figure 1.1 Critical Infrastructures

Model is unique because, as discussed before, while other models focused on protecting the critical infrastructure from unknown threats, my model centered on rebuilding the critical infrastructure. Several decision-makers such as manager of Federal Emergency Management Agency or a director of National Response Plan U.S. Northern Command or corresponding policy maker would be supported by model in terms of following two areas.

1. Allocation of Resource
2. Overall Process supervising

First of all, model provides the priority of restoring the infrastructure. Since there are various groups of attending the rebuilding phase such as U.S. Army Corps of Engineers, U.S. Department of Housing and Urban Development or some volunteer groups, the coordination and allocation should be essential issue. Decision-maker can decide what kind of resource or group should be deployed at the right location as the time go by. Also, model would be useful to oversee the rebuilding phase. For example, if we assume that the critical section of highway was washed away by the flood and there are not bypass road, then bottleneck happens and it may interrupt whole rebuilding process before it fixed up. However, most of available resources are allocated to recover other infrastructure not a swept road. In this case, the manager who is charge of supervising the overall phase can recommend repairing the road with first priority.

Model will not consider more than state level scenarios. In other words, the boundary was set limit to state level. At first glance, restriction of boundary seems like to make fastidious problem that interaction between supporting city and other cities is hard to represent. However, interaction is indispensable element on the model since most of infrastructures are located at overlapped area so that it serves to multiple regions. Thus, other cities' resources are included in the model as an external agent. Even though it doesn't have physical entity, it will act with logical attribute.

Model will not be implemented for particular case or scenarios. It means that model is generalized. There are two reasons why the model should be generalized. At first, it is because we can not expect the disaster perfectly. And each region has different combination of infrastructure. For instance, some of cities may have thermal power plants while other cities have only fossil fuel plants. Hence, model will regard as many possible cases as can. Secondly, there exist various cases which can utilize the generalized rebuilding model such as Iraq operations of U.S. or other country's disaster.

This model leaves the infrastructure long-term issues out of considerations. For example, new technology on each infrastructure or aging and replacement issues are not considered. However, it deserves much about consideration. If statistical data of those are occupied, then long-term issues can be adapted just by adding or modifying the parameter in the model.

Moreover, I do not consider whose asset is critical infrastructure. In other words, it does not matter whether infrastructure is investor-owned, government-owned or state-owned. Although it could degenerate the model in terms of validation the real world, such

an overall management model is required because of following reasons. At first, rebuilding phase is large size task. Because there are lots of volunteer in most of post-disaster scene, utilization of huge force of volunteer is crucial issue. In order to use these non-owned groups, overall plan is critical. Secondly, if aught there are a lot of crews who belong to investor-owned infrastructure company, there exists more valuable things than company' profit. That is a livelihood of victims. The recovery of infrastructure can not be an ultimate goal unless it guarantees that revive the people to what they as were. It means that destroyed infrastructure should be recovered as soon as possible and only a concentration of effort can make it.

1.3 Methodology

Following section is introduction to methodology. Briefly, the various methods are introduced. Detailed contents will examine in the methodology chapter. Restrictions on data collection will be introduced at first. As previously mentioned, infrastructures are not only very complex system but also they are correlated to each others. In order to express such a complex infrastructure, I implemented the three layers system those are physical, information and spatial layer. The notation on those and clear examples will be examined. Some approaches on how the simulation model restores the infrastructure and how the model set their priority and how priority affects the rebuilding process will be discussed. Simulation optimization takes major part in my research. Simulated annealing which is one of the meta-heuristic techniques will be examined with pseudo code and flow diagram. Optimization model works in concert with the simulation model. I'll

explain how they are related to each other that is interaction between optimization model and simulation model.

1.4 Research Objectives

My research aims to following three objectives.

- i. Investigate the rebuild priority of critical infrastructures and their interdependencies
- ii. Develop simulation optimization framework to determine optimal rebuild priority of infrastructure
- iii. Examine various rebuild scenarios

As I mentioned before, some people may think the water infrastructure should be recovered with the first priority. While others insist that transportation infrastructure is more important because without transportation, any rebuild operations can not be conducted since mostly repair vehicle or crews are deployed via road or rail which is included in transportation infrastructure. This is a notation of rebuild priority. Thus, I focused on investigation of rebuild priority of critical infrastructure.

Also, I developed simulation optimization framework in order to determine optimal rebuild priority of infrastructures. Simulation optimization framework which is based on meta-heuristic technique can find the minimum total time to rebuild by configuring the initial priority (i.e., initially defined priority set by user).

Lastly, in order to verify the robustness of simulation and optimization model, I conducted three rebuild scenarios. Since each scenario assumed different impact area (i.e., the region where disaster strikes), we can evaluate whether the simulation and optimization model can represent various situations of real world.

1.5 Overview of thesis outline

Thesis is consisted of 5 chapters. I briefly reviewed the relevant literatures at chapter 2. Literatures in chapter 2 include rebuilding process article, infrastructure interdependency researches, and short introduction on structure of all infrastructures. Also, dynamic system and simulation optimization articles are introduced. Chapter 3 is methodology. Chapter 3 is consisted of data collection, global rebuilding model and three layers system, and simulation optimization. Chapter 4 is results and analysis. Some dynamic relationship graphs are examined at first. Those graphs give us an insight on how the model works. Optimization results of three scenarios are followed next. Chapter 5 is devoted to recommend the further research.

II. Literature Review

2.1 Introduction

In this chapter some specific literature were reviewed which are applicable to the model. Some articles are just introduced in order to provide the background knowledge to reader while some articles are both summarized and mentioned how they affect to my model in terms of techniques or insight. At first, certain rebuilding literatures which dealt with hurricane Katrina are introduced. Those literatures are related to initiation condition and termination threshold for model. Moreover, those plays a key role in verify and validate the model since the object of model is to imitate such a real world. Then critical infrastructure interdependency literature follows. Even though those articles are the one which are focused on protection-oriented, it provided the insight with respect to the interdependency between infrastructures. Following section described with introduction of various infrastructure. Each critical infrastructure is too complex to understand for non expert. Thus, in this section each infrastructure is just introduced within the limit of conceptual diagram. Some literatures in terms of dynamic system and design of experiment and simulation optimization follow. In the last sections, various simulation techniques are introduced.

2.2 Rebuilding after disaster

There are a few literatures which dealt with post-disaster reconstruct model with simulation techniques or operational research approach. Most of rebuilding literatures are written by a man of ripe experience. Reading those articles and finding some insights are

crucial because they (the author of empirical literature) are the one who certificate the model whether it mimic the real world well or not.

After deadly hurricane Katrina, New Orleans is going through a rebuilding phase. Some tasks are done already while some tasks take several years. (ULI, 2005:5) The author stressed the three key stages that have to be accomplished. Those are recovering stage, rebuilding stage and growing stage. Each definition was cited from the document. (ULI, 2005:57)

Stage 1- Recovery stage: Things that have to be completed before the emergency is declared over and the federal emergency response agencies leave town.

Stage 2- Rebuilding stage: Redirect and transform the existing infrastructure systems of a city of 500,000 to support and sustain the rebuilding of the city in the next five years.

Stage 3- Growing Stage: The city is well on its way to creating a safe, connected, and sustainable infrastructure for New Orleans' fourth century. (ULI, 2005:58)

Considering the written year of their article, my model may aim to stage 1 and 2 (i.e. Recovery stage, Rebuilding stage) with respect to their view. For providing safety to New Orleans, recovery of levee system in Southeastern Louisiana was emphasized. (ULI, 2005:60) Moreover, in order for city to be fully recovered, they insist that assessing the current condition of the infrastructure should be ahead of other process. Also, in the sense of sustainability, they suggest that realign the infrastructure systems are needed in order to serve the re-populated people from current locations to remote locations. (ULI, 2005:62)

2.3 Critical infrastructure interdependency

As was mentioned in the previous chapter, Steven M. Rinaldi *et al* are the people of distinction to the critical infrastructure dependency study. First of all, Rinaldi *et al* describe the infrastructure as an agent in the Complex Adaptive System and each agent has three kinds of entity that are a location, capabilities and memory. The memory entity depicts its experience. For example, in the case of oil pump, memory property includes past oil flow and operating statuses such as pressure, temperature. (Rinaldi *et al*, 2001:13)

Each infrastructure is either dependent or interdependent to other infrastructure in terms of whether it is supporting infrastructure or supported one. Rinaldi *et al* defined dependency and interdependency as follows. (Rinaldi *et al*, 2001:14)

Dependency: A linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other

Interdependency: A bidirectional relationship between two infrastructures through which the state of each infrastructures influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other.

Rinaldi *et al* classify the interdependencies into four classes (i.e. physical, cyber, geographic and logical) physical interdependency means that there is relation which can be expressed by unit of material between two infrastructure whatever that material is. The significant difference between physical and cyber infrastructure is that “commodity” transferred between those are not a physical material but an information. Geographic interdependency is defined as spatial proximity. Finally, Rinaldi *et al* describe the logical interdependency as all kind of dependency but is not included into other three classes (i.e.

physical, cyber, geographic). In the logical dependency, financial relation and human decision element are the primary element to consider. (Rinaldi *et al*, 2001:15-16). These interdependencies became the fundamental idea of overall simulation model frame and hence, three of interdependencies classes out of four are involved conceptually to my model that are physical, cyber and geographic. Following figure 2.1 gave me the keynote for developing conceptual model.

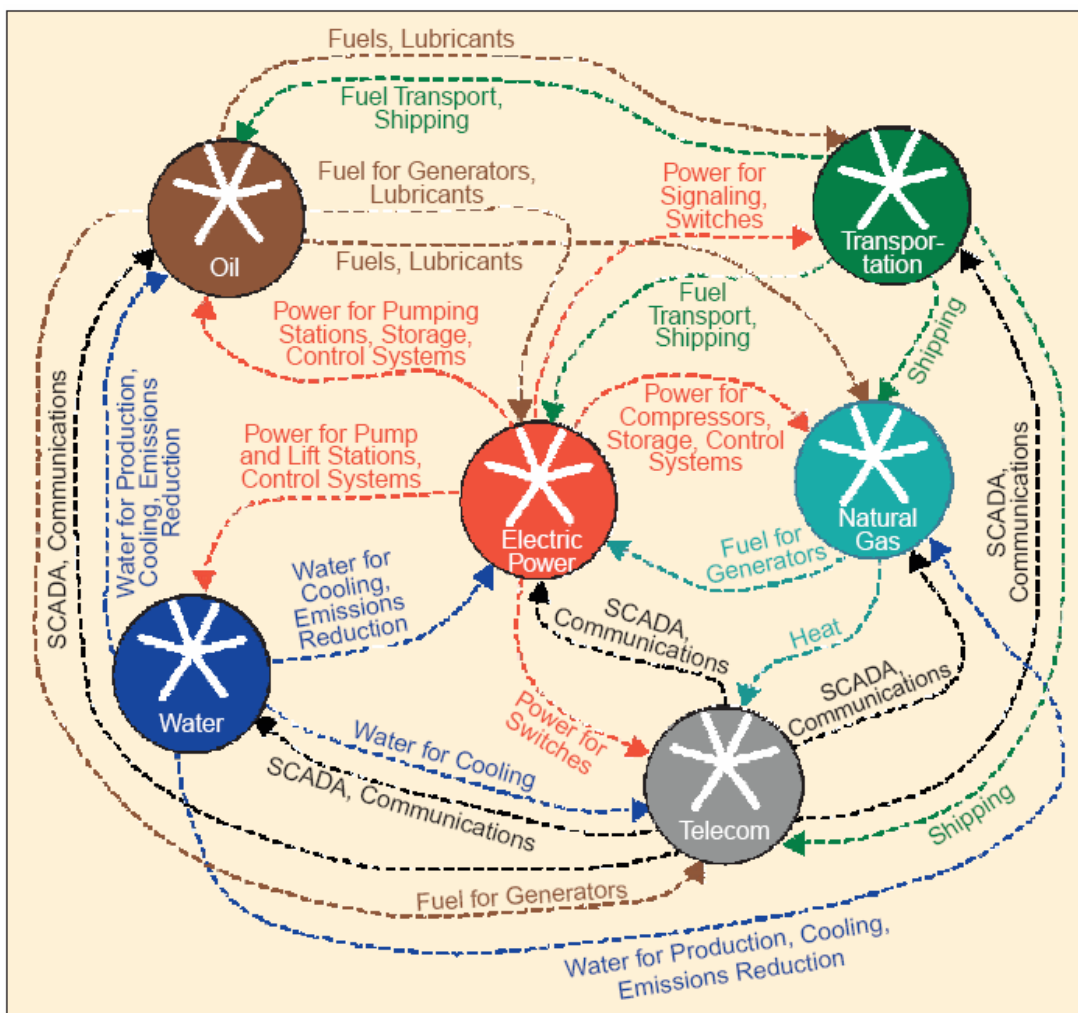


Figure 2.1 Infrastructure interdependencies (Rinaldi *et al*, 2001:15)

Rinaldi *et al* introduced the techniques to express interdependencies in terms of n th-order. Briefly summarizing, i is linked to j and j is linked to k and as state i changes, also state k change. (Rinaldi *et al*, 2001:19) It seems like very simple concept. However, it is directly applicable to rebuilding model because rebuilding model may have n th-order effect but it has a reverse order. Also, it should be determined that how many order does each infrastructure has during rebuilding process.

Three years later (2004), at the 37th Hawaii International Conference on System Sciences, Rinaldi presented the ‘Modeling and Simulating Critical Infrastructures and Their Interdependencies’. At this time, he mostly focused on M&S (Modeling and Simulation) techniques to represent the infrastructure interdependencies. In this article, it is encouraging that he pointed out the importance of strategies for response, recovery, remediation and reconstitution by M&S. (Rinaldi, 2004:5)

Given that resources (funding, personnel, material) for protecting infrastructure are generally limited, different resource allocation strategies can be simulated and compared for effectiveness. Of particular interest is recovering from multiple, simultaneous infrastructure disruptions as quickly, effectively, and efficiently as possible. In certain instances, there may be constraints that dictate what can be reconstituted (e.g., restore electricity to the public health system first). M&S may be able to play a role in these types of constrained, strategy optimization problems. (Rinaldi, 2004:5)

Rinaldi also stressed the challenges for modeling the infrastructure. At first, integrating the multiple infrastructures would be hard since each infrastructure has different types of data (e.g. emergency procedure, policies) (Rinaldi, 2004:6) Secondly, obtaining the data is not easy since crucial data are not allowed for sharing. Lastly, it is

challengeable to provide the appropriate data on time (e.g. real-time monitoring of infrastructure) (Rinaldi, 2004:7)

James. Peerenboom *et al* introduced concept of rebuilding duration that is the time required to restore the critical infrastructure components. Generally, the disaster impacts are not linearly scaled. It means that the impacts of a week outage are not same as septuple of a one day outage. Similarly, a day outage also is not represented as a certain point estimate. Instead, the duration of an outage should be represented as a probability distribution. The tool which is developed to consider that concept is Critical Infrastructure Interdependencies Integrator (CI³). Restoration process can be break down into several detail steps. Each step has own probability distribution curves and it is influenced by other steps. For instance, in order to replace the damaged pipeline, people and equipment must be dispatched. In this case, robust transportation infrastructure can bring about delay or quick service with respect to its condition. There are various factors that can increase or decrease the restoration times such as time of day, day of week or weather. (Peerenboom, 2001:4)

Jeffrey hunker insisted that the methodologies and techniques which dealt with coupled interdependent infrastructure are unripe even though there are various models and simulation tools with respect to individual infrastructure. (Hunker, 2002:708) In his article, infrastructures are not an aggregate of individual physical components unless it considers the more important factor that is people. In other words, integrated model only is worthwhile if it contains human factor in terms of public risk, security, and reliability.

(Hunker, 2002:710) He believed that a truly integrated system on infrastructure has social and human behavioral aspects. (Hunker, 2002:710)

A simple infrastructure management protocol (SIMP) for infrastructure monitoring and management is introduced by Jiang *et al.* As the title implies, they proposed network protocol approach. However, it provided fully examined notation for infrastructure layer system. SIMP allows state and government decision maker to access real-time data from SIMP grid. (Jiang *et al.*, 2002:2) SIMP grid consists of five layers: layer 1(Infrastructure sensor webs), layer 2(infrastructure information sharing mode), layer 3(Adaptive modeling in operational environment), layer 4(infrastructure interdependency), layer 5(assessment, planning and decision) (Jiang *et al.*, 2002:2)

Zhang *et al.* introduced dynamic game theoretic model of multi-layer infrastructure networks at the 10th international conference on Travel Behavior Research Lucerne. They examined multi-layer infrastructure network (MIN) by using flow model and agent based model. Infrastructure systems can be represented as networks which composed of nodes, links, and paths. (Zhang *et al.*, 2003:5) For example, in energy system, electricity plants are nodes, while transmission lines, pipeline, and roads are links. (Zhang *et al.*, 2003:5) Infrastructure networks do not have same types of flows. Telecommunication systems may have message and data as their flows while transportation system has vehicles, trains as their flow. (Zhang *et al.*, 2003:5)

As compared to Rinaldi's classification, they divide interdependency into six forms: physical, functional, budgetary, market, information, environmental interdependencies. (Zhang *et al.*, 2003:7) They pointed out some challenging issues when we model the

multi-layer network. One of the issues is that each layer has different time scales. (Zhang *et al*, 2003:7) For example, time scale of transportation networks is day-to-day level. In other words, drivers do not change the decision within a day. On the other hands, telecommunication networks have within-day basis. Information and data flows are changed much faster than flow of transportation. (Zhang *et al*, 2003:7) As I mentioned above, they tried agent based simulation approach either. They insisted that the characteristic of ABS such as “behave” and “memory” of agent are appropriate for combining with other optimization methods. ((Zhang *et al*, 2003:21-22)

Aamir *et al* introduced an agent-based modeling approach for rebuilding New Orleans. However, the object what they centered on is not critical infrastructure but a flow of population. In other words, their interacting agents are the habitat workers and households. (Aamir *et al*, 2006:5) In agent-based model, agents follow designated rules. For example, people rebuild their town if they are willing to reside there again. (Aamir *et al*, 2006:7) One of the future research issues what they suggested is initial condition matter. Initial condition such as the degree of damage, unemployment is really matter because it significantly affects the redevelopment. (Aamir *et al*, 2006:9) Followed their enhancement recommendation is that collecting more accurate information on New Orleans damage and realistic spatial data (i.e., geographic information system) for examine the scenarios more realistic. (Aamir *et al*, 2006:10)

2.4 Introduction to critical infrastructure

Even though we are not a specialist in infrastructure, it is desirable to grasp the basic frame of each infrastructure because we need to know what we would like to mimic. Secondly, because the critical infrastructures are consisted of a lot of complex components, it is not easy to understand each infrastructure. For example, the natural gas infrastructure has 276,200 wells, 45,000 miles of gathering pipeline, 726 gas processing plants, 254,000 miles of transmission pipeline, 410 underground storage fields, 54 LNG facilities, and 981,000 miles of distribution pipeline. (Peerenboom, 2001:3). Thus, chapter 2.4 is advance preparation for understanding following chapters. However, only a concise content which should be simulated was introduced. Also, I believe these makes the model more reliable in the sense of validation. Moreover, telecommunication and transportation infrastructures are omitted even though they were on the list of modeling because we are familiar to those. In other words, unfamiliar infrastructures such as thermal power plant or crude oil refinery are introduced.

2.4.1 Water infrastructure

Water infrastructure is defined as a stock of facilities to develop and manage water resources to customers. And it includes delivery, treatment, supply and distribution of water. (PDD, 2006:97) Water infrastructure is consisted of two sub-infrastructure that are drinking water system and waste water system (sewer system).

2.4.1.1 Drinking Water System

Drinking water system uses the ground water and surface water for source. Dams and reservoirs are in charge of storage for water. Generally, small-scale industries in urban areas get a supply of water by public water systems, while large-scale industries have own water systems. (PDD, 2006:104)

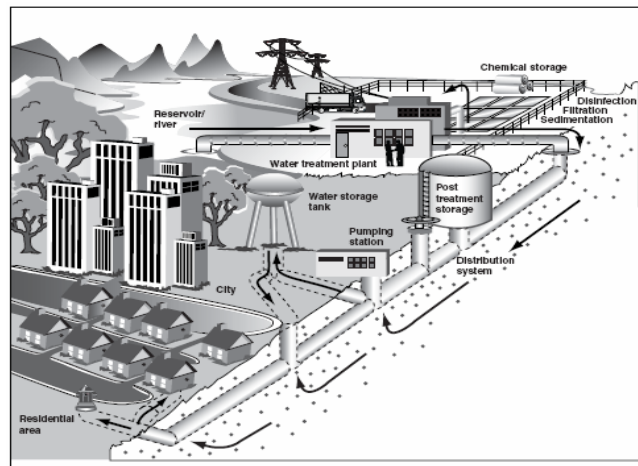


Figure 2.2 Key component of typical drinking water system (GAO, 2003:15)

Figure 2.2 shows clearly how drinking water generated from the water source. Wherever water is come from it was pumped up and treated in sequence of filtration, flocculation and sedimentation. And it was stored at the tank. After passing through distribution center, it was sent out to consumer that can be residents or industry. Even though it was not depicted on the figure 2.2, there is monitor system which oversee and control whole process.

In order to make “realistic” model, the hydraulic behavior should be modeled such as the pressure of pipe, turbulence in the pipes. (Pasqualini *et al*, 2006:5) Although,

widely used model, EPANET can represent hydraulic behavior, most of dynamic model can not depict physical detail components. (Pasqualini *et al*, 2006:6)

2.4.1.2 Waste Water System

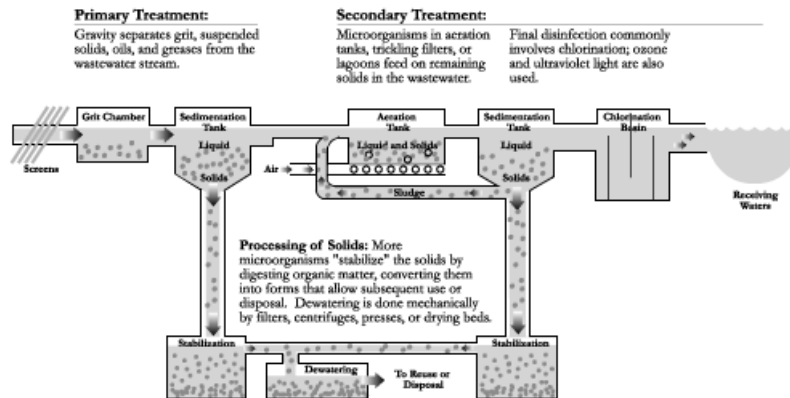


Figure 2.3 Waste water system

Waste water system is more complex than drinking water system. As seen above figure, there are several processes to treat the waste water. Simply, at first, water is treated within the specific treatment system. Second, treated water is sent back to the water source. Lastly, processed waste such as bio-solid dumped down to land.

2.4.2 Electricity Power Infrastructure

There is no classification in terms of electrical power plant. I subjectively classified electricity power plant as following diagram in order for obtaining data easily from electric power annual report (EIA, 2004). Overall process is not different to each other. There are three basic functions (i.e., generation, transmission and distribution). (EIA, 2000:9) Generation is the production of electric energy from various energy sources. Transmission is defined as the delivery of electric power over high-voltage lines

from power plants to the distribution system. Distribution is the local system has low-voltage lines, substations, and transformers. (EIA, 2000:9)

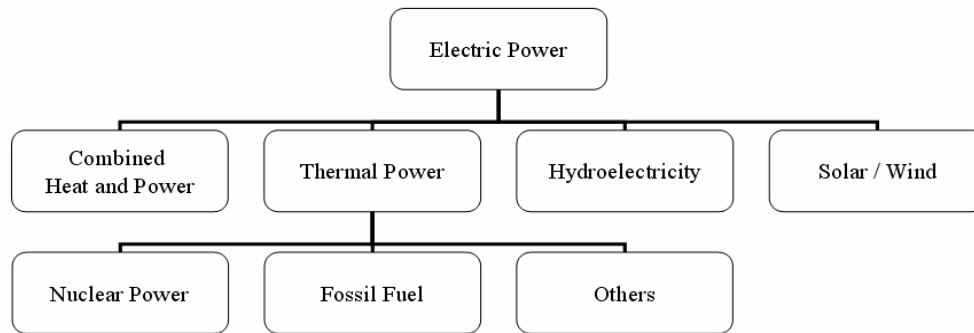


Figure 2.4 Classification of electrical power plant

2.4.2.1 Combined Heat and Power (CHP)

Cogeneration, or combined heat and power (CHP), can be defined as a type of distributed generation that uses the heat which obtained from electricity generation for industrial purpose or heating and cooling applications (McGee, 2006:2) Two reasons why the CHP is installed in recent days are reliability and independence from the power grid. (McGee, 2006:2) Some of the CHP systems are linked to the power grid while others are only used for internal use (i.e. stand alone systems) (McGee, 2006:2)

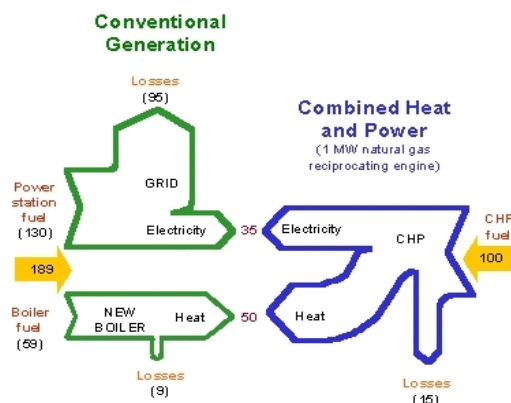


Figure 2.5 Comparison of conventional generation and CHP (uscpha.admgt.com)

As you can see figure 2.5, by capturing the surplus heat, CHP can use more energy than conventional generation, potentially about 70-90% efficiency while conventional generation only can reach to approximately 50% efficiency. (Wikipedia Encyclopedia)

2.4.2.2 Thermal power plant

In thermal power plant, heat engine makes mechanical power. In other words, thermal energy is transformed into rotational energy. Most thermal power stations produce steam. The difference between thermal power plant and combined heat and power plant is whether lost heat is reused or not. In thermal plant, exceed heat lost to the environment. (Wikipedia Web site) Thermal power plants are classified in terms of the type of fuel. Typical thermal power plants are nuclear, fossil fuel and geothermal power plant. Cooling towers plays a key role in thermal power plant. Generally it release the waste heat to the atmosphere by evaporation of water (Wikipedia Web site)

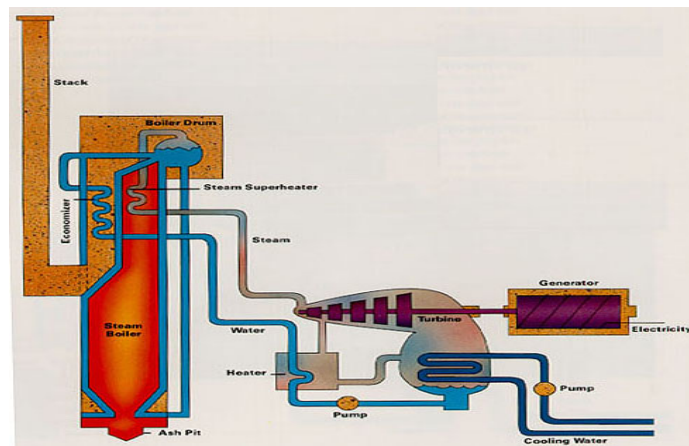


Figure 2.6 Thermal power plant (americanhistory.si.edu)

2.4.2.3 Nuclear Power Plant

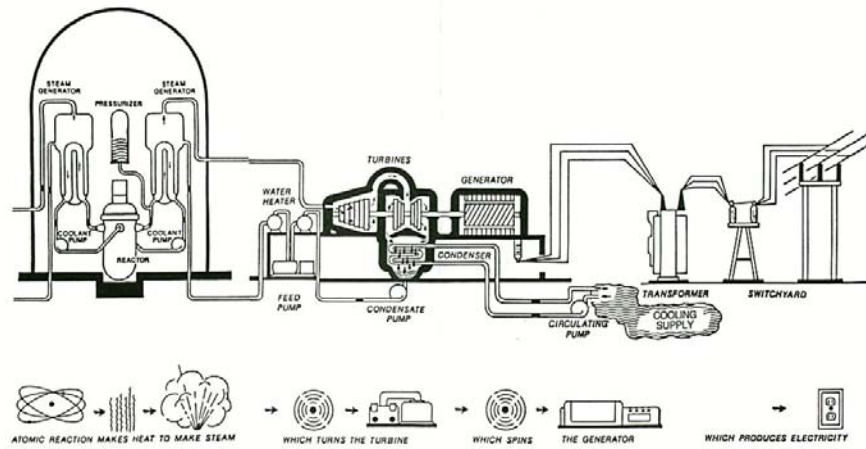


Figure 2.7 Nuclear power plant (www.nucleartourist.com)

Figure 2.7 represent the whole process of nuclear power plant. Moreover, kind explanation is detached under the plant diagram. At first, in the main steam system which are first left part of diagram, high temperature steam was generated by using chain reaction of atomic resource. As we might expect, nuclear power plant uses the uranium as a source. Then, steam operates the turbine and turbine drive the generator. I quoted the definition of turbine from the same site

Turbine: Convert the energy from the high pressure steam to mechanical energy in the form of shaft rotation so that the generator will turn.

Cooling system is essential part of all kinds of electric power plants including nuclear power plant. It removes the heat from the boiled steam to reuse or discharge to the water source.

2.4.2.4 Fossil Fuel Plant

Coal, petroleum, and gas are regarded as fossil-fuel. (EIA, 2000:10)

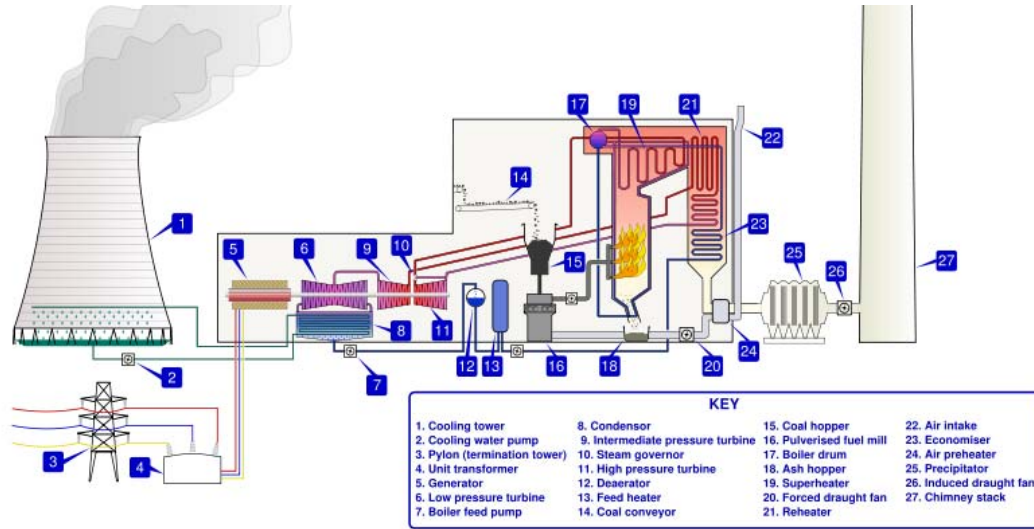


Figure 2.8 Fossil fuel power plant (Wikipedia encyclopedia)

Overall process is not significantly different with nuclear power plant. Same as nuclear power plant, steam was generated and it drives the turbine and generator. Also, necessity of cooling system is same. Only difference between those is what makes high temperature steam. For example, fossil fuel power plant generated the power by using various fuels such as petroleum, coal, natural gas and other gases while nuclear power plant uses the uranium as its fuel.

2.4.2.5 Hydroelectricity plant

Hydro electricity uses the power of mass which is come from dropping the water from height to a lower level. Generally, dam is the most commonly using system for holding the water and allowing the water to flow to the turbine. (SEDA Renewable Energy Web site)

2.4.3 Oil infrastructure

In the Wikipedia encyclopedia, crude oil was defined as below.

Crude oil: Petroleum or crude oil is a black, dark brown or greenish liquid found in porous rock formations in the earth.

Crude oil was transformed to useful petroleum product such as gasoline, kerosene and diesel at the oil refinery. Typically, oil processing in the refinery factory consists of three steps: fractional distillation, conversion and treatment. (www.moorlandschool.co.uk)

Figure 2.9 shows us so simple diagram which represents what kinds of petroleum product was produced at the certain temperature level. Also, Figure shows that refined products are broke down into different products.

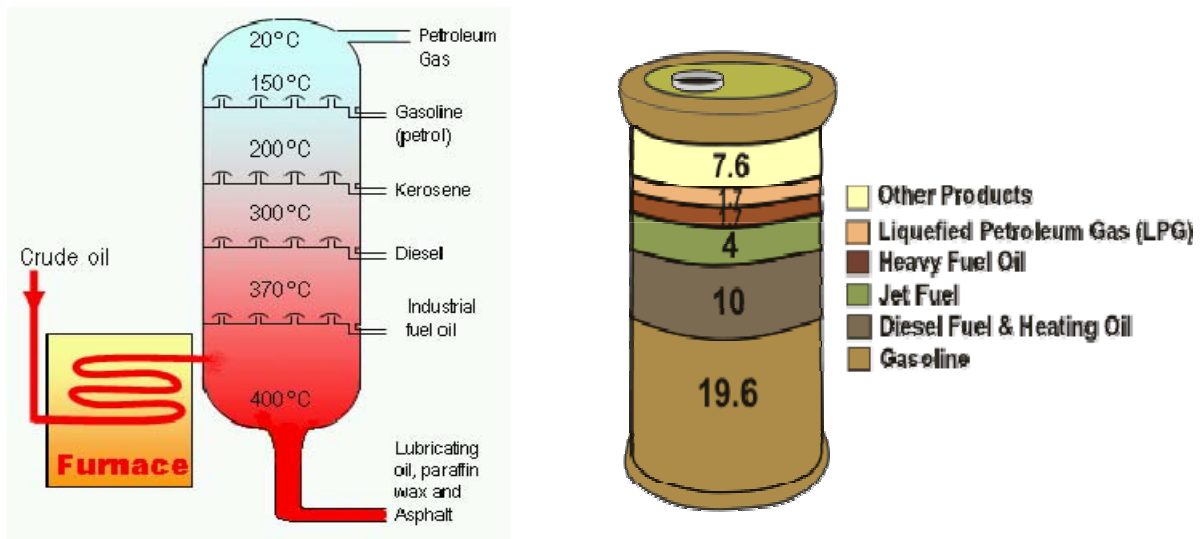


Figure 2.9 Production by temperature and production made from a crude oil (EIA.com)

After crude oil is refined into various products, these products are distributed to customers by transportation such as ship and truck or by pipeline.

2.4.4 Natural Gas

Since natural gas produced at the gas well mostly contains contaminants, it should be cleaned before it can be transported to the pipelines. (EIA, 2006:1)

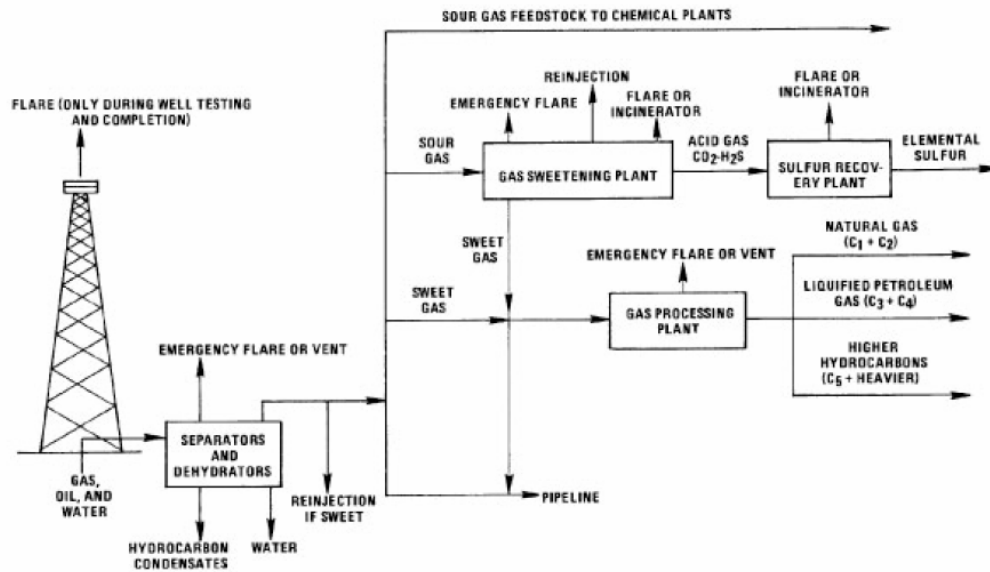


Figure 2.10 Natural gas industry

Simple process of natural gas system introduced as follow. All data was come from natural gas company Aquila's web site. (www.aquila.com)

1. Natural gas is flushed out from the ground through gas wells. The pressure of the gas allows it to rise to surface naturally.
2. Once in the well, the gas is treated and cleansed of any sand, dust contaminants and water.
3. In order to meet year-round customer demand, gas is compressed in the underground storage fields between April and October when demand is low. During cold weather months, the gas is drawn out
4. A compressor station increases the gas pressure to move it through a network of mostly underground lines.

5. High pressure pipelines transport the gas to the distribution system through a network of mostly underground lines.
6. Regulators reduce the pressure of the gas entering the distribution system and inject an odorant into the gas so that its presence can be detected.
7. The distribution system consists of both medium and low pressure mains which distribute the gas from the regulator station to the customer.
8. Individual pipes connect the distribution system to the customer.

2.5 Dynamic system

Rinaldi put a stress on dynamic simulation when we model and simulate the multiple infrastructures as a one of the approaches. (Rinaldi, 2004:5) Each infrastructure generates the commodities and services to others. Also, there are consecutive activities such as distribution and consumption. Those kinds of activities can be represented as a flow and an accumulation in the sense of dynamic simulation. (Rinaldi, 2004:6)

Some useful notations are explained in the *Business Dynamics* (Systems Thinking and modeling for a Complex World, John D. Sterman, 2000). The full model is assembled by replicating the generic project phase. For example, if the major activity is ship construction, then construction was divided into various activities (e.g., hull, piping, etc.) Also, workforce of ship construction was disaggregated by several crews (e.g., steelworkers, electricians, etc.). In this case, the individual generic phases were linked by overall program management structure. (Business Dynamics, 2000:61)

Above of this page, I mentioned complex system such as infrastructure multi-layer can be represented as flow and stocks. Casual diagrams can simply map these activities (Business Dynamics, 2000:190). Following figure is the general structure for stocks and flows.

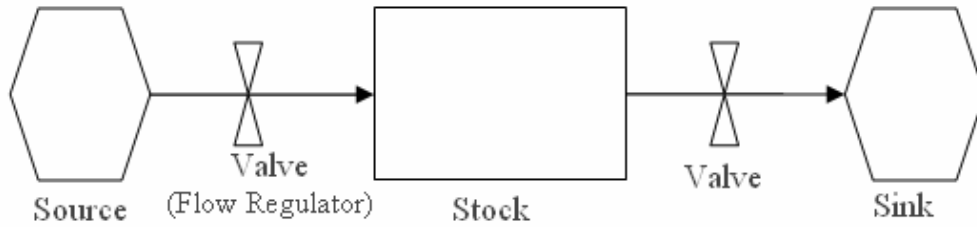


Figure 2.11 Stock and flow diagram (Business dynamics, 2000:193)

The notation of path dependence is introduced which is helpful for assuming the general flow tendency. Sterman illustrated the path dependence as a pattern of behavior in which the final state (i.e., equilibrium) depends on the initial conditions (Business Dynamics, 2000:350). For example, Microsoft's Windows and Intel's processors have control of personal computer market. We could not help admitting this mostly subjective tendency however because we can observe that these assumption has to be true. In other words, eventual ultimate state (i.e., market tendency of P.C.) of a path-dependent system relies upon the initial state (i.e., a bullish factor of Microsoft or Intel) (Business Dynamics, 2000:350). By using path-dependent notation, flow tendency of each infrastructure in my model (e.g., Electrical power usage of water system, the composition of refinery output) was determined hypothetically from earlier historical data. Various assumptions and further information will be examined at chapter 3. Following simple equation account for how the notation can be applied.

$$Occurrence_of_EventA = \begin{cases} 1: If_Random_number \leq EventA_proportion \\ 0: Otherwise \end{cases}$$

$$Occurrence_of_EventB = \begin{cases} 1: If(1 - Random_number) \leq EventB_proportion \\ 0: Otherwise \end{cases}$$

2.6 Design of experiment

There are three fundamental concepts in DOE those are control, replication, and randomization. (Sanchez, 2005:69) Sanchez defined those three concepts as follow. Control implies that conduct the experiment with systematic manner not trial-and-error approach. Replication means that the experiment is conducted in order to gain enough data which allows narrow confidence intervals and reliable hypothesis test. Randomization can be regarded as probabilistic guard for considering the unknown and randomness characters of real data (Sanchez, 2005:69) Douglas C. Montgomery introduced same notation instead he defined three fundamental element as replication, randomization, and blocking which is corresponding to the control. (D. C. Montgomery, 6th edition: 12)

2.6.1 2^k Factorial Design

2^k design is the most commonly used factorial design. Two levels can be represented as low and high, or -1 and +1. Figure 2.12 shows examples for 2^2 and 2^3 factorial designs.

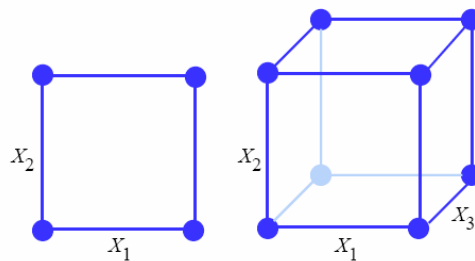


Figure 2.12 2^2 and 2^3 Factorial Design (Sanchez, 2005:74)

Sanchez examined nice properties of factorial designs. At first, factorial designs allows us to identify significant interaction effects. Also, since it is orthogonal design,

analysis of output is simplified because estimates of factor effects and R^2 are not depending on other terms. (Sanchez, 2005:73) Moreover, 2^k design is the useful with related to response surface study because 2^k design is a basic building block for central composite design; one of the most powerful designs. (Myers, 2nd Ed: 85)

Sanchez gave us two solutions when we are faced estimation problem with respect to the degree of freedom. One of those is replication. Replication let us to get degree of freedom and allows identifying smaller effects by reducing the β 's standard error. (Sanchez, 2005:74) Another approach is assumption making. By assuming that does not consider high order interaction term, we can obtain enough degree of freedom. (Sanchez, 2005:74)

2.6.2 Meta-models

Sometimes, we might want to know which parameters and structural assumptions have the strongest effect to optimal performance. In the sense of design of experiment (DOE), parameters and structural assumption are regarded as *factors*, and output is regarded as *responses* (Averill. M. Law, 2000:622). In simulation design, *design of experiment* provides decision before conducting the simulation runs with a certain configurations in the least amount of times (Averill, M. Law, 2000:623). For example, in the rebuilding model, if we have no idea about the factors such as the priority of infrastructure at the 1st week, then we should find out what factors affects significantly to the response that is total duration to finish the rebuilding by trying all combinations or just randomly trying some configurations. However, if we learned about the characteristic

of factors such as ‘since transportation are related to all infrastructure, it might have the first priority at the first time’, then we may want find out more detail behavior of factors and model. In this case, the *meta-modeling* and *response surface methodologies* techniques can be used to achieve those kinds of goals. (Averill, M. Law, 2000:623)

Also, we can regard the simulation model as a *function* because after it takes the some input parameters, it yields an output performance measure corresponding to input data. (Averill, M. Law, 2000:646)

A response surface methodology is the technique that uses the plot to represent the numerical characteristic of the function. (April et al, 2003:71)

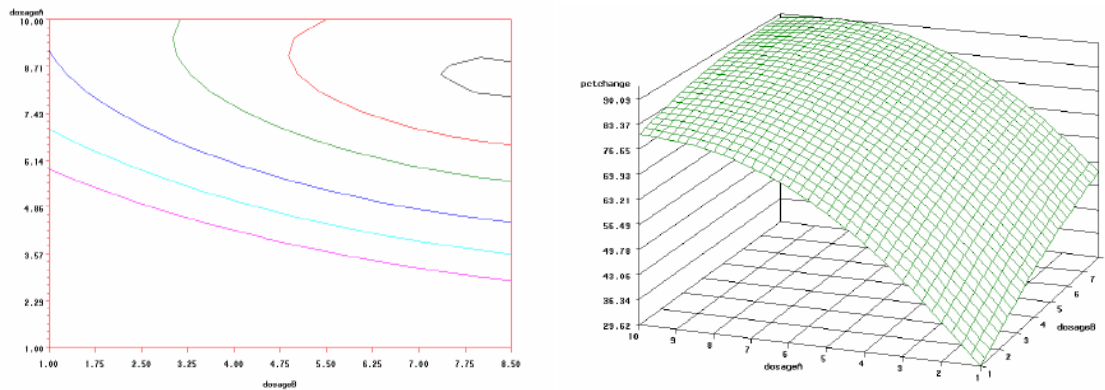


Figure 2.13 Response surface example

Above two figures are the examples of response surface figure. However, to plot such a graph, we need to iterate the run in hundreds of times or more. And, in some cases, complex simulation model takes a lot of times to get a single run output. In that case, rather than response surface, simple algebraic representation might be the worthwhile. That’s the concept of meta-model. (Averill, M. Law, 2000:648)

A meta-model is an algebraic representation of simulation system so that optimizers use it instead of real simulation model. In other words, meta-model approximately express the response. (April *et al*, 2003:71)

Now, with related to heuristic method which will be discussed at the next section, let's look at how heuristic method and meta-model are combined.

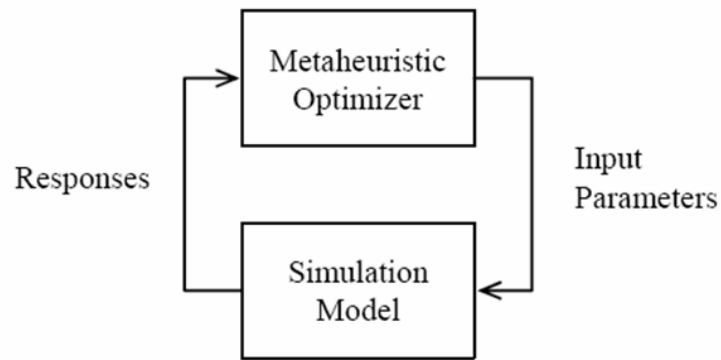


Figure 2.14 Black box approach (April *et al*, 2003:73)

Above figure is the black box approach. (April *et al*, 2003:73) It shows us how meta-heuristic and simulation model interact to each other. Optimizer is similar to 'optimization package' which introduced in Averill's. (Refer Averill, 2000:663) In the optimizer, particular configurations are decided by optimization fashion. Then, simulation model uses it as input parameters. If the obtained response is not satisfying the stopping criterion, then other configurations were set up and used for input parameters again.

Combined all concepts discussed, let me give an example in terms of infrastructure rebuilding model. Following diagram is based on Averill's (Averill, M. Law, 2000:663)

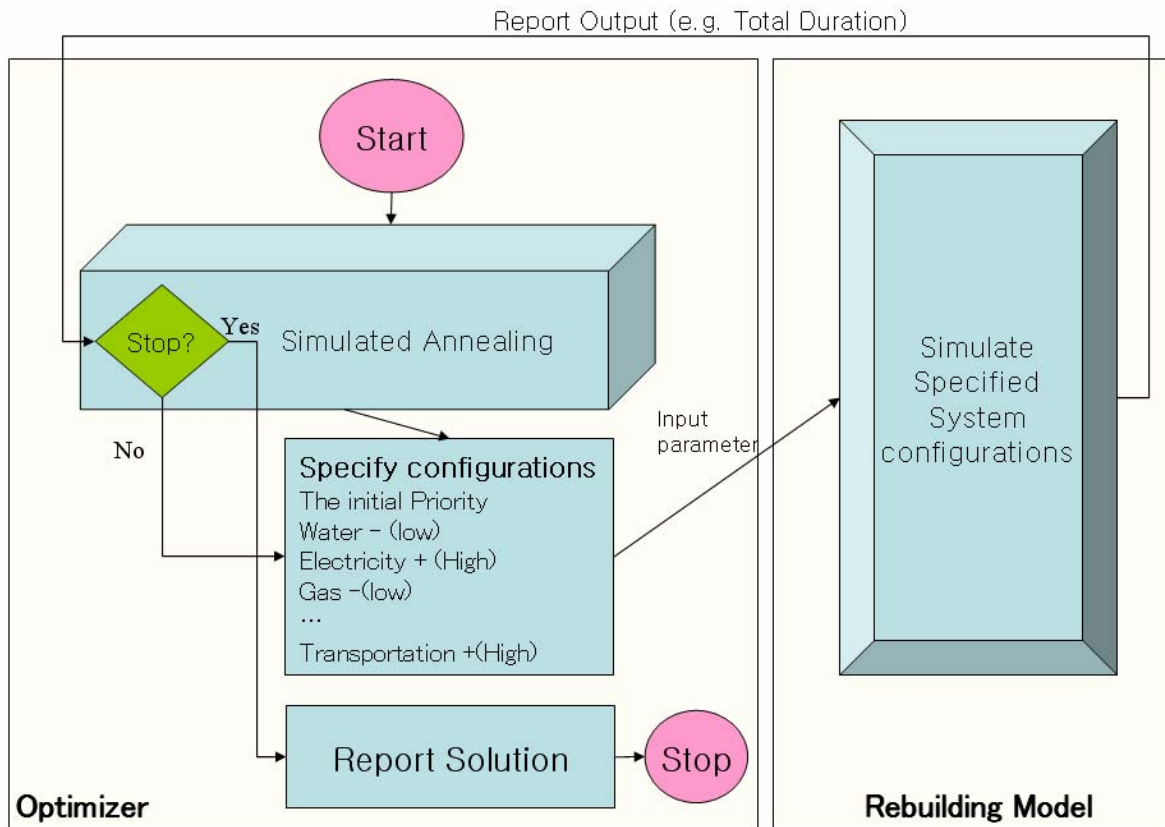


Figure 2.15 Black box approach example (Based on Averill, M. Law, 2000:663)

Assume that simulation optimization technique (Heuristic) was selected as simulated annealing. Once, simulation runs, initial solution was obtained and simulation optimization was conducted. In the DOE sense, the priority can be represented by (-), (+) levels or (-), 0, (+). This configuration was used as input parameter for rebuilding model. And, the response (e.g. the total duration to finish the rebuilding phase) would send to optimizer to judge it is optimal or not by the threshold criterion. If is not, local search occurs in the SA optimizer, alternatives then was obtained. In certain iterations, we can get an optimal solution.

2.7 Simulation optimization

A simulation technique is very useful tool itself for evaluating performance of system. However, there are some cases that simulation is not sufficient for evaluating the system. (Sigurdur, 2002:1) For example, in the case of rebuilding model, we are interested in “total duration to finish the rebuilding the infrastructure”. But, we don’t have enough time since rebuilding phase can not be long term problem. In the simulation model, we can iterate the run to figure out what factors affect significantly and what combinations of infrastructure makes the decision variables (i.e. duration) to be minimized. We may find the optimal value via a lot of iterations. But, it may take hundreds runs or more. If we are restricted by time, then lots of iterations is not good approach. Also, in this case, we strongly depend on user’s conjecture. Even though, we can guess approximately the combination of infrastructure by intuition, sometimes we may not expect any configurations since the both real world and simulation model are very complex. Hence, we need the simulation optimization techniques to find out the optimal value (best configuration) within an appropriate time with systematical approach. Sigurdur defines the simulation optimization as follows in his article.

Simulation optimization is the process of finding the best values of some decision variables for a system where the performance is evaluated based on the output of simulation model of this system. (Sigurdur, 2002:1)

Feasible region is big issue in the simulation optimization since there need constraints to find realistic value. For instance, in the rebuilding model again, the feasible region was limited according to the available resources such as a number of vehicles we can use in a day or an amount of pipes we can construct in a day. Also, time limitation would limit the

feasible region. For instance, the optimal value would not exceed the maximum duration which is stated by FEMA director.

Min *et al* proposed the decision support system based on system dynamic approach with nonlinear algorithms (Min *et al*, 2007:65). They tried to maximize the total economic revenue of all infrastructure and economic facilities in the case of power disruption. They used MINOS optimization package (Min *et al*, 2007:62). MINOS which is introduced by *Murtagh and Sanders* at 1998 is the popular nonlinear optimization package based on gradient and quasi-Newton algorithms (Min *et al*, 2007:62).

2.7.1 Meta-heuristic (Simulated Annealing)

Even though, heuristic method does not guarantee the exact optimal solution, this method is frequently used in recent days because of its properties which are fast computation and easy applicableness. (Reeves, 1993) The purpose of heuristic methods is to detect the solutions under time limited situation. Thus, time is more important than quality of problem solution. (Barr *et al*, 1995:2) Also, Barr *et al* indicated the cases that new heuristic method is accepted if it is: Fast, Accurate, Robust, Simple, High-impact, Generalize-able, Innovative (Barr *et al*, 1995:5).

The name of Simulated Annealing (SA) is derived from metallurgy annealing techniques that contain heating and cooling the material to enhance its strength. (Wikipedia encyclopedia) The inner loop and outer loop are composed as follows.

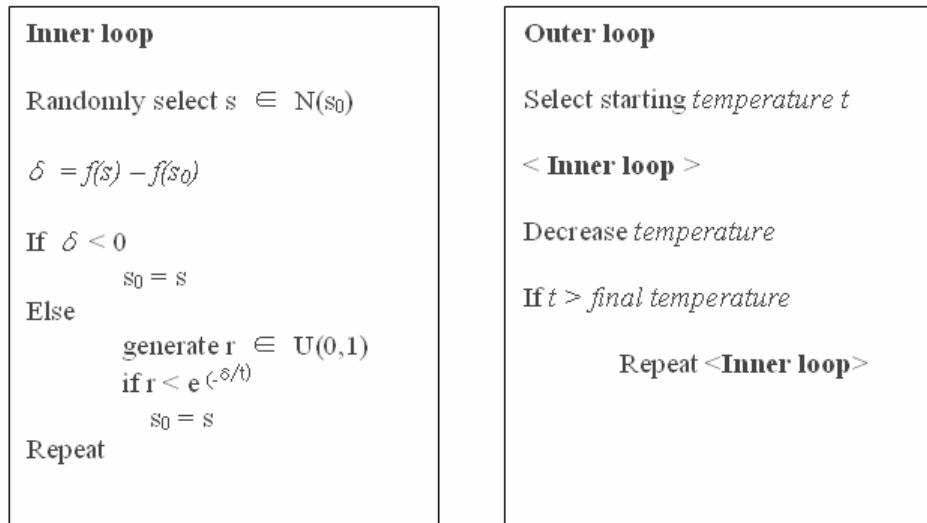


Figure 2.16 SA pseudo code (Kinney. Class handout, OPER623, winter 2006)

Following examples let us understand simulated annealing easily. When we roll red ball down a slope from initial point, ball may fall into local minima. In order to exit the local minima we should wave the hill. If we wave the hill with strength that the ball barely can escape the local, the ball may get to the global minima. In the Simulated annealing the strength that wave the hill have to be strong at the first time and decreased gradually until the strength come to the zero. We can regard this strength as temperature at the SA algorithms. In other words, start with high temperature and after certain number of iterations, temperature is decreased. Process is repeated until final temperature is reached. The idea is to achieve thermal equilibrium at each temperature.

Most of people say that the essential feature of the SA method is cooling schedule.(Aarts *et al*, 1997) In the geometric case, cooling formula is $t=at$. If a value is very small such as 0.1 , then algorithms reduces the temperature very fast. On the other hand, a value near 1 means slow cooling.

The acceptance criterion is also important. We usually use the following equation which follows Metropolis MC as an acceptance criterion that allows non-improve movement.

$$\text{Exponential}\left(\frac{f(s) - f(s_0)}{T}\right) \geq \text{Random}(0,1)$$

III. Methodology

3.1 Introduction

Even though I examined simple introduction on infrastructures at the chapter 2, it is still difficult to understand because each infrastructure is so complex. Hence, I tried to account for how the overall model and sub model are simulated as detail as I can. First, the restrictions that I faced during the data collection are briefly introduced. Secondly, global rebuilding model is examined. Following sections dealt with three important sub-models those are physical, information, and spatial network with fully depicted diagram and descriptions on that. Last of section is devoted to present heuristic optimization technique. Finally, conclusion followed.

3.2 Data collection

Data collection is one of the difficult parts of whole modeling process. At first, there are too many parameters should be observed. For example, however we consider only electric power sub model, there are about 50 parameters to be estimated for constructing the sub-model. (e.g., capacity of nuclear reactor, water usage of cooling tower,..., capacity of transmission line) Secondly, systematically sorted data package does not exist on the web. It forces me to wander various web sites in order to obtain appropriate data from several article, news, or annual report. Another problem what I met during a journey for collecting data is that data is not identical according to the data source. For example, certain source posted the total amount of oil wells in Louisiana is 19,970 while other sources introduced the number of oil wells as 21,962. The differences

may be caused by own criterion on definition of infrastructure or regional category. At third, I found that previous data may not be useful because earlier data is not independent of current data. For example, on the official energy statistics (Energy Information Administration, 2004), wind electric net capacity is reported as follow: 2000(2,377 Megawatts), 2001(3,864 Megawatts), 2002(4,417 Megawatts), 2003(5,995 Megawatts), 2004(6,010 Megawatts). In that case, does using the mean value (i.e., 4,532 Megawatts) of 5 years data as *expected wind capacity* is reasonable? Obviously, it is not because even if we don't test it whether it is independent or not, intuitively, increasing trends tells us that there may be the technical development on wind electricity plant or there may be the encouragement to use renewable energy. Hence, the reasonable estimator of *expected wind capacity* for following year is not a mean value (i.e., 4,532 Megawatts) but a latest data (i.e., 6,010 Megawatts). Finally, most of critical infrastructure data on the web is firmly secured because of safety regulations. For instance, pipeline data is only accessible to the federal, state and local government agencies.

Above problems are settled by simplest solution that is making assumption. The limitations on lack of data are solved by corresponding assumption. And, I referred all assumptions for further study.

3.3 Global rebuilding model

Global rebuilding model is divided into three layers: physical, information, and spatial. However, each network is not externally distinguished. In other words, global model is consisted of not expressly three sub-models but rather conceptual three sub-models. For example, physical network sometimes deal with variables such as 'rebuilding

rate' which is belongs to information network. Or, some variables are jointly used amongst three layers. In summary, global rebuilding model operate by three inter-acting sub-models.

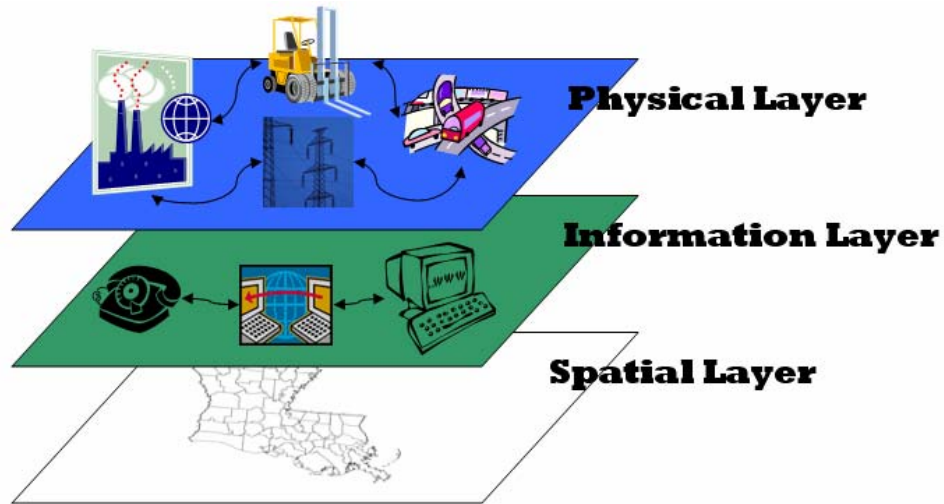


Figure 3.1 Three inter-acting sub-models

Physical layer is the dynamic flow model in which deal with all physical flows. Physical flows contain the amount of power generation, product of oil refinery, or anything whatever it is transported from start node (e.g., oil wells) to destination node (e.g., oil pipeline). Model is unlike common dynamic flow model to consider pipeline or transmission line as a not link but a node. I expressed overall physical layer by using the *MATLAB*.

Information layer is the mathematical model in which deal with mostly mathematical calculation. In order to understand the role of information layer, let you regard it as a kind of decision maker. Decision maker can oversee and control all physical flows. He gives consequence to most important infrastructure. Also, he has to act as a

mediator between demand and supply. In the global model, information layer play such a decision maker's role.

Spatial layer is the grid-based layer in which provide coordinate information of corresponding infrastructure in the physical layer.

Three distinct sub-models are fully examined at the following section.

3.4 Physical network

3.4.1 Electronic infrastructure

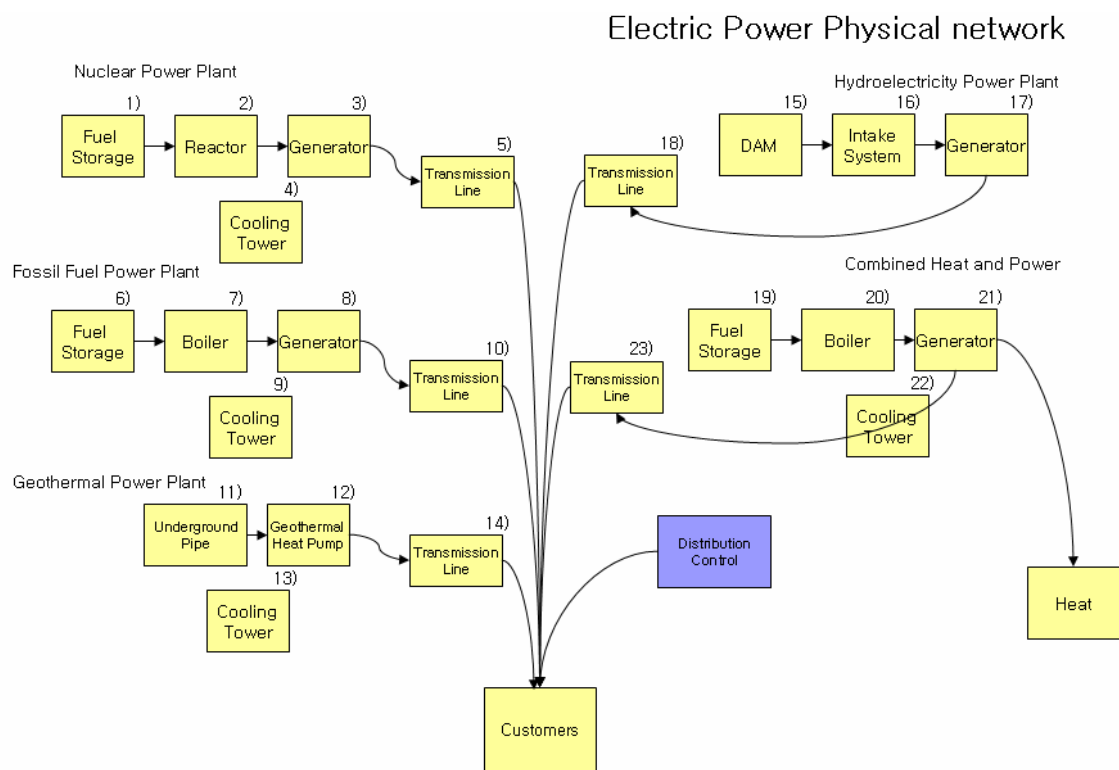


Figure 3.2 Power infrastructure physical layer

I'll go over above diagram from left-top side that is nuclear power plant. Fuel storage¹⁾ needs Uranium as its input source. Hence, the first condition for nuclear power

plant to be operated is that transportation infrastructure has to be restored. Because, transportation infrastructure can deliver resources for repairing such as crews, stuffs and it also can transport the Uranium (fuel). Most of agents in the sub-infrastructure model needs transportation infrastructure in order to be restored. Each agent has *state*. Fuel storage agent state is represented by percentage. And, we can regard it as a *capacity*. For example, 45% of current state means that 45 tons of Uranium can be stored in the fuel storage under the assumption that fully recovered fuel storage can hold 100 tons. Reactor²⁾ takes fuel to make progressing power. Progressing power is the just conceptual word in order to represent previous status of power. Thus, progressing power is not real existed output. Progressing power becomes the power (Megawatt/hrs) by generator³⁾. In the model, some agents are affected by another agent. For example, reactor and generator have their state respectively. However, reactor and generator are affected by cooling tower⁴⁾. It means that even though reactor is perfectly recovered, it can not generate progressing power unless cooling tower is repaired to a certain degree.

Next plant will be examined is fossil fuel power plant. Fossil fuel plant has to store fuel (Coal / Petroleum / Natural Gas / other gases) in the fuel storage⁶⁾. We can found that fuel storage needs transportation infrastructure as same as nuclear fuel storage, and it also needs natural gas infrastructure and oil infrastructure for storing the fuel. Boiler⁷⁾ and Generator⁸⁾ generate the power from a various kinds of fuel. Boiler needs waters for steam. It means that boiler agent is correlated with water infrastructure. Generated powers from different sources are represented respectively. Remaining agents are not different as nuclear power plant.

Geothermal plant uses geothermal heat for energy source. Likewise the water source, geothermal heat is considered as infinite. Geothermal heat is collected by underground pipe¹¹⁾. And, geothermal heat pump¹²⁾ needs water in order to transform it into a heated steam.

Hydroelectricity power plant is consisted of a dam, intake system, and a generator. Dam¹⁵⁾ is actually belongs to water infrastructure. The amount of water generated by hydroelectricity plant is strongly depends on the condition of dam. Intake system¹⁶⁾ is the facilities that gathering and controlling the water from dam to generator¹⁷⁾. Intake system includes penstock.

The basic notion of Combined Heat and Power (CHP) is introduced at the chapter 2. In the physical network model, CHP is almost same as fossil fuel plant except that the final outputs are divided into power and heat. Heat is another product of CHP and it is represented as just variables.

The agent that is not introduced yet is transmission line. This agent is not only modeled in the physical network but also represented in the spatial network. Transmission line in the model is the agent what delivers the generated power to customers.

3.4.2 Water Infrastructure

Water infrastructure is composed of two systems that are drinking water system and waste water system. Below diagram represent drinking water system.

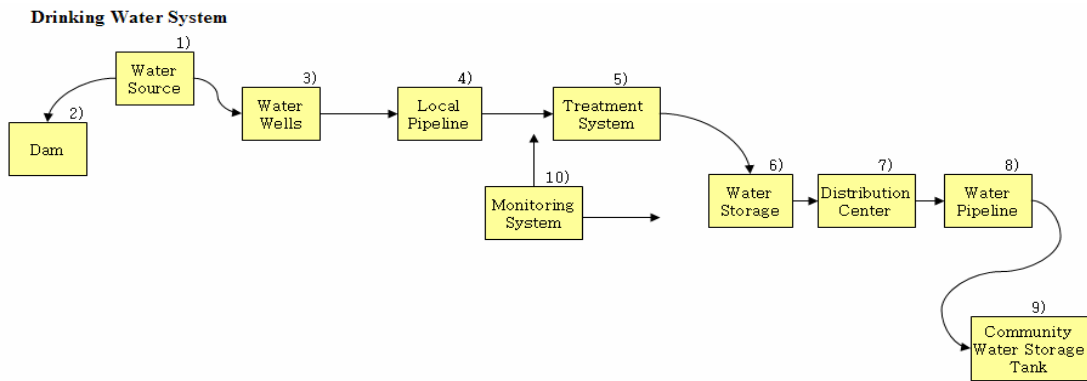


Figure 3.3 Drinking water physical layer

Water source¹⁾ provides water for drinking water system. Water source can be regarded any nature such as river, reservoir, or subterranean water. In the model, water source has infinite resources. In other words, it can supply exact amount of water for demand. Even though, there are two types of water those are spouted out from water source (ground water and surface water), I dealt with both waters as a one. Also, I only consider the water for industrial purpose. It means that residential and commercial purpose water is not modeled since there are no agents like residents or commercial element in the model. Water wells³⁾ are scattered around area and each of water wells are depicted as a spatial agent that has a coordinates. In order for each water well to be restored, two restoration conditions should be fulfilled. One of conditions is transportation. If transportation infrastructure in the vicinity of well is repaired then 1st condition will be satisfied. Another condition for operating the water well is provision of electricity since pump needs power. Now, operated water well affects whole aggregated percentage (i.e., capacity of total water wells) by simply averaging the whole water wells. Note that water wells entity in the physical layer has an aggregated percentage as a

capacity. However, in order to calculate that capacity, information network has to consider all scattered water wells. Local pipeline is belongs to each water well. Treatment system for water⁵⁾ have percentage stage. It means that unlikely water wells it can treat the water even though it is not fully recovered. The amount of water which is treated by treatment system is calculated as follow equation.

*Eq.3.4.1) The amount of treated water = current capacity of treatment system * the amount of water when a system is fully operated.*

Now, treatment systems have treated water as their output flow and there are some losses by treatment ratio.

*Eq.3.4.2) Treated water with loss = the amount of treated water * treatment ratio*

Model forwarded the treated water from treatment system the water storage and distribution center. Distribution command decides where the water sends for and controlled by ‘distribution control’ agent in the information network. In order to supply the water to population, distribution center has to obtain permission from Monitoring System¹⁰⁾. Monitoring system is the facilities which inspect the water quality whether it is potable or not. Monitoring system needs power to be operated. Thus, if *state of monitor system is operate and needed power for monitoring system is satisfied* then it checks the *quality of current water*. This monitor system is concerned about only potable water that should be supplied for the population. Water for industry (i.e., other infrastructures) does not need quality permission.

Waste Water System

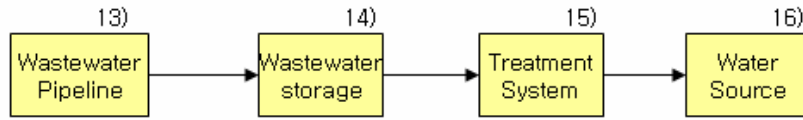


Figure 3.4 Waste water physical layer

There follow waste water system. Wastewater pipeline¹³⁾ serves for all infrastructures. Wastewater Treatment system¹⁵⁾ dispose the waste material and send purified water back to the water source¹⁶⁾. Disposal process needs transportation infrastructure.

3.4.3 Oil infrastructure

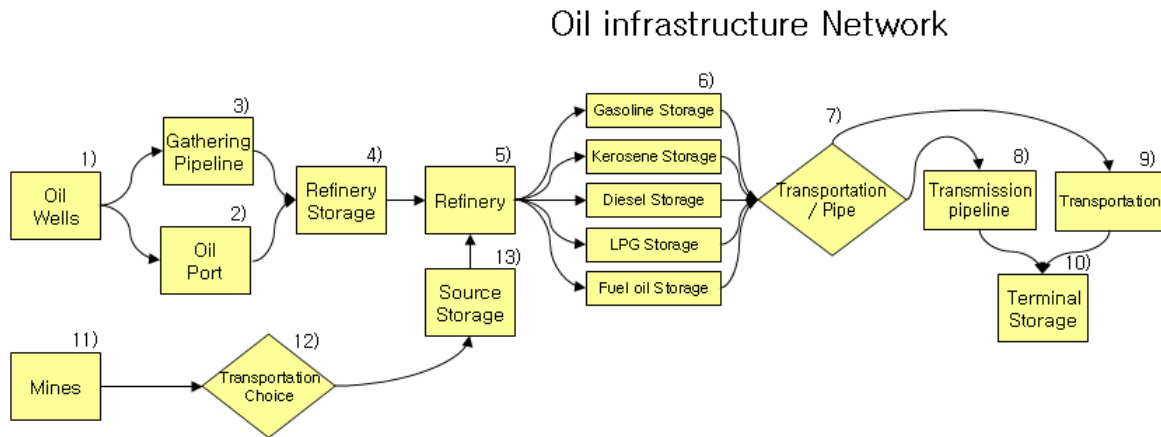


Figure 3.5 Oil infrastructure physical layer

Raw oil is collected by oil wells¹⁾. The amount of crude oil extracted by oil well is estimated by following equation.

$$Eq.3.4.3) \text{ crude oil from oil wells} = \text{capacity of oil wells} * 207,000 \text{ (Barrels)}$$

Where, 207,000 is the total amount of crude oil when oil wells are in the normal condition. In this case, I know the mean value of amount of crude oil however there are no further information in terms of its variance or distribution.

Since, the model uses the day as a time unit, all parameter have to be converted into day unit. For example, unit of above value is the barrels per day. Crude oil is delivered by using two possible measures those are oil port and pipeline. In the real world, gathering pipeline and transmission pipeline is not same. However, as I mentioned before, because of lack of information, I could not get the information of both. It forces me to make an assumption that crude oil uses the same pipeline whatever it is gathering pipeline or transmission pipeline. Refinery storage keeps the raw oil in order for refinery⁵⁾ can use raw oil. Only a satisfaction of raw oil can not allow refinery to produce the various products because refinery needs coal that is dig out from mines¹¹⁾. Mines (Coal industry) generate coal from an infinite source and it highly depends on transportation infrastructure since transportation is the only way to deliver. In the decision on transportation measure, mines need to choose amongst rail, truck, barge / other as their shipping measure. In other words, mine agent is interested in a sub-infrastructure capacity not an overall transportation infrastructure capacity. Likewise real world, in the model, refinery in the state needs not only crude oil in the state but also one the imported from other states or foreign. Three kinds of external agents those are OCS, foreign and other state supply the crude oil for state. OCS means that Outer Continental Shelf. As I introduced at the literature review, refinery can produce 6 kinds of products

(Gasoline / Kerosene / Diesel / LPG / Fuel Oil / asphalt) by historical rate. For example, amount of gasoline products is estimated by following equation.

*Eq.3.4.4) product Gasoline = crude oil in the refinery storage * 19.5 * capacity of oil refinery.*

When a final product is generated, decision on delivery method for that should be conducted. This agent has an inclination toward information network. Based on capacity of transmission pipeline and transportation, agent makes decision whether products are delivered by pipeline or transportation. Even though in real world there are designated routes for each production, I need to assume that 6 productions can be delivered by same transmission pipeline.

Assumption: transmission pipeline can deliver any of 6 productions.

3.4.4 Natural Gas infrastructure

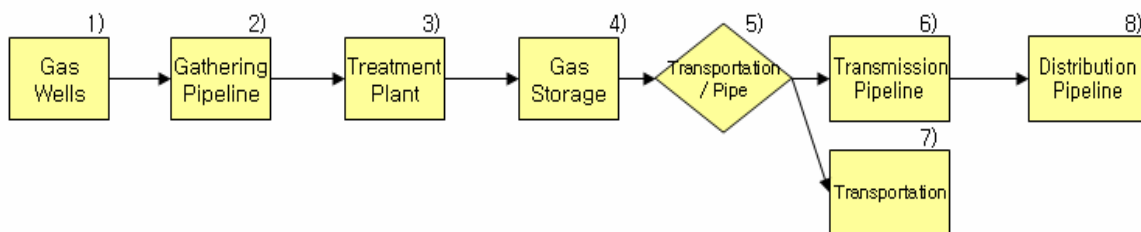


Figure 3.6 Natural gas infrastructure physical layer

Natural gas physical structure is as simple as you can see above. Various gas wells spread out over the region. Gathering pipeline is the only agent that represented in the spatial layer in the natural gas sub-model.

Gathering pipeline can not transmit 100% contents to treatment plant since there are some factors that affect the efficiency of pipeline. Whatever factors are, we named it as *loss rate*. By applying the loss rate, output of gathering pipeline will be $Raw\ gas * (1 - loss\ rate\ by\ gathering\ pipeline)$. The concept of raw ratio can be applied for any pipeline in other infrastructure or treatment systems.

3.4.5 Transportation infrastructure

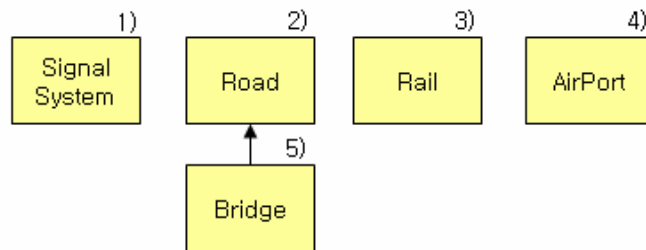


Figure 3.7 Transportation infrastructure physical layer


As you can see above figure, transportation physical layer is consisted of 4 distinct agents those are not affected by each other except the bridge; bridge agent is belongs to road agent. Signal System¹⁾ affect the whole transportations (i.e., road, rail, Airport) in real world. However in the model, it is represented as one of agents in the physical layer. It means that even though signal system is destroyed completely, there are still traffics in the road because even though there is no signal traffic at all, vehicles can move with very careful in real world. Road²⁾ also needs transportation itself to be repaired. And it needs certain amount of asphalt for repairing (i.e., oil infrastructure). Gasoline, diesel and LPG also needed for transportation system because the vehicles are included in transportation system. Likewise pipeline, each segment on the grid system

has percentage. Also, aggregated percentage represents whole road's state. Output of road agent is road transportation capacity. Output of transportation infrastructure will be examined at the information network. Bridges contribute to capacity of road segment which belongs to. Basically, rail and airport agent is same as road.

In the model, the choice of *unit* of transportation infrastructure output is critical. I defined the transportation unit as follow.

Unit: When a particular system is completely destroyed, it needs unit for repairing in a day.

Table 3.1 Example on refinery rebuilding

Infrastructure	Current Capacity	Need Workers	Need Trucks	Rebuilding Time
 Refinery	0% (Completely Destroyed)	100	0	30 Days
	30% (70% Destroyed)	70	0	30 Days
	30% (70% Destroyed)	30	0	70 Days

For example, let me assume that refinery in the oil infrastructure is disrupted and estimated current capacity is 30%. Also we assume that when refinery is totally damaged it needs 100 crews in order to rebuild the refinery in 30 days. Because current capacity is 30% the refinery needs 70 crews; current capacity 30 % is equal to 70% destroyed. Then the number of crews that is needed for repairing in a day is still 70 until at least 30 days. However, if there is another disruption so that can not allocate whole resources to refinery, then refinery may not be restored in 30 days. Now, think of end days of

rebuilding as 70 days not 30 days. Since disrupted refinery needs 70 persons for 30 days we can estimate that now 30 crews are needed for 70 days. Of course, unrealistically, other factors such as synergy effect when crews are aggregated are not considered here. Unfortunately, there are no clues with related to resources for repairing the refinery now. So, simply *I assumed that refinery needs 30 crews in a day in order to restore the system within a fixed α days*. If α is fixed whatever the number is, then the number of crews for any other infrastructures will be estimated with criterion that it must be restored within α days. Now, the crews become *unit* for modeling. In same fashion, even though I introduced the crews as a resource, we can think *unit* as the number of trucks with certain tones or their combinations. The amount of *unit* for repairing the particular system is decided by intuition. I left the scientific approach for estimating the rebuild resources for further study and it will be discussed at chapter 5. Criterion on deciding the amount of unit for repairing certain system is examined below.

Assumption

- 1) *The widely spread system needs 50 units. (E.g. pipeline, oil wells, road)*
- 2) *The major (main) system needs 30 units. (E.g. treatment plant, refinery)*
- 3) *The sub-agent of main plant needs 20 units. (E.g. storage)*

Table 3.2 Transporation unit of oil infrastructure

<i>Coal Mines</i>	<i>Source Storage</i>	<i>Oil Wells</i>	<i>Oil Pipeline</i>	<i>Oil Ports</i>	<i>Refinery Storage</i>	<i>Refinery</i>	<i>Terminal Storage</i>
20	20	50	50	30	20	30	20

Above table shows how the assumption is adopted. Since oil wells and oil pipeline are distributed to various areas, it needs 50 units. Since refinery is not the one that scattered widely compared to pipelines and since it is the main system it needs 30 units. Refinery storage is sub-agent of that main system (i.e., refinery) so it needs 20 units. However, of course, it may mainly depend on size of system. That's the reason why oil ports needs 30 units even though it is distributed to wide range; indeed, oil ports are clustered in particular region.

3.4.6 Telecommunication infrastructure

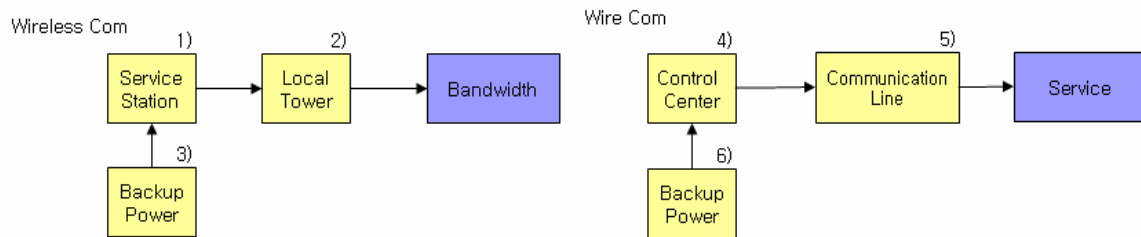


Figure 3.8 Telecommunication physical layer

In the physical layer, telecommunication infrastructure is consisted of wireless Service and wire service. Wireless services include cell phone and internet service. Service station¹⁾ depicts a commercial station belongs to company such as Cingular, Verizon Wireless, and Sprint in real world. Service station needs power for providing service (i.e., Bandwidth). Telecommunication infrastructure provides the service to not a specific industry but an area.

Since a telecommunication service is critical in a real world, there are a lot of communication facilities which have its own generator for managing the emergency

situations. Back-up power³⁾ includes both electricity and battery backup. Assumption here is that back-up power is only available within 10 days after it operates. It means that after 10 days, telecommunication infrastructure is dependent to electrical infrastructure. Wire service in the model is representing the Public Switched Telephone Network in real world. Wire service includes all possible products that are provided by using wire (Internet, telephone, voice mail, etc). Control center⁴⁾ has electronic switches. Thus, it needs power and there is back-up power same as wireless substation.

3.5 Information layer

3.5.1 Electronic infrastructure

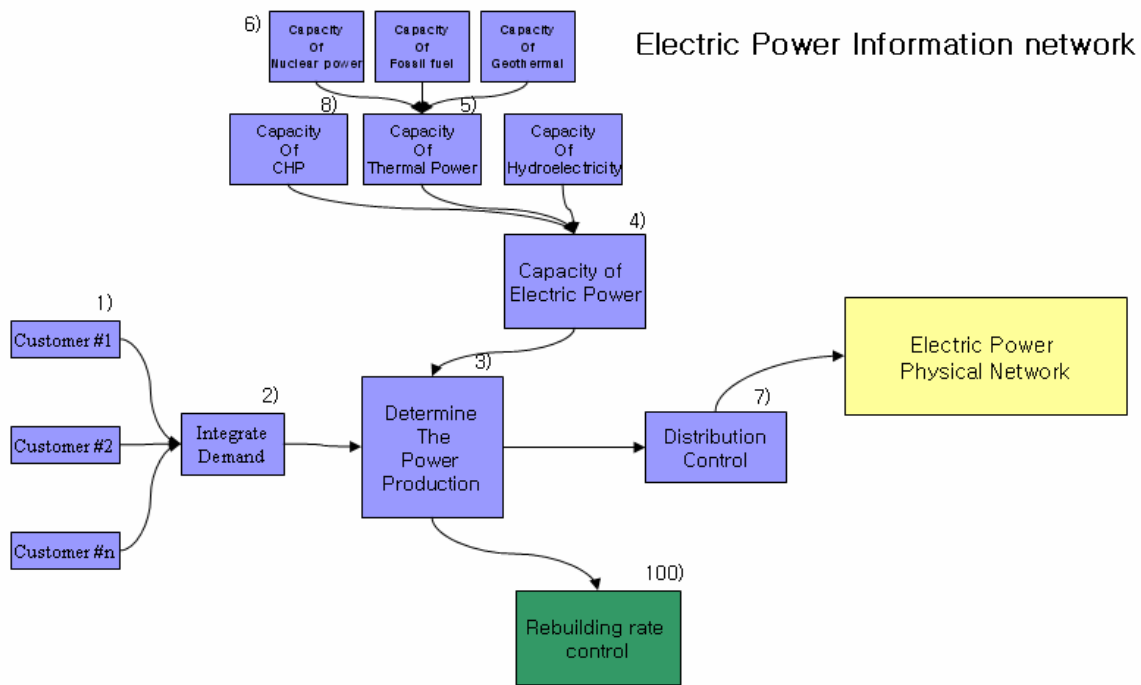


Figure 3.9 Power infrastructure information layer

Each customer can be regarded as any infrastructure. For example, customer #1 can be the drinking water system which needs certain amount of (Megawatt/hrs)

electricity power for pumping and treating the water. All demands of customers with related to electricity are collected by Integrate Demand agent.

Total demands = customer #1 demand + ... + customer #n demand

And, define the total power demand as '*total_demand_power*'. Since electricity infrastructure took requests, model should determine the amount of power production. Then, how much of power should be generated? Does it have to generate exactly same amount of power corresponding the demands? Or, just capacity of power plants should be produced without consideration of demand? The answer is not simple like those. In order to make a decision on the amount of power generation, *both supply* of electric power infrastructure and *demand* of power should be considered simultaneously. Now, define the total supply of power infrastructure as '*total_supply_power*'.

If *total_demand_power > total_supply_power*

Then, *Not_available_power = total_demand_power – total_supply_power*.

Now, send the value of *Not_available_power* to Distribution Control⁷⁾ because distribution control agent has to decide which infrastructure would be supplied with the high priority. More detail discussion about the distribution control follows below. And, because we figure out that there is discordance between demand and supply, we should solve this problem. It is obvious that as demand increase, supply has to be increased. In other words, in order to increase the supply, *rebuilding rate* should be increased. However, that is not simple because we don't have enough resources. Problem will be considered at the 'rebuilding rate control agents': Global information network agent.

Whole capacity of electric power infrastructure are determined by combining all categories those are capacity of thermal power, capacity of hydroelectricity power, and capacity of CHP.

Total capacity of power = total capacity of thermal power + total capacity of hydroelectricity + total capacity of CHP

If we look into the capacity of thermal power, by the classification of encyclopedia, thermal power plant is consisted of nuclear power, Fossil fuel power and geothermal / renewable power by the type of fuel. Simply, it is the summation of agents.

Total capacity of thermal power = total capacity of nuclear + total capacity of fossil fuel + total capacity of geothermal

Each capacity of power plant is estimated by the minimum value of agent's capacity. For example, nuclear power plant is consisted of generator, reactor, cooling system, and energy source storage and transmission line. Even though, all other sub agents are in the normal operation status, malfunction of one of them makes limitation of whole nuclear power system's production.

Thus, *total capacity of nuclear = min (capacity of agents)*

3.5.2 Water infrastructure

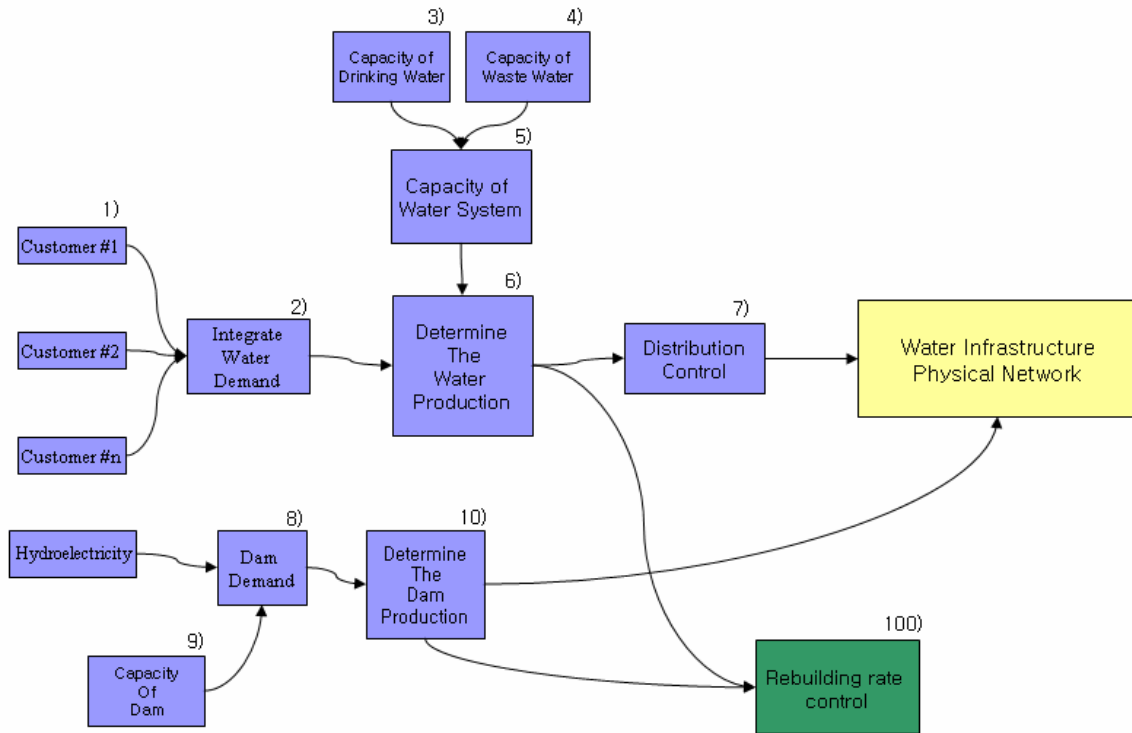


Figure 3.10 Water infrastructure information layer

Customers¹⁾ can be any infrastructure. Hydroelectricity demand is dealt with separately for convenience. Since hydroelectricity needs unique water which obtained from its own supplier dam, demand of hydroelectricity is managed separately. In the water infrastructure information network, only drinking water demand is generated. In other words, waste water demand is not generated. Because, basically, *total amount of drinking water = total amount of waste water*

But, capacity of drinking water³⁾ and capacity of waste water⁴⁾ should be estimated individually.

Capacity of drinking water can be estimated as the minimum value of all agents as follows.

Capacity of drinking water = Min (capacity of water wells, capacity of local pipeline, capacity of treatment system, capacity of water storage, capacity of distribution center, capacity of water pipeline, capacity of community water storage tank)

For example, although water wells can gather the 3,000 barrels in a day, if treatment system only can conduct the 1,000 barrels in a day then water infrastructure system may fall into bottleneck status. Capacity of waste water is same as one for drinking.

Capacity of waste water = min (agents of waste water system)

As I mentioned before, generally, *total amount of drinking water = total amount of waste water*. Thus, *capacity of water system = min (capacity of waste water, capacity of drinking water)*.

Since we estimated the capacity of water system, our interest moves to determine the water production⁷⁾. There are two cases in terms of balance between supply that comes from capacity and the demand.

Case 1) Supply of water system at time $t < Demand of water system at time t$

Then, *Not_available_water = Demand of water system - Supply of water system*

And now, network broadcasts *Not_available_water* to Distribution Control agent⁸⁾.

Because of discordance between supply and demand, *rebuilding rate* of water infrastructure should be increased. '*Rebuilding rate control agent*' will be discussed later.

Case 2) Supply of water system at time $t > Demand of water system at time t$

Basically, it seems to have no problems between supply and demand in this case. However, if we look into this case, there occurs another problem that is ‘sharing the resources’. Note that our ultimate goal is that minimize the rebuilding duration. Thus, we should allocate surplus resources to other infrastructure recovery plans. To deal with all these problems with global information network, send *surplus_capacity_water* to ‘rebuilding rate control agent’

3.5.3 Oil infrastructure

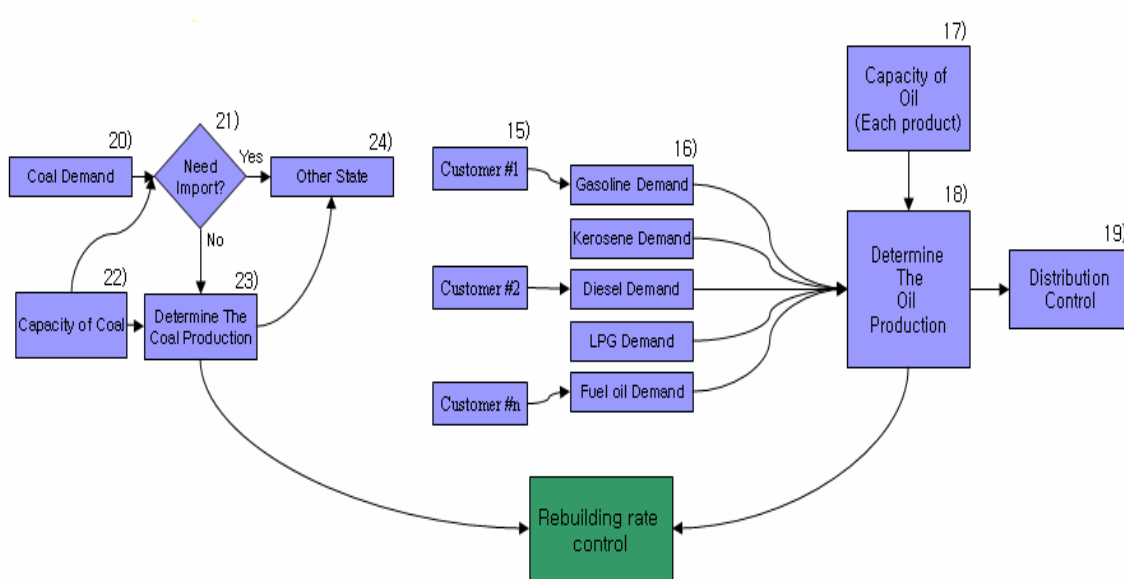


Figure 3.11 Oil infrastructure information layer

Demand on 6 productions¹⁶⁾ are collected separately. Likewise, the amount of each product needs to be assessed respectively. For example, the total amount of gasoline is estimated as follow.

*Total amount of gasoline = capacity of oil system * the amount of gasoline when oil system is 100%*

If the capacity of oil system is 30% and generally, gasoline is generated by 500 (Million gallon / day) when an oil refinery is normal condition, then we can estimate the total amount of gasoline as $500 * 0.3 = 150$ (Million gallon / day).

The one of the particular characteristics in oil infrastructure is that there exist other state²⁴⁾ agent. Let me give you an example on coal. Coal is not only for oil infrastructure rather than electricity plant is the best consumer of coal. However, simply, coal industry is classified into oil infrastructure. In fact, there are only a few states digging the coal with majority. Hence, most of coals in the 'minor-coal' states are the one being imported. Thus, even though all coal industries in the 'minor-coal' area are perfectly recovered, there still exist coal trades. Thus, *Total amount of coal = imported coal from other sources + coal from local*. Since mine is the only agent the coal industry has, *total amount of coal is exactly follow linear relation with capacity of mines*. If decision agent ²¹⁾ decides to import the coal then exterior sources such as other states or foreign generate the certain amount of coal by itself considering own capacity. Amount of coal imported from other state follows distribution function which obtained by historical data.

3.5.4 Natural Gas infrastructure

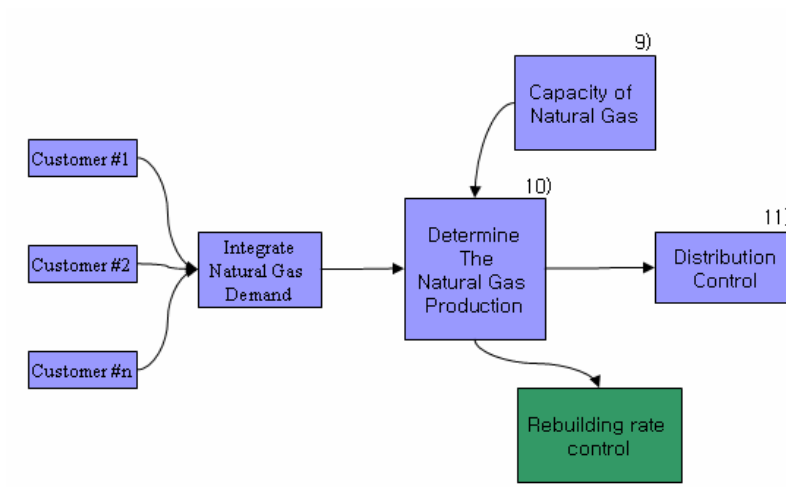


Figure 3.12 Natural gas infrastructure information layer

Basically, organization of natural gas information layer is not different as other infrastructure. Power infrastructure and transportation infrastructure are the major customers. Their demand is integrated and the amount of natural gas production is determined by capacity of natural gas. Now, demand and supply become the issues and there are two cases.

Case 1) Supply of Natural Gas at time $t > Demand of Natural Gas at time t$

Since supply is larger than demand, all customers receive what they had requested.

Case 1) Supply of Natural Gas at time $t < Demand of Natural Gas at time t$

Since demand is larger than supply, somebody has to intervene between demand and supply. That's the role of distribution control¹¹⁾. Distribution control agent at first checks their score that is comes from their priority and the degree of discordance on demand and supply. Now, by the score, available natural gas is allocated into customers. Distribution control is more examined at the section 3.5.7.

3.5.5 Transportation infrastructure

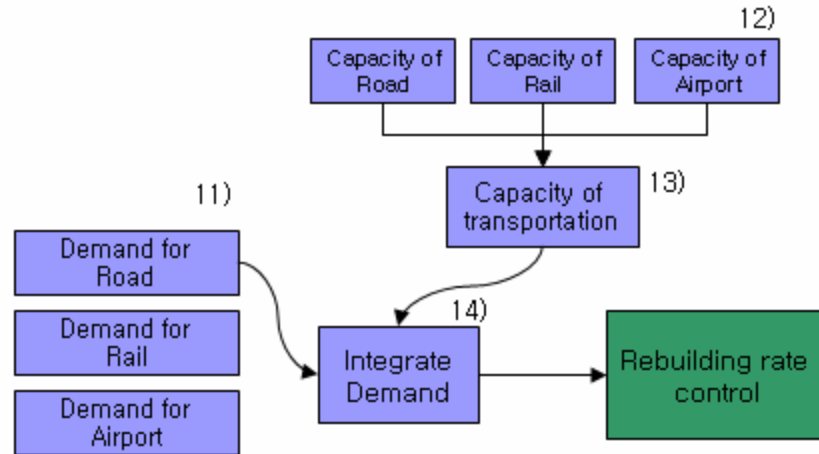


Figure 3.13 Transportation infrastructure information layer

Since our ultimate interest is minimizing the total rebuilding duration, outputs of transportation dominate the rebuilding duration. For example, let me assume that *road #100* (number 100 means nothing) can deliver 100 vehicles in an hour when it is under 100% condition. If *road #100* is repaired by degree of 50%, then it means that 50 cars can drive on that road. In the same fashion, we can think that certain amount of crews or repair devices can be delivered. The unit of output is not important whatever it is ‘*number of cars in a day*’ or ‘*the amount of tons in a day*’. The most important concept is percentage which representing the capacity of transportation. Infrastructures in the vicinity of *road #100* would have 50% as transportation capacity. For example, assume that *road #100* is 50% repaired again. But, facing problem is how the capacity is transformed to the ‘*rebuilding duration*’. This problem will be discussed in the rebuilding rate control agents.

3.5.6 Telecommunication infrastructure

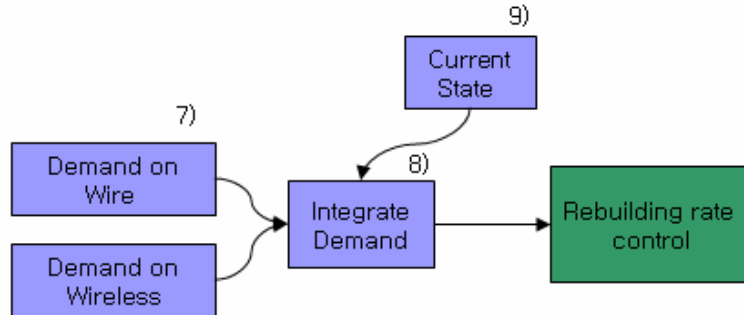


Figure 3.14 Telecommunication infrastructure information layer

Telecommunication demand is not detailed modeled since I assumed that regardless of current rebuilding phase, the demand on communication system might be consistent. Of course, at the initial phase of recovery, there occurs huge amount of requests on communication. It was reflected in the model; however, it was not a big issue. Because telecommunication infrastructure has various alternative plans that can be proposed itself. For example, even though communication line is disrupted in wire service, customers can keep up a correspondence with each other via cellular phone, e-mail and internet phone service. Similarly, disruption on wireless services can not be a matter only if wire communication service is doing well. Thus, in the model, output of telecommunication (i.e., bandwidth, service) only affects the whole rebuilding process in terms of rebuilding rate when both of wire and wireless services are not in good condition.

Equation 3.5.6) if Bandwidth (wireless) < λ and telecom service (wire) < λ

Then, Whole Rebuild Rate = Rebuild Rate – μ

3.5.7. Resource allocation

Now, we need to examine how Distribution Control agent distributes the productions. Assume that drinking water system needs 2,000 kilowatt/hrs and natural gas plant needs 3,000 kilowatt/hrs. But, capacity of power infrastructure is limited to 4,000 kilowatt/hrs. Then one of them or both of them can not take powers what they need by 1,000 kilowatt/hrs. In other words, *Not_available_power* is 1,000 kilowatt/hrs. In this case, ‘distribution control’ agents should arbitrate the power between two demanders. In order to understand how the model distributes the resource, below diagram should be introduced ahead of others. At first, the initial priority is decided by user. For example, if I think power infrastructure is the most important one so that it has to be recovered by the most top priority, then power infrastructure would get the number one priority. Similarly, if I regard the telecommunication infrastructure as worst one, then number 6 priority will be granted for telecommunication. This process strongly depends on user’s intuition. Once initial priority is selected, it dominates whole time of model run because it determines the initial score. By the initial priority, score is given for each infrastructure. Then, scores decides the next time priority. Finally, resources are allocated to each infrastructure in terms of its priority. If this cycle goes on, then initial priority never changed during the run. However, even though initial priority is significant, there occurs situation that priority must be changed. First, if one of infrastructures reaches the termination criterion, its priority should be decreased in order for other infrastructures to have more resources. Second criterion is the discordance of demand and supply. Scores

of infrastructure that are showing sequential discordance of demand and supply should be decreased.

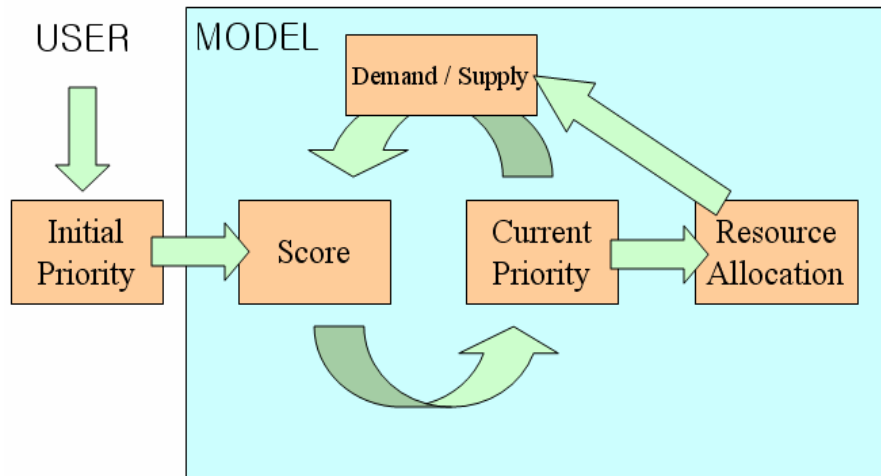


Figure 3.15 Relationship of score and priority

Now, I'll examine how the resources are allocated to infrastructure concretely. Following table shows us the scores and demands of 6 infrastructures. On the table, water infrastructure gains the first priority which has 95 as its score. And telecommunication infrastructure is the worst one since it has 30 as its score. Sum of all demands is 9,200. Now, let me assume that supply at current time is only 5,000. In other words, available resources at this time are 5,000.

Table 3.3 Example of resource allocation

<i>Infrastructure Type</i>	<i>Score</i>	<i>Demand</i>
<i>Water</i>	95	3000
<i>Power</i>	90	1500
<i>Oil</i>	50	2000
<i>Gas</i>	60	2000
<i>Telecommunication</i>	30	600
<i>Transportation</i>	70	100
Σ SUM	395	9200 <i>(Where Supply is 5,000)</i>

The resources have to be distributed into each customer. That is,

$$Resource_{TOTAL} = R_{water} + R_{power} + R_{oil} + R_{gas} + R_{telecom} + R_{trans}$$

Following equation is used for allocating the resources reasonably.

$$Eq.3.5.8) Resource(i) = Supply * Weighted Score Rate(i) * Demand Rate(i) * Constant$$

Where, $i=Water, Power, Oil, Gas, Tele, Trans$

Following table shows how the equation works with previous example. Note that at the previous example, the score of water infrastructure is 95. At this example, weighted score of water is 857,375 and it is calculated by using cubic. If we would like to intensify the score more than demand, then we can use bigger number as a multiplier. Score rate and demand rate is just ratio between summation and object number. On the 5th column and last row of table, 1040.44 is the sum of all numbers on the 5th column. Now, constant is estimated by dividing 5000 (supply) by 1040. In other words, constant transforms the rate number to real usable number. At the last column, we can figure out that water infrastructure can get 2924.115 unit for its resource. Recall that demand of water infrastructure was 3000. Since water had a first priority, it can obtain almost resources without big loss. Oil and gas requested the same amount of demands. However, as you can see at the result, gas infrastructure gained nearly twice of one of oil because its score is better than oil infrastructure. This method may not be the best. However, by adjusting the parameter, it works pretty well in the model.

Table 3.4 Example of resource allocation function

INFRA	Weighted Score	Score Rate	Supply*Scr Rate	Demand Rate	Spv*ScrRate*DmdRate	Resource
WATER	857375	0.3731977	1865.988356	0.326087	608.474464	2924.115
POWER	729000	0.3173187	1586.593395	0.1630435	258.6837056	1243.143
OIL	125000	0.0544099	272.0496219	0.2173913	59.14122214	284.212
GAS	216000	0.0940203	470.1017466	0.2173913	102.1960319	491.1184
TELE	27000	0.0117525	58.76271832	0.0652174	3.832351195	18.41694
TRANS	343000	0.1493008	746.5041624	0.0108696	8.114175678	38.99389
SUM	2297375				1040.441951	5000

3.5.8 Rebuilding Rate Control

This agent provides the rebuilding rate of all infrastructures. Repair rate and rebuilding rate function is defined as follow.

Eq.3.5.9) Repair rate of Agent i

$$= \text{Rebuilding Rate of infrastrucutre that agent } i \text{ belongs to} * \frac{\text{Transportation Resource for Agent } i}{\text{Transportation Demand of Agent } i}$$

Eq.3.5.10) Rebuilding rate of infrastructure (t) = Rebuilding rate of infrastrucutre (t - 1) ± λ

At first, note that agent in the infrastructure has the repair rate and each infrastructure has rebuilding rate respectively. Repair rate of agent is estimated by multiplying the rebuilding rate of infrastructure which agent belongs to with ratio of demand and allocated resource. For example, we are interested in repair rate of refinery. Since refinery belongs to oil infrastructure, we need to know rebuilding rate of oil infrastructure. Assume rebuilding rate as 0.05 and also assume that 20 unit of transportation is allocated for refinery while refinery request 30 units.

Then, *repair rate of refinery = rebuilding rate of oil * (20(unit) / 30(unit))*

$$\text{Repair rate of refinery} = 0.05 * (20/30) = 0.0333$$

If 30 units are granted for refinery, then refinery could use 0.05 (i.e., rebuilding rate of oil infrastructure) entirely as its repair rate. In order to understand rebuilding rate, recall what we already discussed about the score and priority at the earlier section. At first, increasing order is generated by the score.

For example, assume that water infrastructure score at time t is 56 and natural gas infrastructure score at time t is 80 and oil infrastructure score at time t is 10. Note that 56, 80 and 10 is the score not actual rebuilding rate. Now, let's assume that *water infrastructure rebuilding rate at time $t-1$ is 0.4* and *natural gas rebuilding rate at time $t-1$ is 0.3* and *oil infrastructure rebuilding rate at time $t-1$ is 0.5*. Since, natural gas receives the best score at the time t , natural gas rebuilding rate should increase by $\Delta\lambda$. Thus, *drinking water system rebuilding rate at time t is $0.4 + \Delta\lambda$* . In the same fashion, since oil infrastructure obtains the lowest score, its rebuilding rate at time t will be $0.5 - \Delta\lambda$. In other words, at the time t , certain amount of resource will be allocated to drinking water system from oil infrastructure.

3.6 Spatial layer

In the rebuilding model, spatial aspect should be considered as a critical issue because in a real world, interdependency amongst infrastructures is not as simple as can be represented by just flow of commodity. Even though model is generalized in order for various scenarios can be adopted, the specified area need to be modeled is Louisiana. Thus, I mapped real geographical data of Louisiana into spatial network.

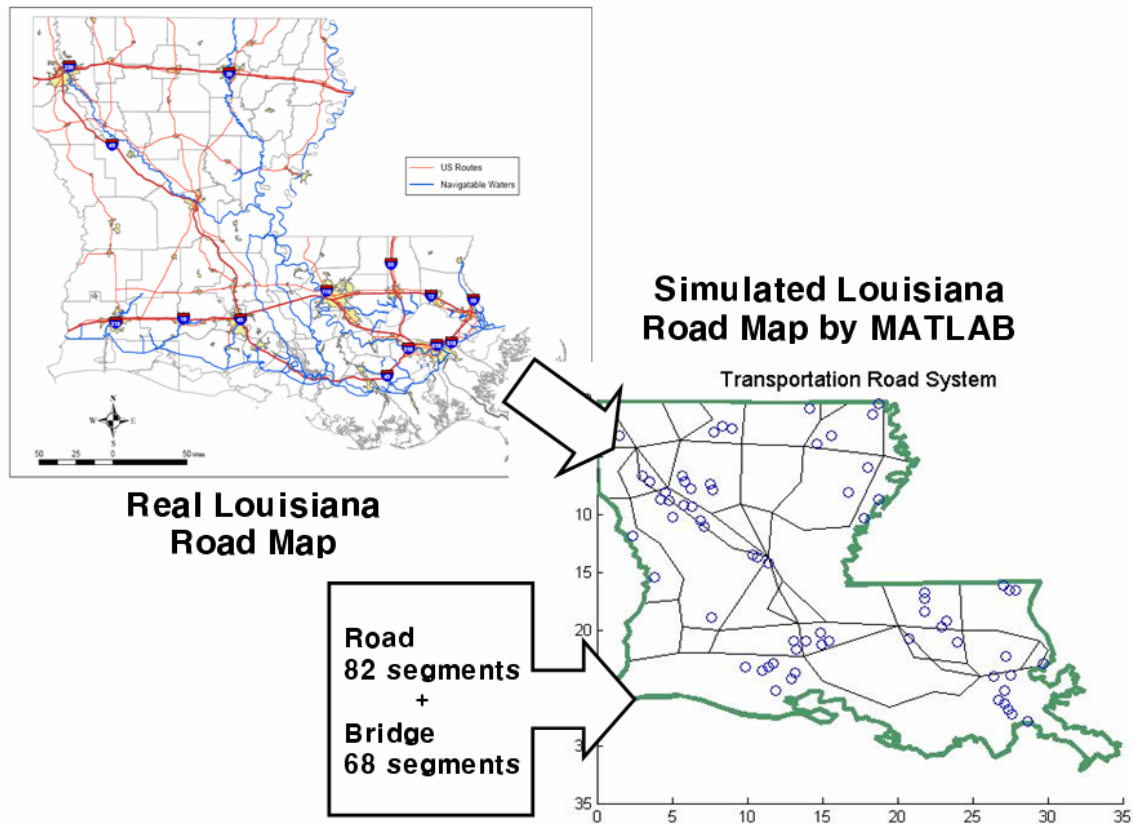


Figure 3.16 Mapped Louisiana road systems in spatial layer

Let me examined the how the real state's data is mapped into model. Above figure is the map of real Louisiana with related to road (*source: louisiana.volpe.dot.gov*). Especially, category is limited into U.S. Route. In other words, roads that are smaller than U.S. route are not considered in the model. And, right hand side figure is mapped road in the spatial model by *MATLAB*. The simulated Louisiana road system is represented by 82 numbers of road segment and 68 numbers of bridge segments. While road segment is represented by line that has starting coordinates and end coordinates, bridge is represented by a point. As I mentioned at the data collection section, most of data are limited to access because of various reasons. In that case, hypothetical grid system is

created by randomized techniques. In the model, mapped road is represented by combinations of segments that have different length.

Table 3.5 Road coordinates and weighted capacity

<i>Index</i>	<i>Start</i>		<i>End</i>		<i>Distance</i>	<i>Current Capacity</i>	<i>Weighted Capacity</i>
	<i>X</i>	<i>Y</i>	<i>X</i>	<i>Y</i>			
1	0.63	0.16	2.64	4.12	4.441	0.9	0.196148
2	0	4.17	2.64	4.12	2.640	0.9	0.116602
3	4.33	0.11	5.54	3.49	3.590	0.6	0.105707
4	6.81	0.11	7.71	1.69	1.818	0.6	0.053531
5	5.54	3.49	9.66	3.8	4.132	0.3	0.060833
6	9.87	0.05	9.66	3.8	3.756	0.3	0.055298
					$\Sigma = 20.377$	Mean = 0.6	$\Sigma = 0.588119$

For example, consider only 6 numbers of data from coordinate table of road. At the distance column, we can figure out that each segment has different length. Current capacity 0.9 (i.e., index 1) means that segment 1 has been recovered by the degree of 90%. In the same fashion, on the index 5, current capacity 0.3 means that segment 5 has been recovered by the degree of 30%. Then, average current capacity of whole road is estimated by averaging the all distances that is 0.6. It also means that whole road system is recovered by 60%. However, since each road segment has non-identical length, this estimator can not be used instead we can use the *weighted capacity* as the estimator.

$$\text{Weighted Capacity} = \sum_{i=1}^n (\text{Current Capacity of } i \times \frac{i^{\text{th}} \text{ Distance}}{\sum \text{Distance}})$$

Where, n is the number of segments in the system

From the above table, even though index 3 and 4 have the same amount of current capacity (i.e., 0.6), they do not have same length of weighted capacity because there is difference between distances (3.59 and 1.818). Also, note that since segment 3 has the twice of segment 1, the amount of affection to overall weighted capacity is greater than segment 1 about double. Estimated overall weighted capacity is 0.588%. The difference between current capacity and weighted capacity $\{(0.60 - 0.588) = 0.02\}$ occurs because each segment has different length.

3.7 Heuristic optimization

3.7.1 Background

Goal of this section is devoted to find best combination of infrastructure priority. Combination means that a set of numbers that range from 1 to 6 and smaller number represents higher priority. For example, if a decision maker guesses power infrastructure plays a key role in the rebuilding process then power infrastructure may have 1 as its priority. Similarly, worst significant infrastructure would get 6 as priority. Even though we have only 6 infrastructures in the model, it is not a good way if we try to find optimal solution by putting all possible combinations into the model since there are 720 combinations. (i.e., 6 factorial) Moreover, most of cases, there may not be enough time for decision maker to grasp the situation in real world. For those reasons, meta-heuristic

technique (Simulated Annealing) which guarantees the relatively fast optimal solution is used to find best combination.

3.7.2 Interaction between Rebuilding model and Optimizer

I already introduced the concept of optimization package and a simulation model at literature review chapter. In order to understand following diagram clearly, I recommend you review the figure 2.6.3 and figure 2.6.4 at chapter 2. My rebuilding simulation model does not need particular optimization software package such as AutoStat, OptQuest, or WITNESS Optimizer (those are introduced in Simulation Modeling and Analysis, Averill M. Law) rather than I implemented simple heuristic model by *MATLAB* that uses Simulated Annealing as search procedure.

Self-evaluation whether my optimization model is desirable or not will be examined at chapter 4 in terms of criterion that mentioned by Averill M. Law (2000:659) Now how the optimizer finds best priority combination with interacting simulation model will be discussed with fully described diagram.

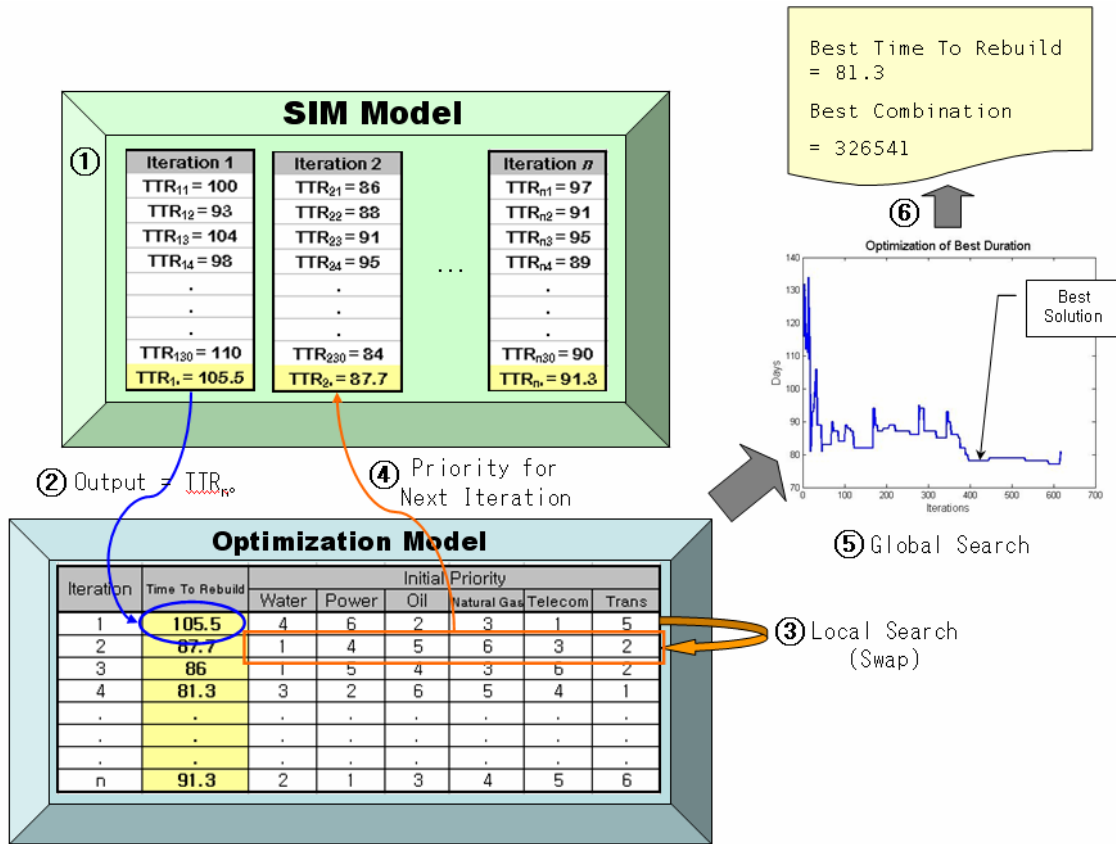


Figure 3.17 Interaction between simulation model and optimization model

Step 1)

In the simulation model, the first run is performed with initial priority that is determined arbitrarily or by user's guess. Output is total time to rebuild (represented as *TTR* in diagram). Required numbers of runs for individual iteration are decided by using following inequality.

$$R \geq \left(\frac{t_{\alpha/2, R-1} S_0}{\varepsilon} \right)^2 \quad (\text{Inequality 3.7.1})$$

Where an initial R is estimated by inequality 3.7.2

$$R \geq \left(\frac{Z_{\alpha/2} S_0}{\varepsilon} \right)^2 \text{ (Inequality 3.7.2)}$$

After R number of replications, we are interested in mean.

Step 2)

Output \overline{TTR}_n (i.e., total time to rebuild mean value of iteration n) is now sent to optimization model with priority combination that used already for previous run.

Optimization model remember the current \overline{TTR}_n and combination as best solution so far.

Step 3, 4)

For the next iteration, optimization model searches the next priority combination by swapping the current one. Both how many numbers will be swapped and what numbers will be swapped are randomly determined. For example, sometimes, only a pair of numbers would be swapped while in other times there occurs 3 pairs of numbers would be swapped. Swapped combination is used for next iterations as initial priority.

Step 5, 6)

In the optimization model, Simulated Annealing algorithm keeps finding the optimal \overline{TTR}_n by seeking path that makes object function smaller or allowing the non-improve movement. Detailed process of optimizing within the model will be examined at the next section. Finally, optimization model finds and reports a set of optimal solution those are best total time to rebuild and best infrastructure combination.

3.7.3 Simulated Annealing

Simple pseudo code for simulated annealing follows below.

- 1) Set the initial temperature
 - a) Initial temperature, T
 - b) Cooling rate, r
- 2) Generate the initial solution and initial object function (i.e., TTR – time to rebuild)
- 3) Generate neighborhood solution and object function (i.e., TTR')
- 4) If $TTR' < TTR$ then $TTR = TTR'$
- 5) Else if $TTR' > TTR$, then accept if $uniform [0, 1] < Exp \{(TTR - TTR')/T\}$
- 6) Iteration = Iteration + 1
- 7) Repeat 3~6 until iteration = max iteration (i.e., inner loop criterion)
- 8) Decrease the T and go back to step 3
- 9) Stop when outer loop criterion is satisfied (e.g., non-improvement, end temperature)

Since optimization model substantially same as ordinary simulated annealing algorithms, figure 3.18 will cover the explanations mostly.

Initial temperature setting is critical in terms of quality of solution and running time. It also means that user can modify the different combinations of parameter with related to situation. For example, under situation that there is not enough time to asses the priority smaller decrease rate (e.g., 0.5) would be preferred since it finds the solution faster but sparsely. Similarly, setting on end temperature as 5 would yield faster solution than what sets the end temperature as 1 when other temperature settings are fixed.

Moreover, smaller initial temperature and smaller iterations threshold condition within the inner loop makes optimization model run shortly. In order to find best initial temperature setting, I conducted several experiments in the context of sensitive analysis. Even though I am not going to explain detail that, it still critical element in the entire optimization processes because we can verify whether global optimal solution is converging or not by modifying the initial temperature setting (i.e., T , r , T_{final}). I attached some graphs with related to various temperature settings at appendix E. Those graphs may allow you to understand how temperature setting affects the global search movement of simulated annealing algorithms.

Consequently, the user can modify those parameters depends on situation what he faces. However, the important facts the user must consider is faster solution may not guarantee the best solution. Real used temperature setting is examined at chapter 4.

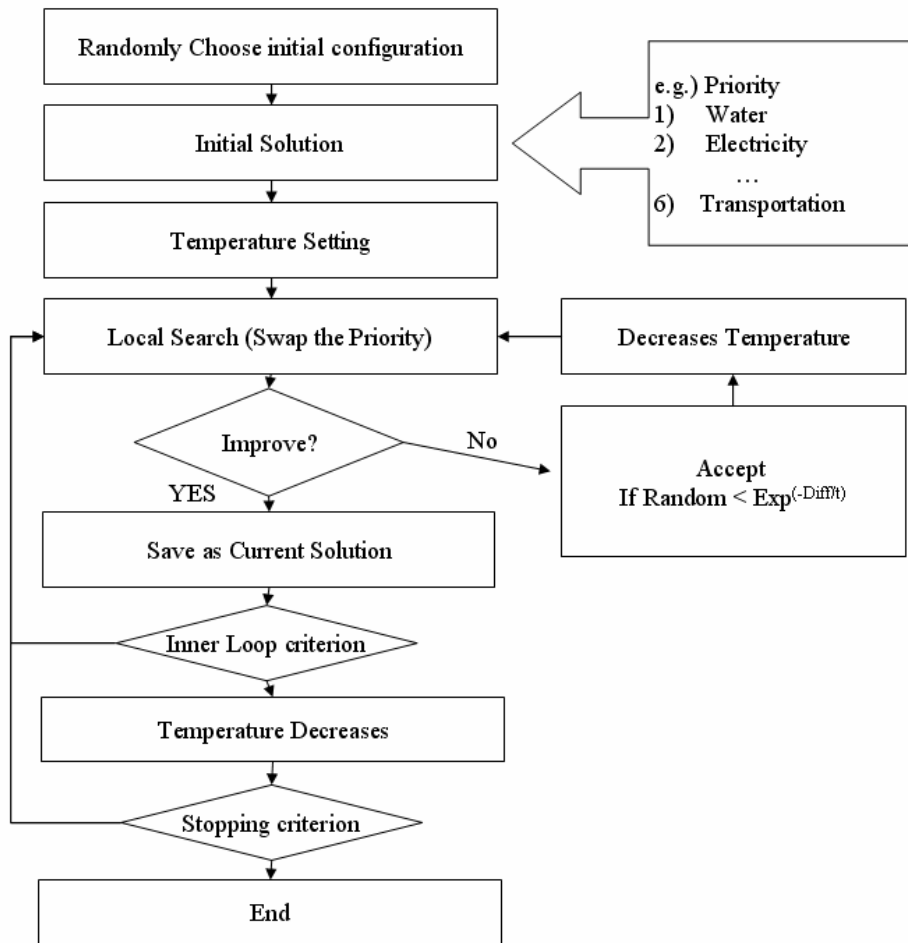


Figure 3.18 Flow diagram of simulated annealing

3.8 Conclusion

At the first section of this chapter, I described the restrictions on collecting data. Unfortunately, lack of essential data is not only degenerate the quality of model but also it forces me to choose unreasonable methodology sometimes. The notion of *unit I* introduced at transportation section is the one of examples. If I knew the rebuilding duration and needed resources for each infrastructure at least empirically then rebuilding process may be modeled by the delivered resources such as crews and trucks. Following

section dealt with global model especially about three interacting sub models those are physical, information and spatial layers. In the information layer section, instead of a lot of explanations on sub-models, I tried to account for how the resources are allocated by the priority and how the rebuilding phase is conducted more clearly. Since the important topic on my research is rebuilding priority, heuristic optimization method was introduced.

IV. Analysis and Results

4.1 introduction

At the first part of this chapter, results of rebuilding model especially that is aim to mimic the hurricane Katrina scenario will be examined. Particular scenario was determined by modifying the coordinates of impact area. Two different models (i.e., initialization model, main model) but those have to be executed simultaneously are illustrated respectively. There follows a validation on various graphs and tables with clear explanation if the results are not reasonable. There follows results on multiple replication to get desirable confidence. Then heuristic optimization model with various scenarios (various impact areas) follows.

4.2 Rebuild model results

4.2.1 Result of Initialization (Katrina Scenario)

As previously discussed, I simulated the Katrina scenario by inputting impact area coordinates into the model. Inserted coordinates of impact area may not be same as real coordinates. However it is not a big deal since the ultimate objective of model is not damage assessment of hurricane Katrina but research on the interdependencies between infrastructures and their priority. Note that a followed result is output of single run. I assumed that below coordinates is represented of hurricane Katrina impact area.

X coordinates: 23.5, Y coordinates: 28

Where, $0 \leq X \leq 35$ and $0 \leq Y \leq 35$

The following three pages present the initialization results of infrastructures that are represented in spatial layer. In each graph, 'x' mark depicts the impact area. Damage on particular area is determined by distance between impact area and target area location. And by the degree of damage, each segment is represented by different color (i.e., Red, Blue, and Black). For instance segments that are depicted by red are the one what mostly damaged while black line means that that region is not damaged seriously. Below assumption was arbitrarily determined to estimate the degree of damage at the first phase.

Assumption:

If a distance between segment i and impact area is

$0 \leq \text{Distance} \leq 7$, then Initial capacity of segment $i \equiv$ Random number around 0.2

$8 \leq \text{Distance} \leq 15$, then Initial capacity of segment $i \equiv$ Random number around 0.7

$15 \leq \text{Distance}$, then Initial capacity of segment $i \equiv$ Random number around 1

(Where, $i = 1 \dots$ number of segment)

Now, initial capacity of infrastructure (i.e., water, power ...) is estimated by averaging the capacity of agent which represented in the spatial layer. What we expect for considering agents in spatial layer is that the degree of damage mainly depends on impact area.

Eq 4.1) Initial capacity of infrastructure $i = \text{Mean} (\text{Capacity of Agent in Spatial layer})$

For example, oil infrastructure has two agents in spatial layer those are oil port and oil pipeline even though those two agents are not the one that all oil infrastructure has. Indeed, oil infrastructure is consisted of 8 numbers of agents. By the above equation, initial capacity of oil infrastructure is estimated by mean value of capacity of oil port and

capacity of oil pipeline. However, we faced the problem in terms of 6 more agents since model seems like does not consider those agents to estimated the initial condition because of it does not belongs to spatial layer. Does the method that estimates the initial capacity by regarding all agents make sense better? Of course it does. Those kinds of restriction of model will be discussed at chapter 5.

Since telecommunication infrastructure does not have agent in the spatial layer, its initial capacity is estimated by mean of any others.

Initial capacities of infrastructure are now generated.

- 1) *Water infrastructure initial capacity: 0.6300*
- 2) *Power infrastructure initial capacity: 0.7319*
- 3) *Oil infrastructure initial capacity: 0.4521*
- 4) *Natural Gas infrastructure initial capacity: 0.6660*
- 5) *Telecommunication infrastructure initial capacity: 0.6397*
- 6) *Transportation infrastructure initial capacity: 0.7184*

Water infrastructure initial capacity 0.630 means that 63% of water systems are capable. In other words, 37% systems are destroyed. We found that oil infrastructure initial capacity is relatively small. If we check the figure at previous pages, we can figure out that oil ports and oil pipelines are clumped together at southern side of Louisiana map. Since hurricane also stroke the southern part, it is obvious that oil infrastructure is seriously damaged than others.

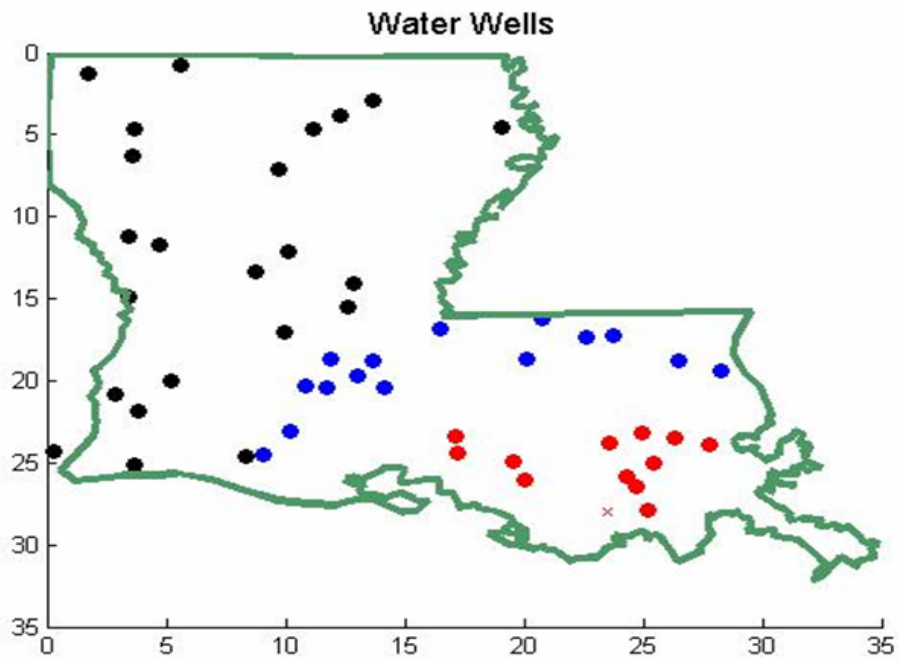


Figure 4.1 Water infrastructure: water wells initialization

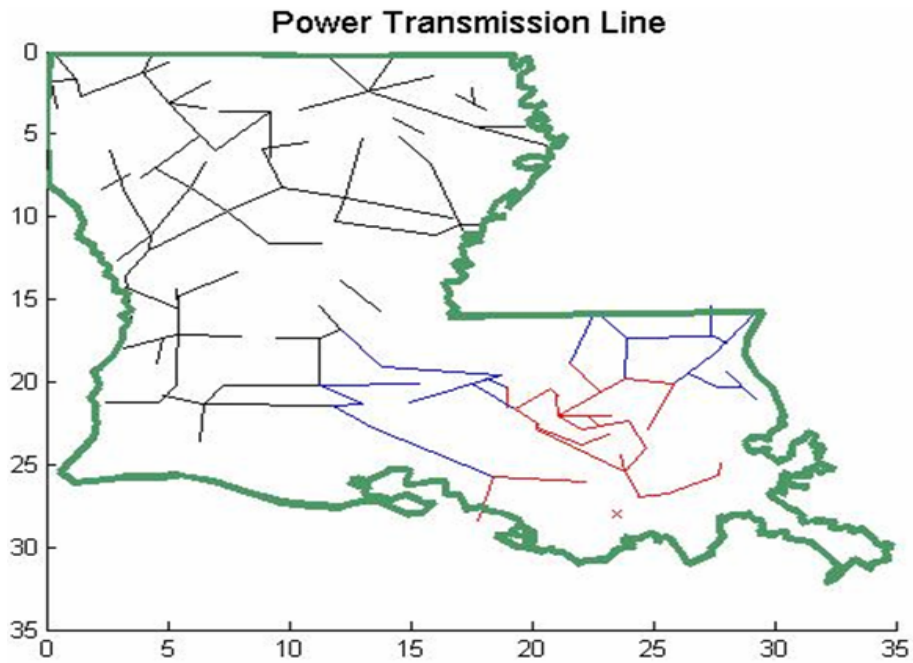


Figure 4.2 Power infrastructure: transmission line initialization

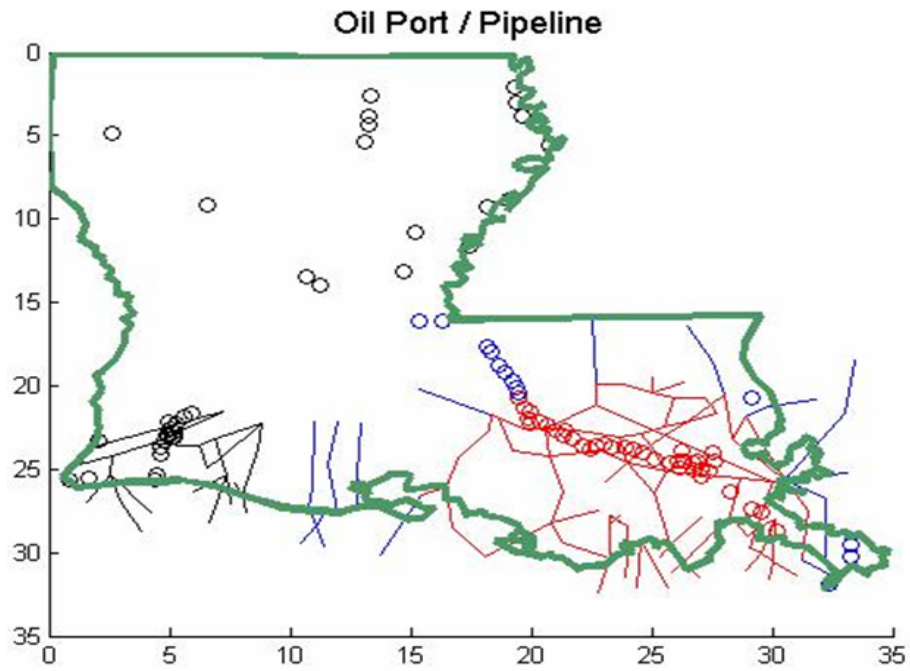


Figure 4.3 Oil infrastructure: port and pipeline initialization

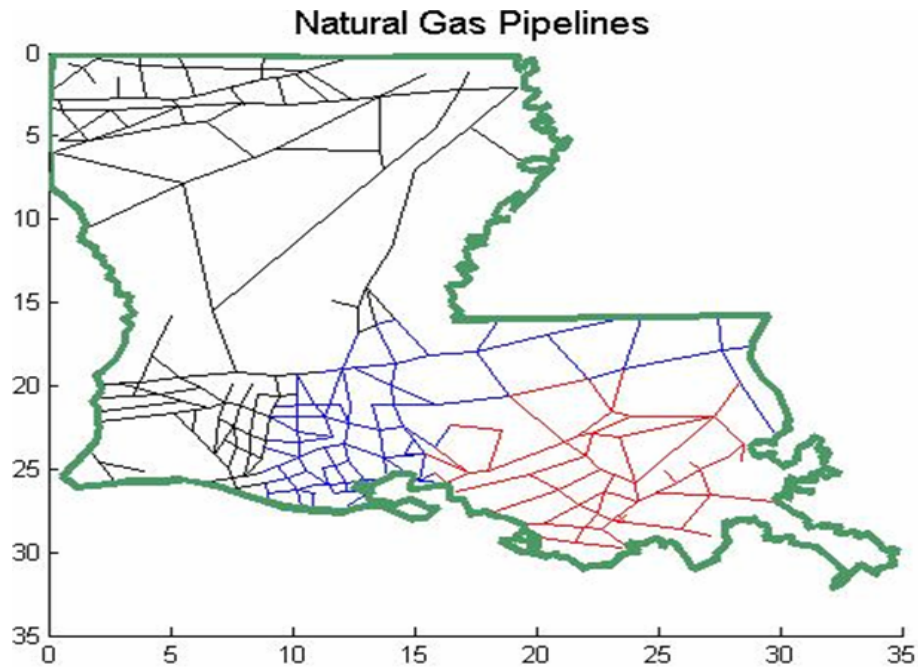


Figure 4.4 Natural gas infrastructure: pipeline initialization

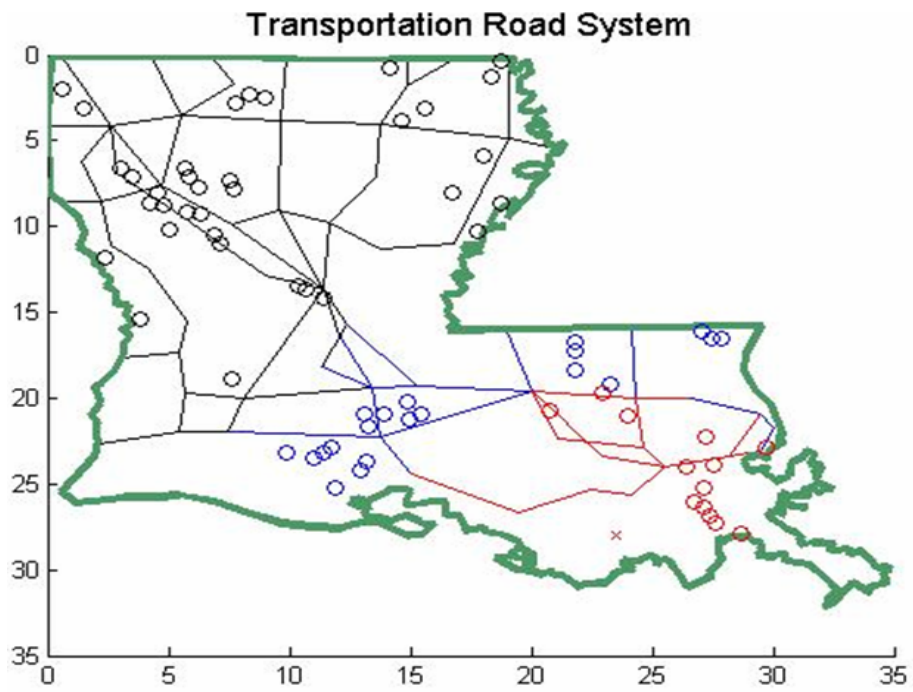


Figure 4.5 Transportation infrastructure: road initialization

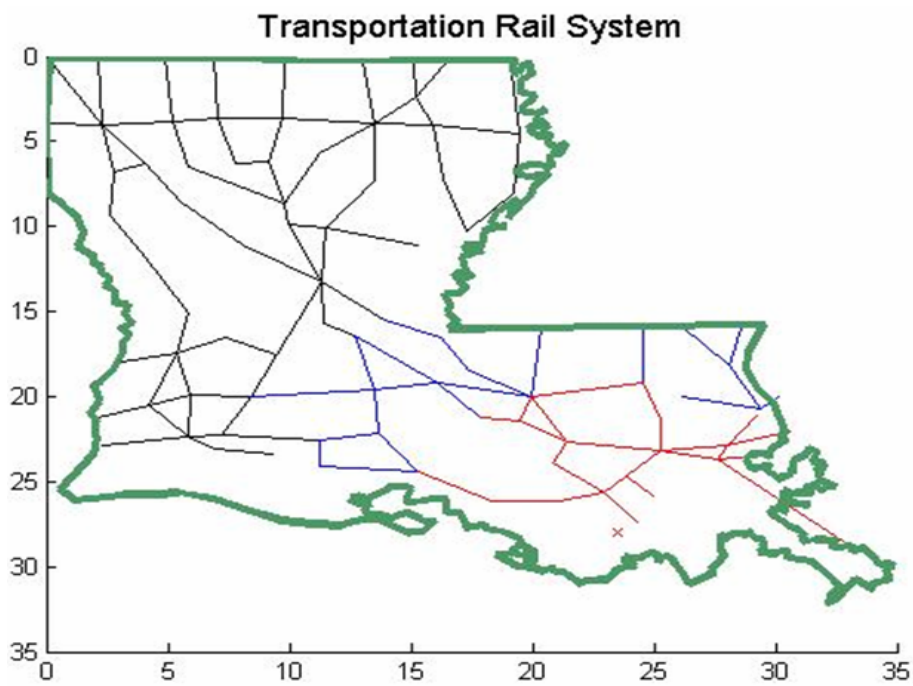


Figure 4.6 Transportation infrastructure: rail initialization

4.2.2 Dynamic relationship of rebuilding model

In order to account for process clearly, I examined various graphs those comes from different initial priority. And I mentioned initial priority for every graph. It also means that you do not need to think carefully about the priority combination in this section. And, note that again all results in this section are output of single run.

Initial Priority and Time to Rebuild

In order to grasp the effect of initial priority combination to rebuilding time, two different initial priorities are choused arbitrarily. Next two figures show the change of all infrastructure capacity by days.

Before the discussion on analysis of two graphs, the threshold condition for terminating the simulation might be mentioned first. Each simulation run is terminated when a mean of total infrastructure capacities are exceed 99%.

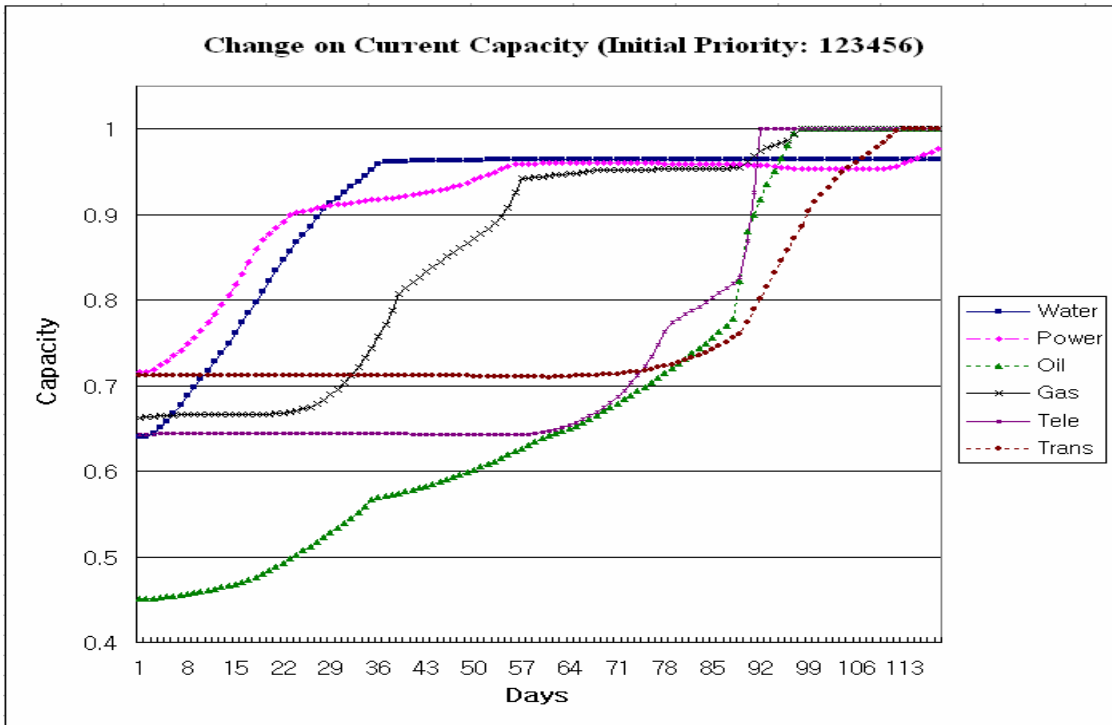


Figure 4.7 Infrastructure dynamic (Initial Priority: 123456)

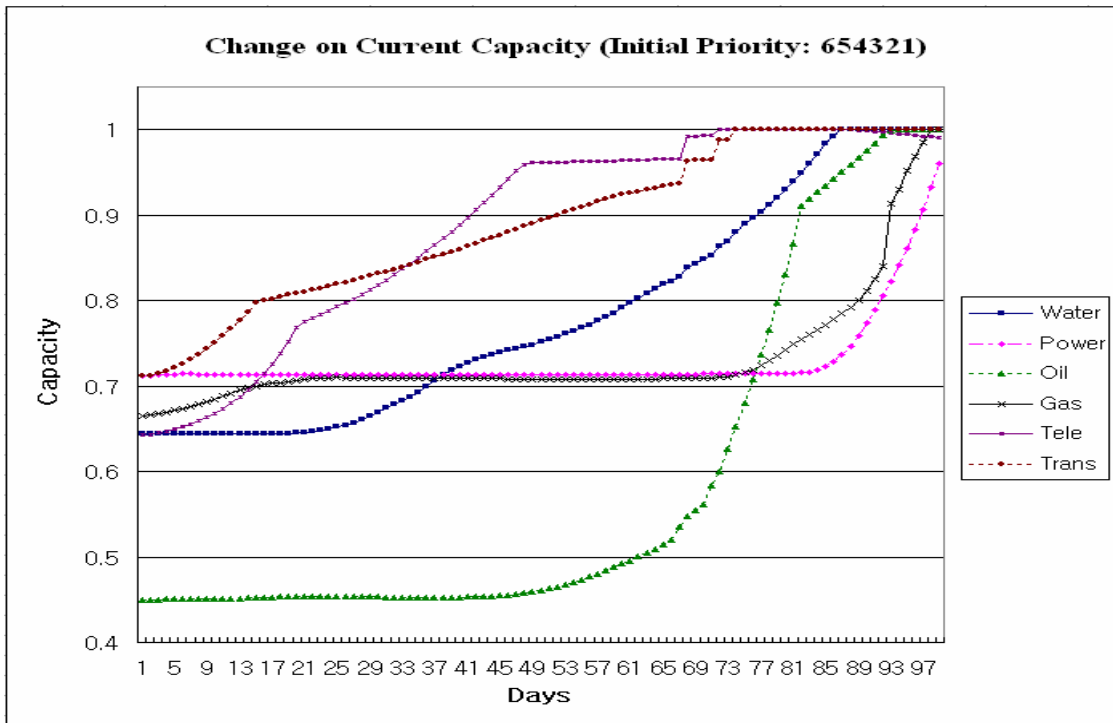


Figure 4.8 Infrastructure dynamic (Initial Priority: 654321)

Figure 4.7 is the graph of all infrastructure capacity that ranges from simulation start to simulation end. Priority combination is 123456 which means that water has the first priority and power has 2nd and oil, gas, telecommunication, transportation have 3rd, 4th, 5th, 6th respectively. From now, I'll mention the priority combinations as just numbers such as 123456. Note that priority combinations order is water, power, oil, natural gas, telecommunication, transportation. It turned out that the simulation is ended at time of 119 days. In other words, total time to rebuild is 119 days when the initial priority is 123456. Of course, time to rebuild is changed by different run because of its variability. What we have to focus on is not 119 days, but observing how the initial priority affect to each infrastructure. In the graph, at the first 30 days, water and power capacity line show us a steep slope and oil capacity line has still rapid slope but not as much as water and power. While, rest three infrastructures capacity lines are almost horizon. As you can guess, capacity lines that has a slope are the one those have the first three priority. At that period, most of rebuild resources may allocate to water, power and oil. And other infrastructures may not have a chance to use them. In the model, when a certain infrastructure reaches to 95% capacity, the model decreases the score of that in order to make infrastructure to have lower priority. In the graph, around the day 34 is the point that power infrastructure reaches 95%. Now, there are some available resources which can be allocated to others. Now, pay attention to natural gas capacity line after 25 days. Natural Gas capacity starts to increase after 25 days. I believe that the discordance between natural gas demand and its supply is relatively large and it may make the natural gas score larger. In the model, if the demand exceeds the supply by 5 sequential times,

then model increases the score of corresponding infrastructure. It means that even though particular infrastructure got the lower priority, it still has a chance to reach terminate condition first. Actually, it turned out that telecommunication infrastructure touches the 100% first in the graph and note that its initial priority was 5th. Oil infrastructure follows next rank and gas infrastructure reaches the 100% recovery state with 3rd rank. Paradoxically, who had the 1st and 2nd priority arrived in end criterion lastly. However, who reaches the 100% first is not the matter at all. Real considerable issue is that all infrastructures have to reach the end condition.

Second graph (i.e., figure 4.8) is the output which has 654321 as its initial priority. Again, water, power, oil, natural gas, telecommunication, transportation have 6th, 5th, 4th, 3rd, 2nd, 1st respectively as its priority. Total time to rebuild is officially 100 days and it is 19 days faster than the first example. Similar to the first graph, at the first period, infrastructures what have the top priority makes rapid slope. Telecommunication (2nd) and transportation (1st) are restored with fast rate until they came to the 100%. Telecommunication infrastructure is attained full recovery first at around 70 days and it outstripped the transportation what has the first priority right after it passed the around 33 days. The interesting movements are occurred at the water and natural gas infrastructure. Water capacity began increase from 20 days even though it has worst priority. And, natural gas capacity is stopped from around 20 days which is almost same time as water capacity starts to increase. I believe carefully that resources for natural gas are transmitted to water for some reasons. There might be serious problem on

demand-supply of water meanwhile natural gas has the capacity that can afford surplus supply at that time.

Consequently, it turned out that capacity fluctuation depends on the initial priority significantly. However, as times go by, score are re-determined continuously. And, renewed score modifies the priority. All of those are aim to allocate the resources reasonably and efficiently.

Score and Rebuild rate

As I mentioned constantly, score dominates rebuilding process because priority of every day is determined by score. Score can be modified if there is demand-supply problem or if one of infrastructures reaches the end criterion. I already examined the notion of rebuild rate at the chapter 3. Now, with figures on the following page, I'll describe how these concepts are reflected in the model. Initial Priority is determined arbitrarily. In this example, I chose 134265 as initial priority. The reason why that combination is chosen is that combination shows dynamic and clear output than others and again whatever combination is, it could not be a big issue. For convenience, initial priority is expressed at the index on following figure; if you look at the index box on the figure, the number in the parenthesis represented the priority respectively.

On the 1st day of figure 4.9, water gains the 90 score since it has the 1st priority and natural gas get the 80 score since it is secondly important infrastructure. The rest of infrastructures also took 70, 60, 50, 40 score by order of priority. Telecommunication score is increased at 6 days since demand on telecommunications exceeds the supply for

five series days. In other words, since the model regards the discordance on demand-supply for five days as critical problem, it increased the corresponding score. On the next day (i.e., day 7), demand on telecommunications is still more than supply. Hence, telecommunication score jump to upper level (i.e., 60) and it forces the oil score to have lower score (i.e., 50). During the run, many infrastructure score are turned over and over. They all compete continuously in order to obtain larger score.

Now, we move to look at other kind of movement. On the 33 day, power score is decreased with very rapid rate. And on day 40, natural gas score also decreased steeply. As I mentioned at just previous section, that situation is the evidence as that power and natural gas capacity come to 95% capacity. Although power and natural gas reach the almost end termination, they may have demand-supply problem yet. You can figure out that power and natural gas infrastructures still try to upgrade their score. However, because the degree of score decreasing when they reach the 95% is significantly large, they can not change the score to high level until around 80 days.

Rebuild rate is strongly depends on score. On the figure 4.10, we can figure out that water infrastructure rebuild rate is increased most rapidly since it receive top score until 12 day. After 12 days, since instead of water, natural gas infrastructure gets the highest score, increasing slope of water is weaken. And at the day of 24 (i.e., time the water score is fell to 60), water rebuild rate starts to decrease gradually. Decrease of rebuild rate also means that someone had the chance to be increased because the resource is restricted. From the time of decreasing the water rebuild rate, telecommunication rebuild rate begins to increase. Natural gas rebuild rate is persistently increased until 40

day. Since natural gas acquired at least 80 score until 40, it can be recovered without any interception until 40 day. Natural gas rebuild rate stopped its increasing when its capacity reaches the 95% of recovery. The common sense that we can observe from this figure is that at the early period (i.e., from 1 to around 30 day), three infrastructures who has the higher priority can increase their rebuild rate. However after 30 days, they can not help allowing their resources to be used for others. And at the late phase, most of rebuild resources are allocated to minor priority group. Especially, oil infrastructure seems to monopolize the resources at the late period and its rebuild rate reaches highest point. To understand situation, we have to consider initial condition; oil infrastructure capacity is very low compare to others.

Score graph and rebuild rate graph is always changed as run the other simulation replications. However the things never changed are that the whole rebuilding process is depends on the initial priority and initial condition.

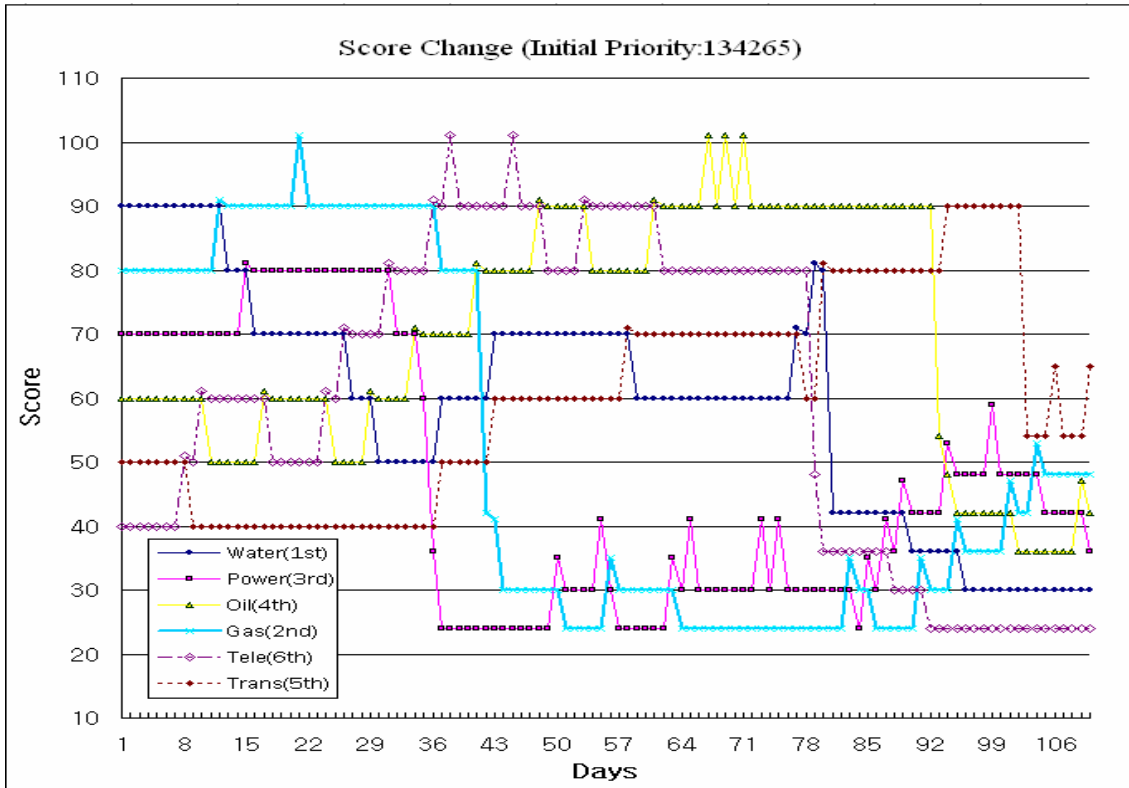


Figure 4.9 Priority and score dynamic (Initial Priority: 134265)

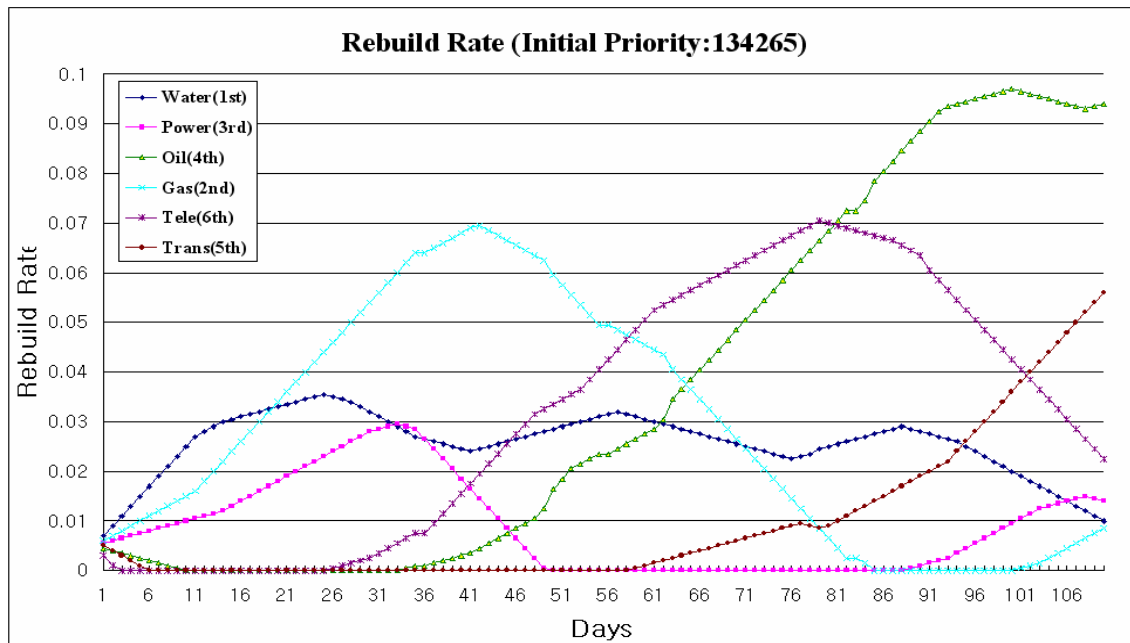


Figure 4.10 Rebuild rate dynamic (Initial Priority: 134265)

Demand and Supply Analysis

From the previous sections, we inferred that the amount of demand and supply at particular time considerably affects the rebuilding process. Now, I'll examine how much initial priority influence the demand and supply for a certain infrastructure. Following graphs are conducted with 215436 initial priority combinations.

The first graph (i.e., figure 4.11) represented the water infrastructure demand and supply by times. Demand on the graph is the request for water from other infrastructures not a request from water. Supply is always depends on resources that are allocated to water. For example, even though water is capable of 4,000 millions barrels at certain time, if power infrastructure did not provide the power to water, then water product can not exceed 4,000 millions barrels. However, demand is estimated by capacity. In means that since capacity is gradually increased, demand also increased steadily. That is the reason why demand line is smooth while supply curve shows relatively big variability.

Note that initial priority is 215436. If we look at the power infrastructure that took 1st priority, at the around 10 days, supply already exceeds the demand. On the figure 4.11, water supply is more than demand after 33 days; note that water took 2nd priority. Telecommunication graph (i.e., figure 4.15) shows that at least 100 days are needed for supply to catch up the demand. And, initial priority for telecommunication was 3rd. Also, we expect that natural gas (4th priority) supply can exceed the demand after 100 days stably. The transportation that has the 6th priority can provide the enough supply after around 95 days. It is relatively faster than telecommunication and natural gas even though

transportation took the worst initial priority. However, it turned out that transportation supply increasing rate is so slow; supply curve almost drew horizontal line on figure 4.16. Consequently, we verified that the initial priority takes part in determining the demand and supply.

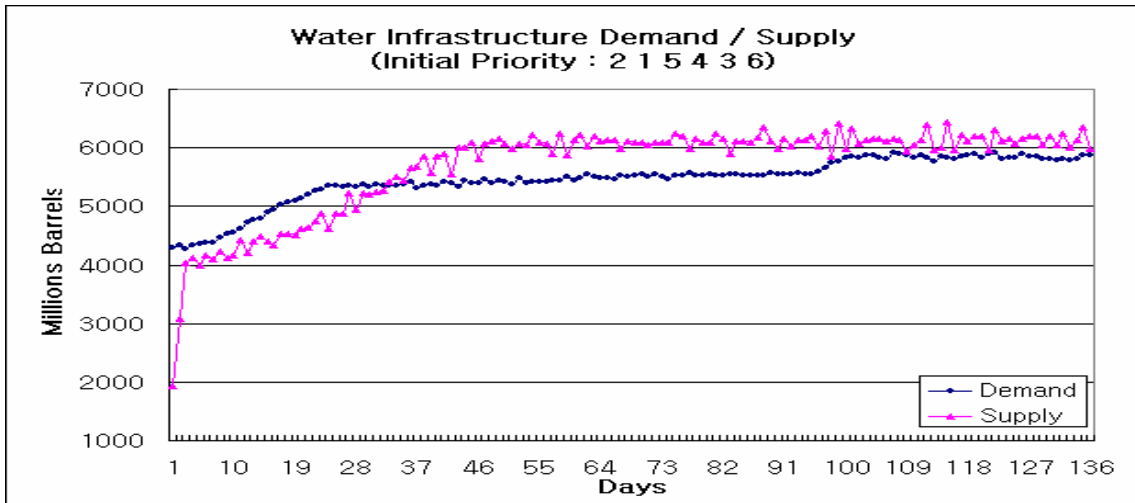


Figure 4.11 Water infrastructure demand / supply (Initial Priority: 215436)

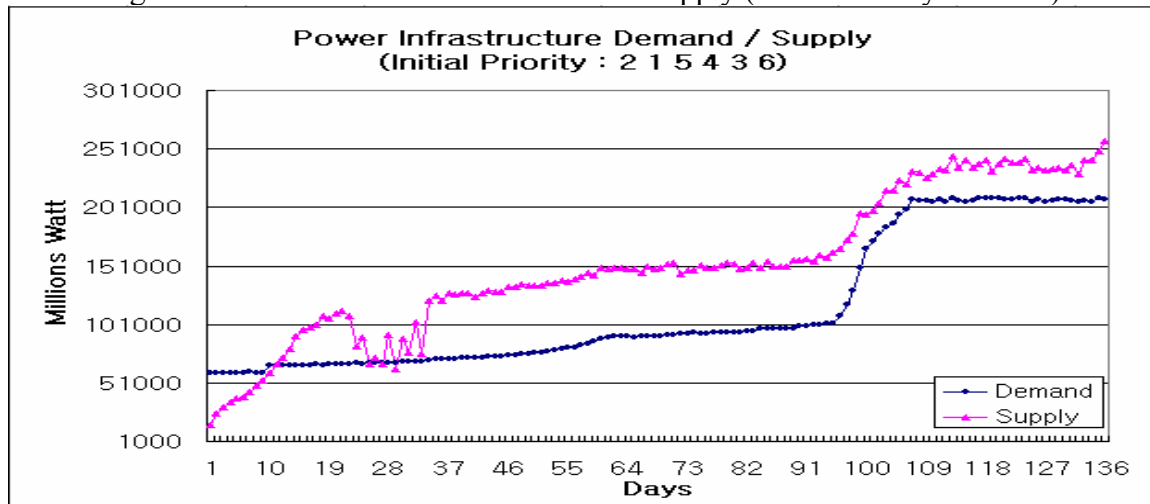


Figure 4.12 Power infrastructure demand / supply (Initial Priority: 215436)

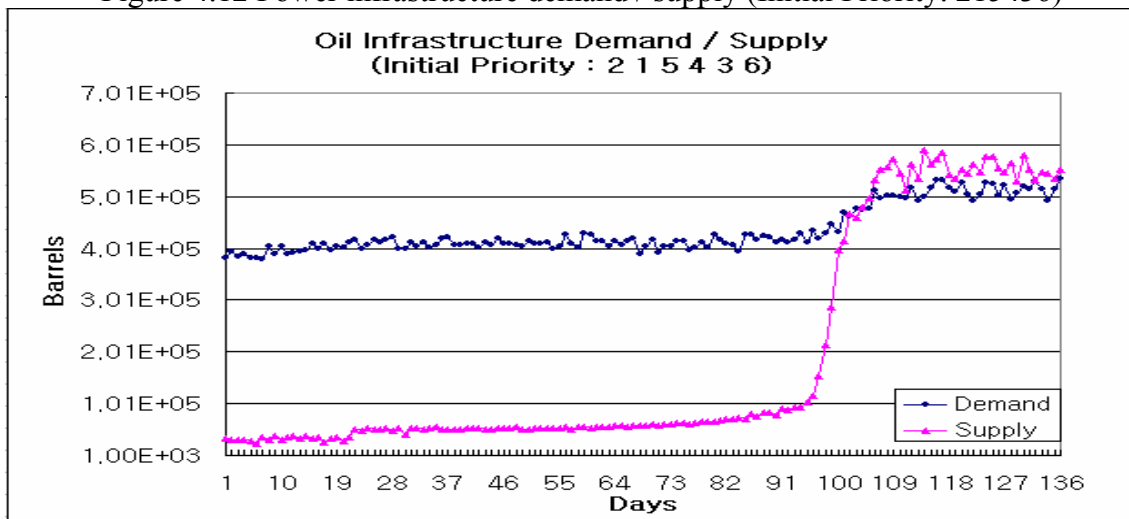


Figure 4.13 Oil infrastructure demand / supply (Initial Priority: 215436)

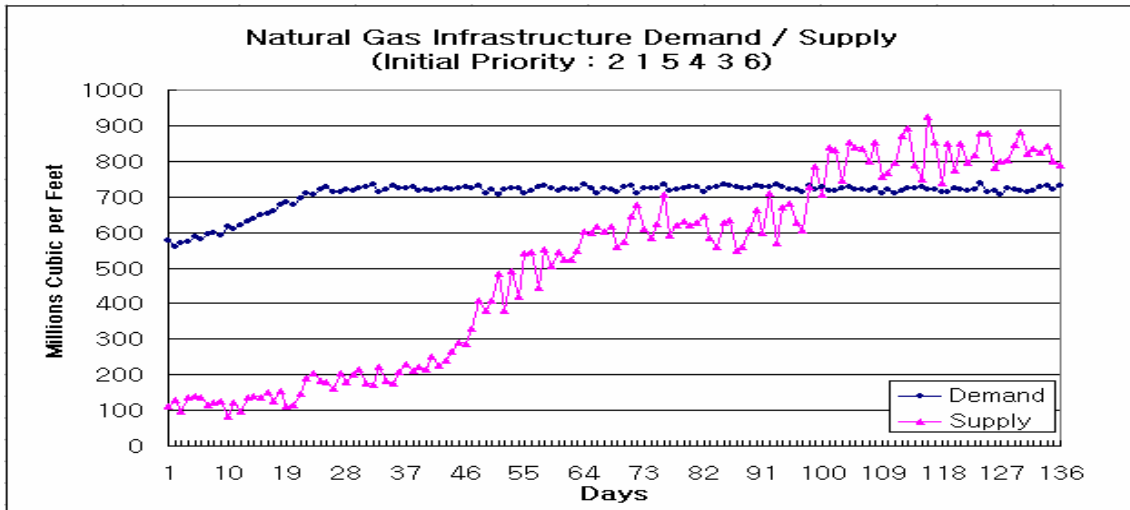


Figure 4.14 Natural gas infrastructure demand / supply (Initial Priority: 215436)

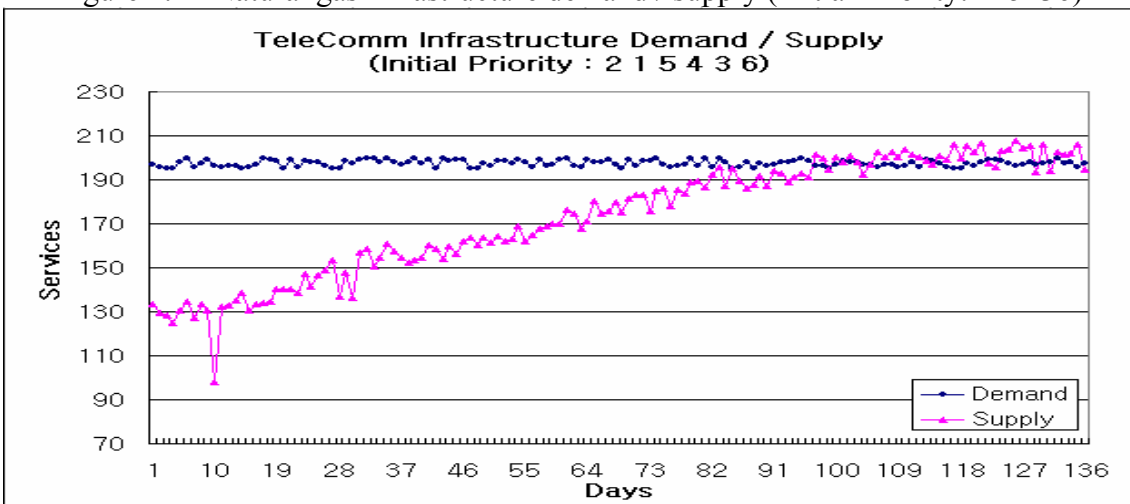


Figure 4.15 Telecommunication infrastructure demand / supply (Initial Priority: 215436)

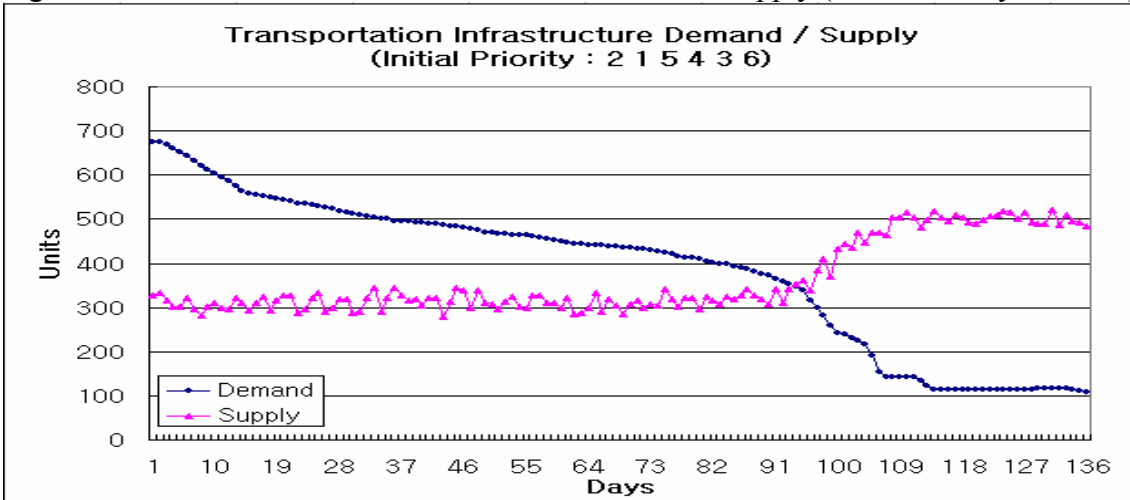


Figure 4.16 Transportation infrastructure demand / supply (Initial Priority: 215436)

4.2.3 Result of Multiple Replications

As I mentioned before, previous sections dealt with the outputs those are conducted for single run. Due to variability of simulation model, certain amount of replications should be performed in order to obtain confidence.

In order to estimate the number of replications, I used the inequality 3.7.1 and 3.7.2 which I already introduced at chapter 3.

$$R \geq \left(\frac{t_{\alpha/2, R-1} S_0}{\varepsilon} \right)^2 \quad (\text{Inequality 3.7.1})$$

$$R \geq \left(\frac{Z_{\alpha/2} S_0}{\varepsilon} \right)^2 \quad (\text{Inequality 3.7.2})$$

Inequality 3.7.2 can be used to estimate the initial number of replications. The error criterion is chosen as 4 days (i.e., $\varepsilon = 4$). The smaller error criterion makes the estimate of replications larger. The confidence coefficient is $1 - \alpha = 0.95$. Now, we need to get initial estimate S_0^2 . The facing problem is that different combinations make various variances. For example, initial priority 642513 yields $S_0^2 = 96.56$ while initial priority 412653 yields $S_0^2 = 25.04$ where initial replication R_0 is 20. Hence, I conducted 50 iterations with 20 replications for each in order to estimate the S_0^2 . To make a iteration independent, initial priority combination is chosen randomly for iteration.

$$S_0^2 \equiv \frac{\sum_{i=1}^{50} S_{i0}^2}{50} \quad \text{where, } S_{i0}^2 = \text{Variance of } i\text{th iteration with 20 replications}$$

Table 4.2.2 on the next page is the results.

$$S_0^2 = 252.85.$$

$$R \geq \left(\frac{Z_{\alpha/2} S_0}{\varepsilon} \right)^2 \Rightarrow R \geq \left(\frac{Z_{0.025} * (15.9)}{4} \right)^2 \Rightarrow R \geq \left(\frac{(1.96) * (15.9)}{4} \right)^2$$

$$R \geq 60.71$$

It means that at least 61 replications are needed. Now, in order to estimate the final sample size, inequality 3.7.1 will be used.

Table 4.1 Estimation of final sample size

R	61	62	63	64
$t_{0.025, R-1}$	2.0002	1.99962	1.99897	1.99834
$\left(\frac{t_{0.025, R-1} S_0}{\varepsilon} \right)^2$	63.225	63.1872	63.1429	63.1076

$$\text{When } R = 64, \left(\frac{t_{0.025, 63} S_0}{\varepsilon} \right)^2 = 63.1076 \leq 64$$

Finally, the number of replications is chosen as 64.

Table 4.2 Estimation of sample variance

iteration	Y	Initial Priority						Variance
1	114.4	6	4	2	5	1	3	96.56
2	108.1	4	1	2	6	5	3	25.04
3	113.25	4	6	5	2	1	3	194.72
4	106.65	3	5	6	4	1	2	59.81
5	111.15	6	4	3	5	1	2	334.87
6	130.75	6	5	2	1	3	4	659.144
7	112.65	3	1	6	2	5	4	243.18
8	97.95	1	3	6	4	5	2	45.41
9	110.55	3	2	1	5	6	4	110.99
10	116	5	6	1	4	3	2	80.5263
11	106.55	3	5	6	4	2	1	66.8921
12	125.45	5	3	1	2	4	6	365.4184
13	103.1	5	2	3	6	4	1	32.2
14	106.1	6	2	4	5	1	3	56.41
15	115.35	6	5	4	3	2	1	165.8184
16	113.4	1	5	3	6	2	4	102.6737
17	101.05	4	1	6	5	3	2	47.9447
18	119.85	3	5	4	2	1	6	452.8711
19	110.7	3	6	2	4	5	1	76.95
20	116	5	1	6	2	3	4	361.1579
21	125.95	6	4	1	3	2	5	769.3132
22	114.8	4	6	5	2	3	1	135.3263
23	103.75	5	1	6	3	4	2	31.7763
24	100.75	4	1	6	5	3	2	48.7237
25	111.35	4	6	5	1	2	3	35.1868
26	122.7	2	5	1	3	6	4	465.5895
27	129.15	6	2	1	3	4	5	819.2921
28	112.35	5	4	2	6	1	3	45.9237
29	126.8	6	4	3	1	5	2	619.9579
30	108.5	2	5	6	4	3	1	550.1579
31	111.65	5	4	6	2	3	1	76.6605
32	104.7	2	3	6	5	1	4	29.2737
33	99.05	4	2	3	5	6	1	15.9447
34	130.35	3	6	1	2	4	5	273.2921
35	132	1	5	3	2	4	6	662.2105
36	123.65	3	4	1	6	2	5	260.2395
37	125.15	2	6	4	1	5	3	642.7658
38	112.85	6	4	1	3	5	2	117.9237
39	114	3	5	2	6	1	4	50.4211
40	110.6	5	3	6	1	4	2	202.2526
41	114.1	5	3	4	1	6	2	611.5684
42	120.3	4	1	2	3	6	5	404.7474
43	123.55	5	4	1	2	6	3	654.9974
44	101.95	3	1	4	5	6	2	78.6816
45	109	1	6	4	3	5	2	116.2105
46	110.95	5	6	4	3	2	1	147.6289
47	130.8	6	5	1	2	3	4	455.9579
48	131.1	3	5	2	1	4	6	610.2
49	105.55	2	5	6	4	3	1	79.1026
50	100.75	1	3	6	4	5	2	52.8289
Mean								252.8548

4.3 Heuristic optimization

At first, the parameters for simulated annealing are defined and various scenarios are conducted. The chosen scenarios are described below.

Table 4.3 Three Scenarios

Scenario Number	Impact Area		Region
	X-Coordinates	Y-Coordinates	
1	23.5	28	Southern
2	5	5	Northern
3	15	15	Center

Scenario 1 is the one which assume that hurricane strikes the southern part of state. Coordinates are already used for previously performed results. Secondly, another scenario is conducted that assume the northern area of state as impact area. The last scenario has the (15, 15) as its impact area coordinates and it assume that the hurricane strikes the center of state.

For all scenarios, initial parameters for simulated annealing are chosen as follows.

$$\text{Initial temperature, } T = 500$$

$$\text{Cooling rate, } r = 0.9$$

$$\text{End temperature} = 0.1$$

$$\text{Iterations within the inner-loop: } 10$$

Above temperature setting allow the optimizer to search the global optimum densely since it has temperature decrease rate as 0.9. Those parameters are critically affect the simulation run time and quality of solution and also those values are permutable to modify by user. Iteration within a scenario involves 64 replications that are determined at previous section.

4.3.1 Scenario #1

Simulation optimization for scenario #1 took 4 hours 5 minutes to be done with Pentium D, 3.00 GHz CPU.

Below table shows the initial condition that is corresponding to how much each infrastructure is damaged right after disaster is gone.

Table 4.4 Initial condition (Scenario #1)

	<i>Water</i>	<i>Power</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Telecomm</i>	<i>Transportation</i>
Initial Condition	0.6424	0.7326	0.4528	0.6664	0.6431	0.7216

Now, following table and figure are the optimization results.

Table 4.5 Optimization results on scenario #1

	<i>Water</i>	<i>Power</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Telecomm</i>	<i>Transportation</i>	TTR (Days)
Best	3	2	6	5	4	1	94.8281
Worst	1	6	2	3	4	5	128.81

In turned out that minimum (i.e., optimum) time to rebuild is 95 days (i.e., 94.8281) and it came from the initial priority combination of 326541. In other words, we can expect total time to rebuild to be minimized when we give privileges to transportation with first priority and regard power infrastructure as secondly critical one and follow the order of water, telecommunication, natural gas, oil infrastructure.

Result may help decision maker in various situations. For example, let me assume that volunteer assistance team arrived in order to help rebuilding the infrastructures from

other states. And, there are collisions between transportation infrastructure recovery team and natural gas infrastructures team because they all insisted that they need more crews. In that situation, instead decision maker allocate the assistance team arbitrarily, he should give ear to transportation recovery team based on optimization result.

Worst total time to rebuild is estimated as 129 days. However, it does not represent indeed maximum value since the optimization model does not aim to find the maximum duration. 129 days is the just largest value amongst the values those are resulted from minimum optimizing simulation run. However, it is worthy to consider here because it proofs that wrong decision on priority selection cause unnecessary time-waste as amount of 34 days

The worst time to rebuild (i.e., 122) – The best time to rebuild (i.e., 95) = 27 days

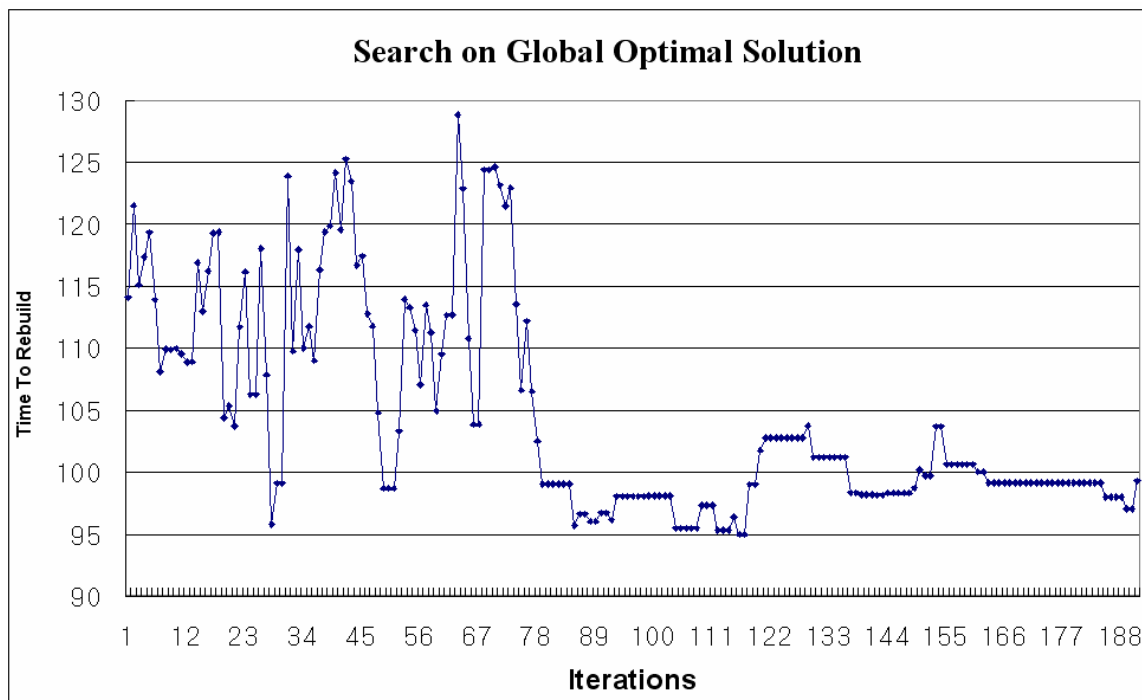


Figure 4.17 Global Optimum Search (Scenario #1)

4.3.2 Scenario #2

Simulation optimization for scenario #2 took 3 hours 57 minutes to be done under same condition as the scenario #1. In the same fashion as scenario #1, various results follow.

Table 4.6 Initial condition (Scenario #2)

	<i>Water</i>	<i>Power</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Telecomm</i>	Transportation
Initial Condition	0.7293	0.6175	0.9138	0.7063	0.7169	0.6177

Compared to scenario #1, initial condition of oil infrastructure is large. Figure 4.2.3 tells us where this difference came from. Since most of oil facilities are gathered at southern part of Louisiana, this scenario (note that coordinates is (5, 5)) has relatively large oil initial condition.

Now, following table and figure are the optimization results.

Table 4.7 Optimization results on scenario #2

	<i>Water</i>	<i>Power</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Telecomm</i>	Transportation	TTR (Days)
Best	3	2	5	4	6	1	89.92
Worst	4	5	1	2	3	6	125.47

Best time to rebuild is 90 days. It is 5 day faster than scenario #1. The best initial priority is 325461. The first, second and third priority is same as scenario #1 (i.e., 326541). Transportation infrastructure takes the first priority again. Power and water infrastructure are followed. The worst solution is found as 126 days with 451236 initial priority. It is completely different with the worst solution at scenario #1 and it is not a

surprise result because as I mentioned before, the worst solution is the just large solution which found during minimum optimization. At the scenario #2, it turned out that choosing the appropriate initial priority can save 36 days, almost a month.

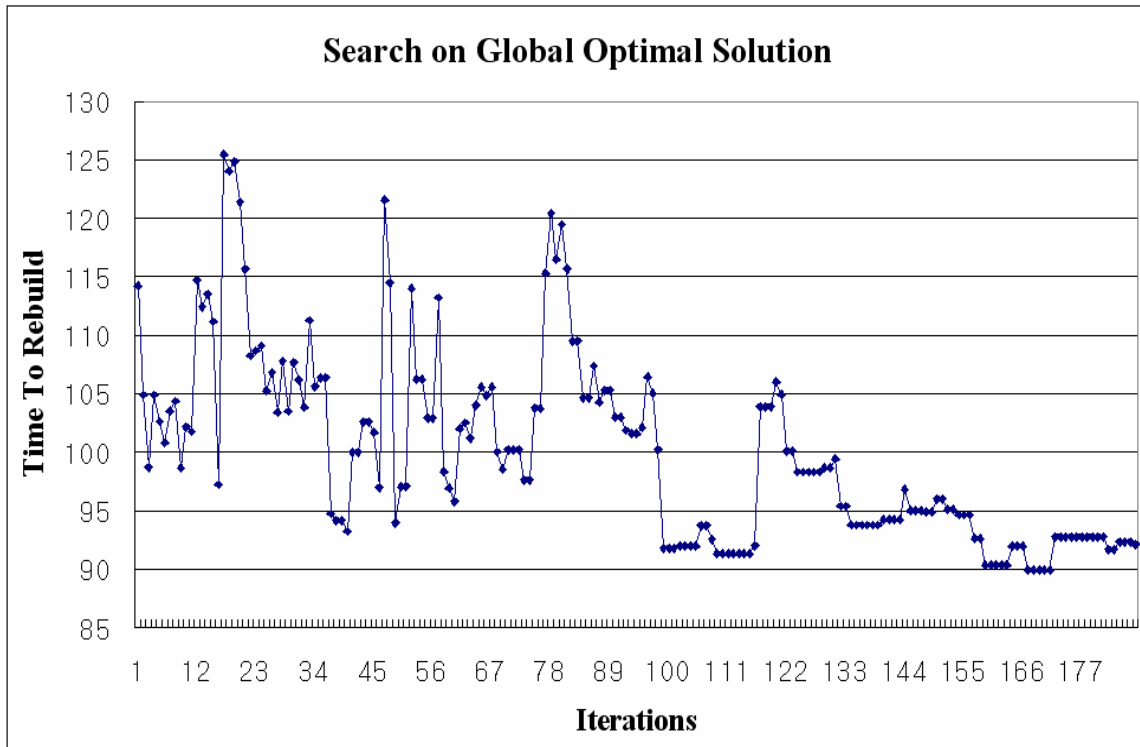


Figure 4.18 Global Optimum Search (Scenario #2)

Optimizer found the best solution at iteration 170. Optimizer tried to search better solution by permitting the non-improve movement after 170 days. However, it could not find the better one and graph shows that searching movement is converging around the best solution.

4.3.3 Scenario #3

Scenario #3 is conducted with (15, 15) as impact area coordinates that is the center of state. Simulation optimization for scenario #3 took 6 hours 12 minutes to be done under same condition as the scenario #1. This scenario took most long run time. We can guess that it is caused by overall small initial condition as you can see below table.

Table 4.8 Initial condition (Scenario #3)

	<i>Water</i>	<i>Power</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Telecomm</i>	Transportation
Initial Condition	0.4892	0.4926	0.6443	0.5491	0.5368	0.5026

Table 4.9 Optimization results on scenario #3

	<i>Water</i>	<i>Power</i>	<i>Oil</i>	<i>Natural Gas</i>	<i>Telecomm</i>	Transportation	TTR (Days)
Best	3	1	5	6	4	2	130.28
Worst	2	6	3	4	1	5	165.14

Same as scenario #1 and #2, transportation, power and water infrastructure hold the higher priority. However, transportation could not maintain the first priority. Other infrastructures hold different priority as run the various scenarios. This scenario makes most long total time to rebuild that is 131 days. It still shows that wrong decision on initial priority bring almost a month to be spent and it is obviously unnecessary expense.

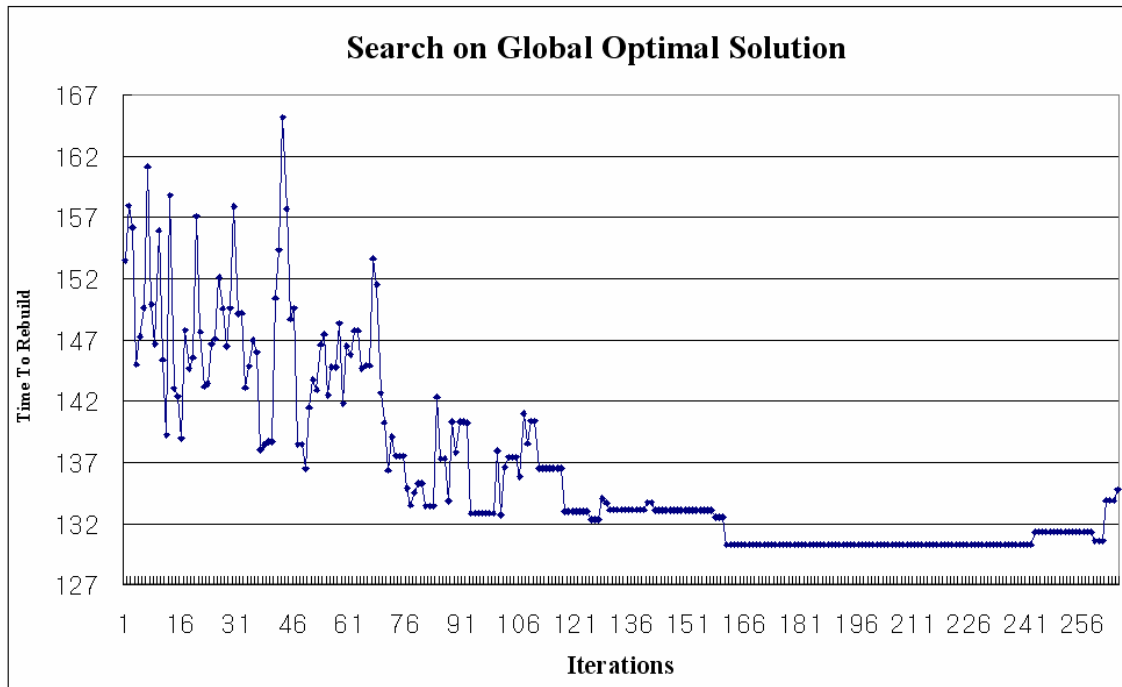


Figure 4.19 Global Optimum Search (Scenario #3)

Optimizer detected the best solution at around 160 iterations. Total iterations are 265 days. Unlike previous scenarios, this graph shows us pretty good converging. Consequently, we can figure out that initial priority affects significantly to *TTR* since iteration is conducted with different initial priority.

From the results of three scenarios, it turned out that minimum *TTR* is found when transportation, power and water infrastructures occupy the top three priorities. And, other infrastructures (i.e., oil, natural gas, and telecommunication) could not take higher priority at all. Let's look at scenario #1 results on page 99. There is interesting output that even though oil infrastructure had a smallest initial condition, oil infrastructure took 6th priority as best solution. Intuitively, it seems unreasonable because we can think that more damaged infrastructure should be recovered at first. Why oil infrastructure took the

worst priority? We would find answer by considering kinds of incident matrix which represents interdependency between infrastructures. I attached incident matrix of infrastructure interdependency at appendix D. In the matrix, red cell means that there is interdependency or dependency between infrastructures. We can figure out that infrastructures those have many red cells (i.e., have more relations) are transportation, power, and water those occupied top three priorities in three scenarios. In short, simulation results tell us that infrastructure that has more number of dependencies should be recovered with higher priority.

4.3.4 Evaluation of Optimizer

Self-evaluation is examined whether rebuilding optimization model is desirable or not. All criteria are based on contents in the Simulation Modeling and Analysis (Averill M. Law: 659).

1) Quality of the solution and execution time

Since indeed optimal solution is not known, it is hard to evaluate the optimizer clearly such as 95% quality of true object value. However, by the feature of heuristic method, sometimes a good solution with less execution time is welcome instead of a perfect solution with huge amount of execution time. In that fashion, my optimizer is not free from execution time. Actually, rebuilding optimizer took more than 2 hours to get optimum. Sometimes, user has to wait for 6 hours to get it. I strongly believe that large execution times caused from a lot of replications within iteration. Note that we conducted 64 replications for iteration because we have large sample variance. However,

fortunately, the time-consuming problem is not the one that never be solved. Modifying the temperature setting such as end temperature, cooling schedule permits the optimizer to have less execution time as I mentioned continuously. For that, the degree of expectation on quality of solution would be decreased.

2) A dynamic display of important information during execution.

My optimizer shows the results on every run. Results includes total time to rebuild and priority combination that be used. If best solution is found, then model display new best solution with combination. Since optimizer displays the critical change of temperature setting, the user can expect that simulation will be terminated in a soon or not. For example, temperature (*i.e.*, t) is 1.122 means that optimization run would be done in a soon because end condition of temperature is 1. However too many displays may cause unnecessary large execution times. Hence, only critical information for user should be displayed for economic execution times.

3) Several stopping rules

Stopping rules in the optimizer are the same as ordinary simulated annealing algorithm. Simulated annealing has both non-improvement termination rule and overall termination condition which is represented as end temperature. Any more stopping rules are not added in optimizer. However, if execution time is critical to user then time-elapsed termination condition can be considered by simply using the wall clock. I introduced simple pseudo-code for time-elapsed termination in *MATLAB*.

Time = clock (Time has time when simulation starts)

Maximum time = [0 0 0 0 0 0] (Year, Month, Day, Hours, Minutes, Second)

While *time (5) + desired run time (min) > Maximum time (5)*

Maximum time = clock

End

4) More replications for the higher-variance configurations.

At the Table 4.2.2 in previous section, it turned out that some configurations (i.e., initial priority) have large variance while other configurations have reasonably small variance. Even though, I estimated the whole sample variance as the average values of picked 50 samples, it does not clearly guarantee that variance estimation is represented for characteristic of indeed variances. Instead of that methodology, doing more replications for the higher-variance is desirable as mentioned in the Simulation Modeling and Analysis (Averill M. Law: 660). Examples for this will be examined at the chapter 5; further study section.

In short, I examined the 4 features which simulation optimization model should have. And, I evaluated the optimizer myself. Consequently, with related to execution time and considerations on higher-variance, it is not quite good. However, in the sense of quality of solution, stopping rules and dynamic display, my optimizer seems like desirable.

4.4 Summary

This chapter provided the results on various experiments. At first, single simulation runs are conducted with different initial priority. Results on initialization gave us an insight on how spatial layer is structured and what is the role of spatial layer in the model. In order to understand the rebuilding process in the model, I examined several experiments with single run. Fluctuation of each infrastructure capacity and movement of score curve are described with carefully. And I emphasized on both infrastructure capacity and their score with related to priority because they take big portion on simulation model.

At the last part of this chapter, since ultimate goal of this simulation is to find best combinations of infrastructure priority, several optimization experiments are conducted. And, since we have 700 possible configurations, heuristic optimization technique is chosen as appropriate approach. From the 3 kinds of scenarios, transportation infrastructure is admitted as most valuable one. In other words, simulation proved that fast recovery on transportation guarantees the minimum duration to rebuild. Even though different scenarios yields different outputs, commonly, water infrastructure and power infrastructures are turned out to be priority order while oil infrastructure, natural gas infrastructure and telecommunications are not quite urgent than transportation, water and power. The important fact that we have to consider is that we can not come to a conclusion rashly because the results very depend on the initial condition and initial priority or impact area.

V. Recommendations and Further research

5.1 Introduction

This chapter provides the drawbacks of model with suggestion on that for improving the simulation model in terms of realistic and performance. Following restrictions on model include what I could not because it is beyond me and what I did not because of circumstances permit. Restrictions and recommendations are examined simultaneously in the same section.

5.2 Restrictions on model and future research

Following 7 major drawbacks are self-evaluated. It means that proposed recommendations may take a subjective view of mine. I did not try to verify the system with written document or existing model or any expert's opinion. Indeed there are no comparable models against mine since rebuilding model dealt with unique topic that is research on critical infrastructure priority during rebuilding phase.

1) Data Collection

The problems on data collection are steadily mentioned in this article. And, it is connected with following problems directly or indirectly. I strongly believe that accurate and plenty information is the one of the key features that must be ensured in order to simulate the real world with high credibility. For further research, I attached the parameters table which represents what I could obtain and what I could not. Bold and italic and underlined word or sentence in table means that value is not came from credible source instead it chosen arbitrary or it includes the values that even though it came from

officially credible site, values are modified arbitrary because values are not matched each other.

Table 5.1 Estimate of parameters (1)

Infrastructure			
Water			
Water Production		6290 MGD	: Only consider industrial purpose in Louisiana
Water demand from water			
Water Wells	301.35 MMWh		: 6.027 MMWh * 50 (Number of Water Wells)
Treatment System	7560 MMWh		: 6.3 MMWh * 1200 (Number of Treatment system)
Waste Water	900 MMWh		: 4.5 MMWh * 200 (Number of Waste water system)
Power			
Power Production			
Nuclear	88363.41 MMWh		: 32,252,644 MMWh / 365 (Days)
Fossil Fuel			
Coal	125282,208 MMWh		: 45,728,006 MMWh / 365 (Days)
Petroleum	15733,8082 MMWh		: 5,742,767 MMWh / 365 (Days)
Natural Gas	183954,151 MMWh		: 67,143,285 MMWh / 365 (Days)
Other Source	8011,03014 MMWh		: 2,924,026 MMWh / 365 (Days)
CHP			
Coal	136,586301 MMWh		: 49,864 MMWh / 365 (Days)
Petroleum	364,736986 MMWh		: 133,129 MMWh / 365 (Days)
Natural Gas	655000,3589 MMWh		: 23,725,131 MMWh / 365 (Days)
Other Source	6713,51781 MMWh		: 2,450,434 MMWh / 365 (Days)
Geothermal	1673 MMWh		
HydroElectric	2442.3 MMWh		: 891,441 MMWh / 365 (Days)
Water Demand from Power			
Nuclear	1702 MGD		: 17 Gallons per 1 kWh => 1,502,177,930 Gallons => Modified as 1702 MGD
Fossil Fuel	2430.8 MGD		: 7 Gallons per 1 kWh => 2,330,866,980 Gallons => Modified as 2430.8 MGD
Geothermal	570 MGD		
CHP	550 MGD		: 7 Gallons per 1 kWh => 505,506,400 Gallons => Modified as 550 MGD
Oil and Natural Gas Demand from Power			
Fossil Fuel			
Coal	84765.3 tons		: 30,939,331 tons / 365 (Days)
Petroleum	28192.65 Barrels		: 10,290,317 Barrels / 365 (Days)
Natural Gas	588.81 Mcf		: Total amount of Natural Gas for Power * (Percentage of Fossil Fuel)
CHP			
Coal	38.38 tons		: 14,375 tons / 365 (Days)
Petroleum	921.21 Barrels		: 336,241 Barrels / 365 (Days)
Natural Gas	191.17 Mcf		: Total amount of Natural Gas for Power * (Percentage of CHP)
Other gasses	42.28 Mcf		: 15,453 Mcf / 365 (Days)
Oil			
Oil Production			
Crude Oil	207,000 Barrels/Day		
gasoline	281882.25 Barrels/Day		: 1 crude oil makes 19.5 Gallons of Gasoline => Transform to Barrels => * 35% (In-state use)
Diisel Fuel oil	132990.6 Barrels/Day		: 1 crude oil makes 9.2 Gallons of Diisel => Transform to Barrels => * 35% (In-state use)
Kerosene (jet)	62189.85 Barrels/Day		: 1 crude oil makes 4.3 Gallons of Kerosene => Transform to Barrels => * 35% (In-state use)

Table 5.2 Estimate of parameters (2)

Water Demand from Oil	Coal	Fuel oil	33247.65 Barrels/Day	:1 crude oil makes 2.3 Gallons of Fuel Oil => Transform to Barrels => * 35% (in-state use)
		LP G	27465.45 Barrels/Day	:1 crude oil makes 1.9 Gallons of LP G => Transform to Barrels => * 35% (in-state use)
		Asphalt	18792.15 Barrels/Day	:1 crude oil makes 1.3 Gallons of Asphalt => Transform to Barrels => * 35% (in-state use)
			11506.85 tons	: 4.2 millions short tons / 365(Days)
	Oil Wells		6.952 MG/May	: 0.8 Gallon per Crude oil
	Refinery		695.52 MG/May	: 80 Gallons per Crude oil
	Oil Plant		124,200 MWh	: 600 kWh per a Barrel
	Coal (Mines)		1.5M MWh	
				Barrels * 42 = Gallons MG: Million Gallons
Power Demand from Oil				
Natural Gas Production				
	Natural Gas		3550.82 Mcf	: 1,296,048 / 365(Days)
	Usable Natural Gas		3182.91 Mcf	: Loss Ratio (0.0354% lease fuel, 0.0357% Plant fuel, 0.0325% pipeline)
Natural Gas Consumption				
	Industrial use		2213.66 Mcf	: Total Natural Gas * 0.695%
	Vehicle		0.3978 Mcf	: Total Natural Gas * 0.0001%
	Electric		787.288 Mcf	: Total Natural Gas * 0.25%
	Others		181.569 Mcf	: Total Natural Gas * 0.056%
Water Demand from Natural Gas			3M MGS/Day	
	Gas Treatment Plant		550M MWh	: Estimated by (Total Power * Industrial Use (0.383%) - Already used Power for other infrastructures)
	Gas Wells		92M MWh	
Telecommunication Production				
	Bandwidth		100 %	: Wireless Service
	Service		100 %	: Wire Service
Power Demand from Telecomm			8648.68 MWh	: Total Power * Other Use (3.5%) * (50% ; transportation takes 50%)
			(MWh/E=20)	: Assumption (Regardless of day, demand for telecommunication is consistent)
Transportation				
	Power Demand from Transportation		8648.68 MWh	: Total Power * Other Use (3.5%) * (50% ; telecom takes 50%)
Demand for Oil from Trans				
	Asphalt		18792.15 Barrels/Day	Assumption All oil productions for in-state use are consumed by vehicle (Transportation) Do not consider residential use or commercial use
	gasoline		281882.25 Barrels/Day	
	Diesel Fuel oil		132990.8 Barrels/Day	
	Kerosene (jet)		62158.65 Barrels/Day	
	LP G		27465.45 Barrels/Day	
Demand for Transportation				
	Well(50), Treatment(30), Waste water(30)			
Water	Coal mines(20), Storage(20), Well(50), Pipeline(50), Port(30)			
	Refinery(30), Refinery Storage(20), Terminal Storage(20)			
Oil	Well(50), pipeline(50), plant(30), storage(20)			
	Signal(50), Road(50), Rail(50), Airport(50), Bridges(50)			
Natural Gas	Wireless(station(30), Local Tower(50)), Wire(Ctr Center(30), Line(50))			
Transport				
	Nuclear (Fuel Storage(20), Reactor(30))			
	Fossil Fuel (Storage(50), Boiler(20), Generator(30), Cooling(20))			
	Geothermal(underground storage(20), heat pump(20), cooling(20))			
	Hydro(Dam(30), intake system(20), generator(20))			
	CHP(Storage(30), Boiler(20), Generator(20), Cooling(20))			
	Transmission Line (50)			

2) Flow and Stock

The physical layer in the model aims to be flow and stock model. However, the concept of stock did not adopted into model. For example, let me examined the fossil fuel power plant that is power infrastructure sub-model. Fossil fuel storage usually stores petroleum, coal, natural gas and other gases because generator in fossil fuel plant has to use them in order to generate power. Let me assume here that 8,000 barrels of petroleum is stocked at time 30. (i.e., the amount of petroleum in the fossil fuel storage at time 30 = 8,000) And, 5,000 barrels of them are consumed at time 30. Then, 3,000 barrels of petroleum (i.e., 8,000 – 5,000) have to be stored in the storage and the amount of petroleum in storage at next time event would be estimated by following equation.

The amount of petroleum in fossil fuel storage at time 31 = delivered petroleum at time 31 + petroleum already stored from time 30

However, the model set the petroleum remains in the storage as 0. It means that unused petroleum is gone. Consequently, concept of inventory is not considered in the model.

Adoption of inventory system is quite simple however it should consider the demand.

The amount of fuel in storage at time t = The amount of fuel in storage at time t-1 + the amount of fuel which is deliver at time t - the amount of fuel which is consumed at time t

And, demand for fuel is estimated as follows.

Demand for fuel at time t = request for fuel at time t – the amount of fuel in inventory

Moreover, there are many considerations in order to implement stock concept in the model such as maximum capacity of storage or product's life. For example, if maximum

capacity of natural gas storage is 5,000 Millions cubic per feet and stocked gas is already 5,000 but there are no customers for a while, then natural gas should not be generated anymore unless inventory level is decreased. Also, if we assume that quality of petroleum is decreased as days go by, then petroleum in inventory should be classified by date. Even though there are some complex tasks to be considered, it is obvious that notion of stock enhances the reality of flow model.

3) High-variance problem

As I mentioned at chapter 4, different combinations of initial priority make different variances and mostly those variances are large. Large variance may be caused by internal factor within simulation model. Large and unstable variances resulted in a lot of replications in order for the simulation output to have certain amount of confidence. In order to enhance speed and efficiency of simulation model, reducing the variance of output is indispensable. Grasping the factor which makes variance larger and settlement on that left for further study.

4) Resource allocation in the system is not secure

In my model, resource for infrastructures is allocated by the function of demand and its score as I introduced at chapter 3. Even though method which I used works well in the model empirically, that still can not be perfect solution.

Figure 5.1 is the graph that represents the power demand (i.e., demand in index) from telecommunication infrastructure and power allocation to telecommunication (i.e.,

resource in index). Simulation is conducted with 136452 as an initial priority. On the graph, after 40 days, power infrastructure provides the power to telecommunication faithfully. However, after 130 days, it turned out that power allocation to telecommunication is rapidly decreased and rapidly increased again. It seems like unstable. I believe that the reason why power allocation to telecommunication is interrupted is that at that time, telecommunication may be deprived of its score by another infrastructure. It means that another infrastructure who has larger score at that period took away power from telecommunication. However, sudden suspension of power like graph (i.e., power resource is steeply decreased from 8,000 to 2,000) would cause serious problem in real world. Thus, model needs a rule which function as a shock-absorbing. For example, following rules will prevent the simulation model from making extremely unrealistic results.

e.g.) decreasing rate of power allocation to any infrastructure at time t can not exceed 3,000.

And, set of those rules are considered as constraints in the simulation model.

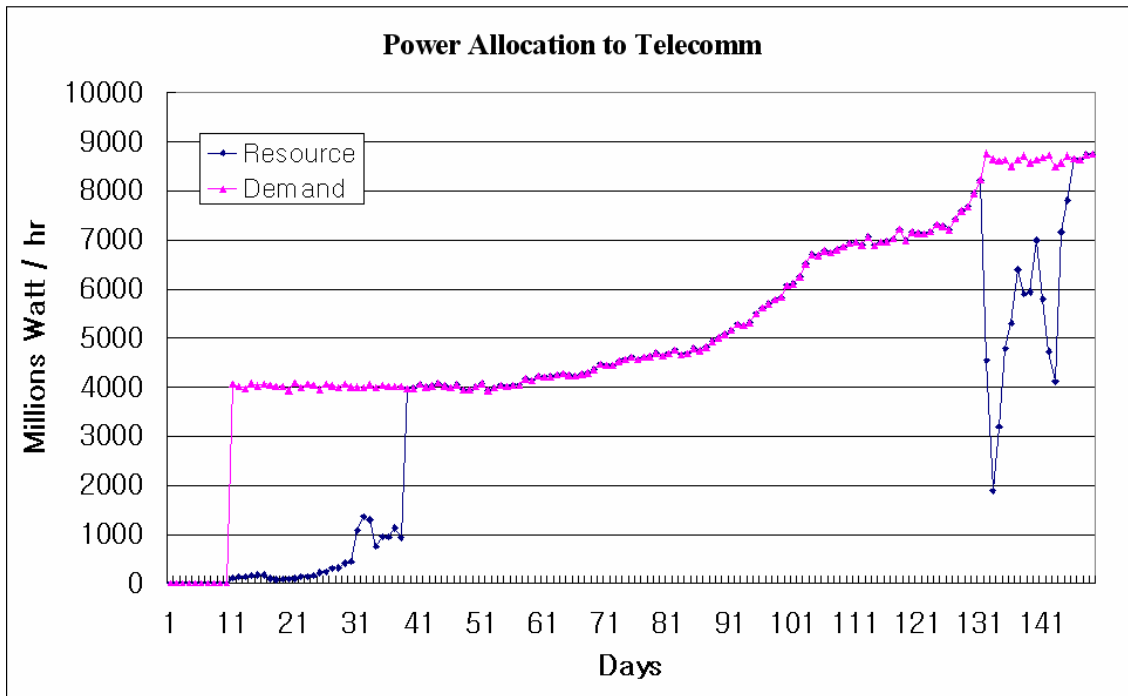


Figure 5.1 Power allocation to Telecommunication

5) Transportation unit should be described detail with tonnage or number of crews.

This drawback is related to 1) that is restriction on data collection. Water infrastructure produces the water and its unit is represented as a barrel. In the same fashion, transportation should produce real exist objects such as tonnage or number of trucks as its unit to make simulation model realistic. Gathering the data which can answer the questions such as ‘how many trucks should be deployed in order to restore the broken bridges’ or ‘how many crew could be transported via road when road is damaged by 30%’ must be ahead of modeling for further research.

6) Spatial Layer should have all agents in his layer.

A final object for spatial layer is that have all agents within its system. For example, power transmission line is the only one which is modeled in the spatial layer. However, power infrastructure is consisted of about 20 numbers of agents. Since each of rest also has its unique locations, they also need to be modeled in the spatial layer. For doing that, coordinates of rest of them are needed. However, as we add up the agents to spatial layer, we can obtain more realistic and reasonable results on initialization. Also, we can expect the some extension with related to priority by zone. This will be discussed next part of this section.

7) Priority Extension

We tried to find best initial priority combination and priority combination is consisted of series 6 numbers because each infrastructure takes only 1 number as its priority. However, more extension on initial priority would enhance the quality of simulation model. In other words, I believe various extensions can add a fidelity to simulation model. Figure 5.2 shows possible extension examples.

Current Model

Water	Power	Oil	Gas	Telecom	Trans	TTR
1	2	3	4	5	6	104
3	4	5	6	1	2	98
.
.



Possible Extensions

Priority Extension on Sub-Models

Water			Power				TTR	
Drinking	Nuclear	...	Fossil Fuel	...		
Wells	Treatment	...	Storage	Generator	...	Storage	Generator	
1	8	...	56	34	...	17	12	110
40	9	...	33	21	...	11	2	98
.
.

Priority Extension on Region

Zone1	Zone2	Zone3	...	Zone n	TTR
34	2	11	...	20	130
1	5	8	...	19	102
.
.

e.g.) Zone 1
Zone 2



Figure 5.2 Possible extensions in terms of priority

For example, assume that nuclear power plant takes 95% of generated power in a certain state. Decision maker may think nuclear power plant has to be recovered with the first priority while other power plant does not need to be restored with highest priority since they only can produce 5% of power in a state. If we use current rebuilding model, this situation may not be solved reasonably. However, extensions on priority to a level of sub-models make those kinds of problems to be solved easily. If we extent the priority level, then we can assign the degree of importance to nuclear plant even we can extent to generator or fuel storage those are in the smaller level than level of nuclear plant.

Let me assume another situation that there are special offers which recover the particular regions at first because those regions are strongly responsible for importing the goods to foreign. Extension the priority onto regions may solve this problem as you can see the below part of figure 5.2.

Consequently, within the same ultimate goal that is minimize the total time to rebuild, we examined that there are various possibilities to extent the rebuilding model by considering the user's intent and particular situation.

5.3 Conclusion / Summary

This chapter is devoted to examine the drawbacks of simulation model and recommendations on that. It turned out that the first problem that is restriction on data collect affected to other problems directly or indirectly. What I should mention here is that restriction on data collect also includes lack of technique to search the data on the web of mine. I believe 6 major weak points and 1 extension method and a plenty of suggestions allow this study to be continued.

Appendix A. MATLAB code for spatial model

```

=====
% Author: Namsuk, Cho
% Last Modified: 2007. 2. 18
=====
function [waterwells_capacity, power_transmission_capacity, in2, oil_port_capacity, oil_pipeline_capacity,
in3, in1, gas_pipeline_capacity, in4, trans_rail_capacity, trans_road_capacity, trans_bridges_capacity, in6]
= initialization()

impact_area=[23.5 28]; % Scenario #1

% Louisiana Map Coordinates
louisiana=[ 1 1.16 26.13 0.53 25.39;
2 0.53 25.39 1.91 23.43;
3 1.91 23.43 2.06 22.37;
4 2.06 22.37 2.06 21.53;
5 2.06 21.53 1.8 20.89;
...
278 6.86 26.04 5.46 25.65;
279 5.46 25.65 4.59 25.74;
280 4.59 25.74 3.19 25.78;
281 3.19 25.78 1.84 26.04;
282 1.84 26.04 1.16 26.13];
% Louisiana Matrix: [282 by 5]

% Initialization of transportation system
% graphical setting
set(gca,'nextplot','add','ydir','rev')
scatter(impact_area(1),impact_area(2),'rx'); % impact area is represented by "x"
title('Transportation Rail System','fontsize',13)

%=== Transportation Infrastructure Rail System ===
rail.name='transportation infrastructre Rail';
rail.segment=[1 0 0 2.27 4.07;
2 2.14 0.16 2.27 4.07;
3 4.86 0 5.18 3.86;
4 2.27 4.07 5.18 3.86;
5 0 3.91 2.27 4.07;
...
108 28.64 15.64 28.11 18.18;
109 28.11 18.18 29.38 20.77;
110 26.15 20.03 29.38 20.77;
111 29.38 20.77 30.12 19.97;
112 27.63 23.73 32.81 28.53];
% Rail Matrix: [112 by 5]

rail.distance_segment=[];
rail.capacity_segment=[];
sum=0;
for i=1:size(rail.segment(:,1),1)
    rail.distance_segment=[rail.distance_segment;
    distance([rail.segment(i,2), rail.segment(i,3)], [rail.segment(i,4), rail.segment(i,5)])];
    distance_dummy=distance([impact_area, [median([rail.segment(i,2), rail.segment(i,4)]),
    median([rail.segment(i,3), rail.segment(i,5)])]);
    sum=sum+rail.distance_segment(i);
    if distance_dummy < 8
        rail.capacity_segment=[rail.capacity_segment; (0.2-(rand()*0.2))];
        rail_graph=plot([rail.segment(i,4), rail.segment(i,2)], [rail.segment(i,5), rail.segment
(i,3)], 'r');
    end
    if distance_dummy > 8 & distance_dummy < 15
        rail.capacity_segment=[rail.capacity_segment; (0.7-(rand()*0.2))];
        rail_graph=plot([rail.segment(i,4), rail.segment(i,2)], [rail.segment(i,5), rail.segment
(i,3)], 'b');end
    if distance_dummy > 15
        rail.capacity_segment=[rail.capacity_segment; (1-(rand()*0.1))];
        rail_graph=plot([rail.segment(i,4), rail.segment(i,2)], [rail.segment(i,5), rail.segment
(i,3)], 'k');end
end
end

```

```

trans_rail_capacity = rail.capacity_segment;

% estimate the 'total weighted capacity of Rail System'
sum_weight_cap=0;
for i=1:size(rail.segment(:,1),1)
    sum_weight_cap=sum_weight_cap+(rail.capacity_segment(i)*((rail.distance_segment(i))/sum));
end
total_capacity_rail=sum_weight_cap;
trans(1) = total_capacity_rail ;

% Add-on Louisiana Map
for i=1:size(louisiana(:,1),1)
    a=plot([louisiana(i,4),louisiana(i,2)], [louisiana(i,5),louisiana(i,3)], 'linewidth', 3,
        'color', [0.3 0.6 0.4]);
end

%=== Transportation Infrastructure Road System ===
road.name='transportation infrastrucutre Road';
road.segment=[1 0.63    0.16    2.64    4.12;
              2 0      4.17    2.64    4.12;
              3 2.64    4.12    5.54    3.49;
              4 4.33    0.11    5.54    3.49;
              5 6.81    0.11    7.71    1.69;
              ...
              78 29.45  20.91   28.18   23.39;
              79 25.49  24.03   28.18   23.39;
              80 28.18  23.39   29.45   23.08;
              81 25.49  24.03   24.65   22.92;
              82 24.33  19.96   24.65   22.92];

road.distance_segment=[];
road.capacity_segment=[];
% Graphical Setting
figure
set(gca,'nextplot','add','ydir','rev')
scatter(impact_area(1),impact_area(2),'rx');
title('Transportation Road System','fontsize',13)

sum=0;
for i=1:size(road.segment(:,1),1)
    road.distance_segment=[road.distance_segment;
        distance([road.segment(i,2),road.segment(i,3)], [road.segment(i,4),road.segment(i,5)])];
    distance_dummy_road=distance([impact_area], [median([road.segment(i,2),road.segment(i,4)]),median([road.segment(i,3),road.segment(i,5)])]);
    sum=sum+road.distance_segment(i);
    if distance_dummy_road < 8
        road.capacity_segment=[road.capacity_segment; (0.2-(rand()*0.2))];
        road_graph=plot([road.segment(i,4),road.segment(i,2)], [road.segment(i,5),road.segment(i,3)], 'r');
    end
    if distance_dummy_road > 8 & distance_dummy_road < 15
        road.capacity_segment=[road.capacity_segment; (0.7-(rand()*0.2))];
        road_graph=plot([road.segment(i,4),road.segment(i,2)], [road.segment(i,5),road.segment(i,3)], 'b');
    end
    if distance_dummy_road > 15
        road.capacity_segment=[road.capacity_segment; (1-(rand()*0.1))];
        road_graph=plot([road.segment(i,4),road.segment(i,2)], [road.segment(i,5),road.segment(i,3)], 'k');
    end
end
end

% estimate the 'total weighted capacity of road System'
sum_weight_cap=0;
for i=1:size(road.segment(:,1),1)
    sum_weight_cap=sum_weight_cap+(road.capacity_segment(i) * (((road.distance_segment(i)) / sum)));
end
trans_road_capacity=road.capacity_segment;
total_capacity_road=sum_weight_cap;
trans(2) = total_capacity_road;

```

```

% Add-on Louisiana Map
for i=1:size(louisiana(:,1),1)
    a=plot([louisiana(i,4),louisiana(i,2)], [louisiana(i,5),louisiana(i,3)], 'linewidth', 3,
        'color', [0.3 0.6 0.4]);
end

%=== Transportation Infrastructure Bridges ===

bridge.name=' transportation infrastructure bridge';
bridge.segment=[1 0.58 1.95;
                2 1.48 3.17;
                3 3.01 6.55;
                4 3.54 7.08;
                5 4.54 8.03;
                ...
                64 27.13 26.4;
                65 27.34 26.83;
                66 27.6 27.25;
                67 28.66 27.93;
                68 27.18 22.23];

bridge.capacity_segment=[];
for i=1:size(bridge.segment(:,1),1)
    distance_dummy_bridge=distance([impact_area],[bridge.segment(i,2),bridge.segment(i,3)]);

    if distance_dummy_bridge < 8
        bridge.capacity_segment=[bridge.capacity_segment; (0.2-(rand()*0.2))];
        bridge_graph=scatter(bridge.segment(i,2),bridge.segment(i,3),'r');
    end
    if distance_dummy_bridge > 8 & distance_dummy_bridge < 15
        bridge.capacity_segment=[bridge.capacity_segment; (0.7-(rand()*0.2))];
        bridge_graph=scatter(bridge.segment(i,2),bridge.segment(i,3),'b');
    end
    if distance_dummy_bridge > 15
        bridge.capacity_segment=[bridge.capacity_segment; (1-(rand()*0.1))];
        bridge_graph=scatter(bridge.segment(i,2),bridge.segment(i,3),'k');
    end
end

trans_bridges_capacity=bridge.capacity_segment;

% estimate the 'total weighted capacity of bridge System'
total_capacity_bridge=mean(bridge.capacity_segment);
trans(3) = total_capacity_bridge;
in6=mean(trans);

% === Water Infrastructure: Water Wells ===
water_well_segment=[1 0.2676488 24.288211;
                    2 1.758470052 1.291611828;
                    3 2.828597527 20.78202781;
                    4 3.417560681 14.89380499;
                    5 3.44403998 11.19136135;
                    ...
                    46 25.42025513 25.00942263;
                    47 26.33666355 23.45925767;
                    48 26.46594571 18.79291216;
                    49 27.78301836 23.8633817;
                    50 28.24837182 19.37254421];

waterwells_capacity=[];
% Graphical Setting
figure
set(gca,'nextplot','add','ydir','rev')
scatter(impact_area(1),impact_area(2),'rx');
title('Water Wells','fontsize',13)

for i=1:size(water_well_segment(:,1),1)
    distance_dummy_waterwells=distance([impact_area],[water_well_segment(i,2),water_well_
segment(i,3)]);

```

```

if distance_dummy_waterwells < 8
    waterwells_capacity=[waterwells_capacity; (0.2-(rand()*0.2))];
    waterwells_graph=scatter(water_well_segment(i,2),water_well_segment(i,3),'r','filled' );
end
if distance_dummy_waterwells > 8 & distance_dummy_waterwells < 15
    waterwells_capacity=[waterwells_capacity; (0.7-(rand()*0.2))];
    waterwells_graph=scatter(water_well_segment(i,2),water_well_segment(i,3),'b','filled' );
end
if distance_dummy_waterwells > 15
    waterwells_capacity=[waterwells_capacity; (1-(rand()*0.1))];
    waterwells_graph=scatter(water_well_segment(i,2),water_well_segment(i,3),'k','filled');
end
end

total_capacity_waterwells=mean(waterwells_capacity);
inl=total_capacity_waterwells;

% Add-on Louisiana Map
for i=1:size(louisiana(:,1),1)
    a=plot([louisiana(i,4),louisiana(i,2)], [louisiana(i,5),louisiana(i,3)], 'linewidth', 3,
    'color', [0.3 0.6 0.4]);
end

%=== Power infrastructure: Power Transmission line ===

power_transmission_segment=[
    1  0.42  0.32  1.22  1.64;
    2  1.22  1.64  0.21  1.8;
    3  1.22  1.64  1.38  2.75;
    4  0.21  1.8  0.42  3.44;
    5  1.38  2.75  3.97  1.27;
    ...
    117 20.21  22.8  20.21  22.48;
    118 17.04  10.52  17.78  10.47;
    119 17.04  10.52  17.46  11.48;
    120 20.74  20.42  21.06  20.84;
    121 27.36  17.19  27.99  17.61];

power_transmission_distance=[];
power_transmission_capacity=[];

% Graphical Setting
figure
set(gca,'nextplot','add','ydir','rev')
scatter(impact_area(1),impact_area(2),'rx');
title('Power Transmission Line','fontsize',13)

sum=0;
for i=1:size(power_transmission_segment(:,1),1)
    power_transmission_distance=[power_transmission_distance;
    distance([power_transmission_segment(i,2),power_transmission_segment(i,3)], [power_transmission_segment(i,4),power_transmission_segment(i,5)])];
    distance_dummy_power=distance([impact_area], [median([power_transmission_segment(i,2),power_transmission_segment(i,4)], median([power_transmission_segment(i,3),power_transmission_segment(i,5)])]);
    sum=sum+power_transmission_distance(i);
    if distance_dummy_power < 8
        power_transmission_capacity=[power_transmission_capacity; (0.2-(rand()*0.2))];
        power_graph=plot([power_transmission_segment(i,4),power_transmission_segment(i,2)], [power_transmission_segment(i,5),power_transmission_segment(i,3)], 'r');
    end
    if distance_dummy_power > 8 & distance_dummy_power < 15
        power_transmission_capacity=[power_transmission_capacity; (0.7-(rand()*0.2))];
        power_graph=plot([power_transmission_segment(i,4),power_transmission_segment(i,2)], [power_transmission_segment(i,5),power_transmission_segment(i,3)], 'b');
    end
    if distance_dummy_power > 15
        power_transmission_capacity=[power_transmission_capacity; (1-(rand()*0.1))];
        power_graph=plot([power_transmission_segment(i,4),power_transmission_segment(i,2)], [power_transmission_segment(i,5),power_transmission_segment(i,3)], 'k');
    end
end

```



```

end

% estimate the 'total weighted capacity of road System'
sum_weight_cap=0;
for i=1:size(power_transmission_segment(:,1),1)
    sum_weight_cap=sum_weight_cap + (power_transmission_capacity(i) *
    ((power_transmission_distance(i)) / sum));
end
in2=sum_weight_cap;

% Add-on Louisiana Map
for i=1:size(louisiana(:,1),1)
    a=plot([louisiana(i,4), louisiana(i,2)], [louisiana(i,5), louisiana(i,3)], 'linewidth', 3,
    'color', [0.3 0.6 0.4]);
end

% === Oil Infrastructure: Oil Port ===
oil_port_segment=[ 1 2.59 4.81;
                  2 6.56 9.15;
                  3 10.69 13.43;
                  4 11.27 13.96;
                  5 13.34 2.64;
                  ...
                  81 32.34 31.9;
                  82 33.3 30.28;
                  83 33.29 29.54;
                  84 29.15 20.76;
                  85 27.36 25.17];
oil_port_capacity=[];
% Graphical Setting
figure
set(gca,'nextplot','add','ydir','rev')
scatter(impact_area(1), impact_area(2), 'rx');
title('Oil Port / Pipeline', 'fontsize', 13)

for i=1:size(oil_port_segment(:,1),1)
    distance_dummy_oil_port=distance([impact_area], [oil_port_segment(i,2), oil_port_segmen t(i,3)]);
    if distance_dummy_oil_port < 8
        oil_port_capacity=[oil_port_capacity; (0.2-(rand()*0.2))];
        oil_port_graph=scatter(oil_port_segment(i,2), oil_port_segment(i,3), 'r');
    end
    if distance_dummy_oil_port > 8 & distance_dummy_oil_port < 15
        oil_port_capacity=[oil_port_capacity; (0.7-(rand()*0.2))];
        oil_port_graph=scatter(oil_port_segment(i,2), oil_port_segment(i,3), 'b');
    end
    if distance_dummy_oil_port > 15
        oil_port_capacity=[oil_port_capacity; (1-(rand()*0.1))];
        oil_port_graph=scatter(oil_port_segment(i,2), oil_port_segment(i,3), 'k');
    end
end

total_capacity_oil_port=mean(oil_port_capacity);

%=== Oil infrastructure: Oil Pipeline ===
oil_pipeline_segment=[ 1 1.53 23.8 7.2 21.58;
                      2 7.2 21.58 4.23 23.48;
                      3 4.23 23.48 2.59 24.22;
                      4 4.23 23.48 6.24 23.54;
                      5 2.59 24.22 1.27 24.75;
                      ...
                      133 30.53 25.65 32.23 26.76;
                      134 30.53 25.65 31.49 27.5;
                      135 31.49 27.5 31.22 30.41;
                      136 31.22 30.41 32.7 31.57;
                      137 32.23 26.76 32.24 30.41];

oil_pipeline_distance=[];
oil_pipeline_capacity=[];
sum=0;
for i=1:size(oil_pipeline_segment(:,1),1)

```

```

oil_pipeline_distance=[oil_pipeline_distance;
distance([oil_pipeline_segment(i,2),oil_pipeline_segment(i,3)],[oil_pipeline_segment(
i,4),oil_pipeline_segment(i,5)])];
distance_dummy_oil=distance([impact_area],[median([oil_pipeline_segment(i,2),oil_pipe
line_segment(i,4)]),median([oil_pipeline_segment(i,3),oil_pipeline_segment(i,5)])]);
sum=sum+oil_pipeline_distance(i);

if distance_dummy_oil < 8
oil_pipeline_capacity=[oil_pipeline_capacity; (0.2-(rand()*0.2))];
oil_graph=plot([oil_pipeline_segment(i,4),oil_pipeline_segment(i,2)],[oil_pipeline_se
gment(i,5),oil_pipeline_segment(i,3)],'r');
end
if distance_dummy_oil > 8 & distance_dummy_oil < 15
oil_pipeline_capacity=[oil_pipeline_capacity; (0.7-(rand()*0.2))];
oil_graph=plot([oil_pipeline_segment(i,4),oil_pipeline_segment(i,2)],[oil_pipeline_se
gment(i,5),oil_pipeline_segment(i,3)],'b');
end
if distance_dummy_oil > 15
oil_pipeline_capacity=[oil_pipeline_capacity; (1-(rand()*0.1))];
oil_graph=plot([oil_pipeline_segment(i,4),oil_pipeline_segment(i,2)],[oil_pipeline_se
gment(i,5),oil_pipeline_segment(i,3)],'k');
end
end

% estimate the 'total weighted capacity'
sum_weight_cap=0;
for i=1:size(oil_pipeline_segment(:,1),1)
sum_weight_cap=sum_weight_cap+ (oil_pipeline_capacity(i) * ((oil_pipeline_distance(i))/sum));
end

dummy=sum_weight_cap;
in3=mean([total_capacity_oil_port dummy]);

% Add-on Louisiana Map
for i=1:size(louisiana(:,1),1)
a=plot([louisiana(i,4),louisiana(i,2)],[louisiana(i,5),louisiana(i,3)],'linewidth',3,
'color',[0.3 0.6 0.4]);
end
%=== Natural Gas Infrastructure: Gas Pipeline ===

gas_pipeline_segment=[ 1 0.83 0.64 1.42 0.92;
2 0.18 2.25 1.42 0.92;
3 1.42 0.92 1.88 1.84;
4 1.42 0.92 1.97 0.32;
5 1.97 0.32 2.34 0.05;
...
313 22.68 28.58 23.14 28.08;
314 22.68 28.58 23.6 29.56;
315 21.94 28.54 21.55 29.42;
316 21.55 29.42 20.14 29.14;
317 21.55 29.42 23.5 29.7];

gas_pipeline_distance=[];
gas_pipeline_capacity=[];
% Graphical Setting
figure
set(gca,'nextplot','add','ydir','rev')
scatter(impact_area(1),impact_area(2),'rx');
title('Natural Gas Pipelines','fontsize',14)

sum=0;
for i=1:size(gas_pipeline_segment(:,1),1)
gas_pipeline_distance=[gas_pipeline_distance;
distance([gas_pipeline_segment(i,2),gas_pipeline_segment(i,3)],[gas_pipeline_segment(
i,4),gas_pipeline_segment(i,5)])];
distance_dummy_gas=distance([impact_area],[median([gas_pipeline_segment(i,2),gas_pipe
line_segment(i,4)]),median([gas_pipeline_segment(i,3),gas_pipeline_segment(i,5)])]);
sum=sum+gas_pipeline_distance(i);

if distance_dummy_gas < 8

```

```

        gas_pipeline_capacity=[gas_pipeline_capacity; (0.2-(rand()*0.2))];
        gas_graph=plot([gas_pipeline_segment(i,4), gas_pipeline_segment(i,2)], [gas_pipeline_se
gment(i,5), gas_pipeline_segment(i,3)], 'r');
    end
    if distance_dummy_gas > 8 & distance_dummy_gas < 15
        gas_pipeline_capacity=[gas_pipeline_capacity; (0.7-(rand()*0.2))];
        gas_graph=plot([gas_pipeline_segment(i,4), gas_pipeline_segment(i,2)], [gas_pipeline_se
gment(i,5), gas_pipeline_segment(i,3)], 'b');
    end
    if distance_dummy_gas > 15
        gas_pipeline_capacity=[gas_pipeline_capacity; (1-(rand()*0.1))];
        gas_graph=plot([gas_pipeline_segment(i,4), gas_pipeline_segment(i,2)], [gas_pipeline_se
gment(i,5), gas_pipeline_segment(i,3)], 'k');
    end
end

% estimate the 'total weighted capacity'
sum_weight_cap=0;
for i=1:size(gas_pipeline_segment(:,1),1)
    sum_weight_cap=sum_weight_cap + gas_pipeline_capacity(i)*
    (((gas_pipeline_distance(i))/sum));
end
dummy=sum_weight_cap;
in4=dummy;

% Add-on Louisiana Map
for i=1:size(louisiana(:,1),1)
    a=plot([louisiana(i,4), louisiana(i,2)], [louisiana(i,5), louisiana(i,3)], 'linewidth', 3,
    'color', [0.3 0.6 0.4]);
end

```

Appendix B. MATLAB code for rebuild simulation model

```
% =====  
% ===== Rebuilding Simulation Model without Optimization =====  
% ===== SIM area: Louisiana =====  
% ===== Must simulate with initialization.m =====  
% =====  
  
clear all  
t=1; % t means that day, day starts at 1  
  
[waterwells_capacity, power_transmission_capacity, in2, oil_port_capacity, oil_pipeline_capacity, in3, in1,  
gas_pipeline_capacity, in4, trans_rail_capacity, trans_road_capacity, trans_bridges_capacity,  
in6]=initialization();  
% spatial data are loaded from 'initialization.m'  
% loaded data are  
% 1) Water - water wells information  
% 2) Power - Power Transmission Line information  
% 3) Oil - Oil port, Oil pipeline information  
% 4) Gas - Gas pipeline information  
% 5) Transportation - Road, Rail, Bridges information  
  
initial_priority=[6 2 4 3 5 1];  
% Initial priority is randomly decided.  
% Means that 1st:Oil 2nd:Gas 3rd:Power 4th:Tele 5th:Water 6th:Trans  
  
initial_condition=[0.5 0.5 0.5 0.5 0.5 0.5];  
initial_condition(1)=in1; % in1: initialization value of water system  
initial_condition(2)=in2;  
initial_condition(3)=in3;  
initial_condition(4)=in4;  
initial_condition(6)=in6;  
initial_condition(5)=(in1+in2+in3+in4+in6)/5;  
rebuild_total=mean(initial_condition);  
total_current_condition=initial_condition;  
total_capacity_water=initial_condition(1);  
total_capacity_power(t)=initial_condition(2);  
total_capacity_oil=initial_condition(3);  
total_capacity_gas=initial_condition(4);  
total_capacity_trans=initial_condition(6);  
total_capacity_tele=initial_condition(5);  
  
% define the matrix that will be used  
rebuild_rate_cum=[];  
end_time=[1 1 1 1 1 1];  
total_current_condition_cum=[];  
priority_cum=[];  
score_matrix=[];  
priority=[1 2 3 4 5 6];  
% define the initial demand  
demand=[0 0 0 0 0 0];  
supply=[0 0 0 0 0 0];  
resource_for_water=[0 0 0 0 0 0]; % resources which water infra can have at time t  
resource_for_nuclear=[0 0 0 0 0 0];  
resource_for_fossil=[0 0 0 0 0 0];  
resource_for_chp=[0 0 0 0 0 0];  
resource_for_hydro=[0 0 0 0 0 0];  
resource_for_geothermal=[0 0 0 0 0 0];  
resource_for_oil=[0 0 0 0 0 0];  
resource_for_gas=[0 0 0 0 0 0];  
resource_for_trans=[0 0 0 0 0 0];  
resource_for_tele=[0 0 0 0 0 0];  
resource_for_power=[0 0 0 0 0 0];  
for i=1:3  
resource_for_nuclear(t, 6, i)=0;  
resource_for_geothermal(t, 6, i)=0;  
resource_for_hydro(t, 6, i)=0;  
resource_for_water(t, 6, i)=0;
```

```

end
for i=1:4
resource_for_fossil(t,6,i)=0;
resource_for_chp(t,6,i)=0;
resource_for_gas(t,6,i)=0;
resource_for_tele(t,6,i)=0;
end
resource_for_power_transmission(t)=0;
for i=1:7
resource_for_fossil(t,3,i)=0;
end
for i=1:8
resource_for_oil(t,6,i)=0;
end
for i=1:5
resource_for_trans(t,6,i)=0;
end

% Agent's initial capacity is defined as initial total capacity of each infrastructure' s capacity
demand_from_water=[];
not_available_matrix=[];
capacity_waste=initial_condition(1);
capacity_drinking=initial_condition(1);
capacity_treat=initial_condition(1);
capacity_nuclear_storage=initial_condition(2);
capacity_nuclear_reactor=initial_condition(2);
trans_demand_from_nuclear=[];
water_demand_from_nuclear=[];
capacity_nuclear_cooling=initial_condition(2);
capacity_total_nuclear=initial_condition(2);
capacity_fossil_storage=initial_condition(2);
capacity_total_fossil=initial_condition(2);
capacity_fossil_boiler=initial_condition(2);
capacity_fossil_generator=initial_condition(2);
capacity_fossil_cooling=initial_condition(2);
capacity_geothermal_pipe=initial_condition(2);
capacity_geothermal_pump=initial_condition(2);
capacity_geothermal_cooling=initial_condition(2);
capacity_total_geothermal=initial_condition(2);
capacity_hydro_dam=1-(initial_condition(2)*0.5);
capacity_hydro_intake=initial_condition(2);
capacity_hydro_generator=initial_condition(2);
capacity_total_hydro=initial_condition(2);
capacity_chp_storage=initial_condition(2);
capacity_total_chp=initial_condition(2);
capacity_chp_boiler=initial_condition(2);
capacity_chp_generator=initial_condition(2);
capacity_chp_cooling=initial_condition(2);
power_matrix=[];
capacity_oil_mines=initial_condition(3);
capacity_oil_port=mean(oil_port_capacity);
capacity_oil_pipe=mean(oil_pipeline_capacity);
capacity_oil_refinery=initial_condition(3);
capacity_oil_source_storage=initial_condition(3);
capacity_oil_terminal=initial_condition(3);
capacity_oil_refinery_storage=initial_condition(3);
capacity_oil_wells=initial_condition(3);
coal_matrix=[];
capacity_gas_wells=initial_condition(4);
capacity_gas_pipe=mean(gas_pipeline_capacity);
capacity_gas_treat=initial_condition(4);
capacity_gas_storage=initial_condition(4);
capacity_trans_signal=initial_condition(6);
capacity_trans_road=mean(trans_road_capacity);
capacity_trans_rail=mean(trans_rail_capacity);
capacity_trans_airport=initial_condition(6);
capacity_trans_bridges=mean(trans_bridges_capacity);
capacity_tele_service_station=initial_condition(5);
capacity_tele_local_tower=initial_condition(5);
capacity_tele_control_tower=initial_condition(5);

```

```

capacity_tele_com_line=initial_condition(5);
product_ratio_water=0;
a=0;
equi=0;
runonce_tele = 1;
runonce_tele2 = 1;

while rebuild_total < 0.99 % Most Big Loop
% End criterion: Average capacity of all infra exceed 99%

%=====
%===== Water infrastructure Sub-Model =====
%=====

if (total_capacity_water ~ =1.2) % Big Loop within Sub-Model
% Water Wells (Pump)
capacity_waterwells=mean(waterwells_capacity);
waterwells_count=0;
for i=1:size(waterwells_capacity(:,1),1)
if waterwells_capacity(i) < 0.95
% count the number of water wells under 95% capacity
waterwells_count=waterwells_count+1;
end
end
dummy_min=6;dummy_max=6.01;
power_need_water_pump(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [6, 6.01] - Variability
demand(t,2)=power_need_water_pump(t) * (size(waterwells_capacity(:,1),1)-
waterwells_count);
% power demand at time t
% water pumping needs 6027 kWh / day = 6.027 MWh
power_demand_from_water(t,1)=demand(t,2);
% Since, demand [water, power, oil, gas, tele, trans],
% demand(t,2) means that demand for power

demand(t,6) = (50 * (waterwells_count / size(waterwells_capacity(:,1),1)));
trans_demand_from_water(t,1)=demand(t,6);
if trans_demand_from_water(t,1) == 0
trans_demand_from_water(t,1) = 0.001;
end
% Transportation demand for repairing
repair_rate_waterwells=rebuild_rate(1)*(resource_for_water(t,6,1)/(trans_demand_from_water(t,1)));

% Water Treatment Plants
dummy_min=6;dummy_max=6.6;
power_need_water_treatment(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [6, 6.6] - Variability
demand(t,2)=demand(t,2)+(power_need_water_treatment(t) * 1200 * capacity_waterwells);
power_demand_from_water(t,2)=(power_need_water_treatment(t) * 1200 *
capacity_waterwells);

% Transportation demand
demand(t,6)=demand(t,6)+((1.001-capacity_treat)*30);
trans_demand_from_water(t,2)=((1.001-capacity_treat)*30);

repair_rate_treat=rebuild_rate(1)*(resource_for_water(t,6,2)/(trans_demand_from_water(t,2)));
capacity_drinking=min(capacity_waterwells, capacity_treat);

% Waste Water System
dummy_min=4;dummy_max=5;
power_need_water_waste(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [4, 5] - Variability
demand(t,2)=demand(t,2)+(200 * power_need_water_waste(t) * capacity_waste);
%4.5 megawatt * 200 (number of waste system)
power_demand_from_water(t,3)=(200*power_need_water_waste(t)*capacity_waste);

% Transportation demand
demand(t,6)=demand(t,6)+((1.001-capacity_waste)*30);
trans_demand_from_water(t,3)=((1.001-capacity_waste)*30);
repair_rate_waste=rebuild_rate(1)*(resource_for_water(t,6,3)/(trans_demand_from_water(t,3)));

```

```

% Integrate Capacity of Water Sub Model
total_capacity_water=min (capacity_waste, capacity_drinking);

sum_power=0;
for i=1:3
    sum_power=sum_power + power_demand_from_water(t, i);
end
demand_from_water_to_power(t) = sum_power;
demand_from_water_to_trans(t) = trans_demand_from_water(t,1) +
    trans_demand_from_water(t,2) + trans_demand_from_water(t,3);
dummy_min=6260;dummy_max=6320;
water_supply_unif(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [6000, 6500] - Variability
supply(t,1)=total_capacity_water* water_supply_unif(t);
    dummy_min=0.5;dummy_max=0.7;
    rand_for_water=dummy_min+(dummy_max-dummy_min)*rand();
supply(t,1)=supply(t,1) - (supply(t,1) * (1 - (resource_for_water(t,2) / sum_power)) * rand_for_water);

% Repairing Task
waterwells_capacity=waterwells_capacity+repair_rate_waterwells;
    for i=1:size(waterwells_capacity,1)
        if waterwells_capacity(i) > 1
            waterwells_capacity(i) = 1;
        end
    end
capacity_treat=capacity_treat+repair_rate_treat;
    if capacity_treat > 1
        capacity_treat = 1;
    end
capacity_waste=capacity_waste+repair_rate_waste;
    if capacity_waste > 1
        capacity_waste = 1;
    end

end % Big Loop within Sub-Model End

%=====
%===== Electronic Sub-Model =====
%=====

if (total_capacity_power ~ =1.2) % Big Loop within Power Sub-Model
%===== Nuclear Power Plant =====
% Fuel Storage
uranium=100 * total_capacity_trans;
% delivered uranium is estimated by transportation percentage
output_nuclear_fuel_storage=capacity_nuclear_storage*uranium;
demand(t,6)=demand(t,6)+(1.001-capacity_nuclear_storage)*20);
demand(t,6)=demand(t,6)+(capacity_total_nuclear*20);
trans_demand_from_nuclear(1)=((1.001-capacity_nuclear_storage)*20)+(capacity_total_nuclear*20);

% Reactor and Generator
dummy_min=88000;dummy_max=88726;
unif_power_from_nuclear(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [88000, 88726] - Variability

power_from_nuclear_reactor=output_nuclear_fuel_storage*(1/100)*capacity_nuclear_reactor*unif_power_from_nuclear(t);
demand(t,6)=demand(t,6)+((1.001-capacity_nuclear_reactor)*30);
trans_demand_from_nuclear(2)=((1.001-capacity_nuclear_reactor)*30);

% Cooling Tower
dummy_min=1690;dummy_max=1714;
unif_demand_water_nuclear(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [1,690, 1,714] - Variability, When E(t)=1702
demand(t,1)=demand(t,1)+(capacity_total_nuclear*unif_demand_water_nuclear(t));
% 1.7 gallons per KWh / 1702 MGD - modified
water_demand_from_nuclear(1)=(capacity_total_nuclear*unif_demand_water_nuclear(t));
power_from_nuclear_cooling=capacity_nuclear_cooling*power_from_nuclear_reactor;
power_from_nuclear(t)=power_from_nuclear_cooling;
dummy_min=min(capacity_nuclear_storage, capacity_nuclear_reactor);

```

```

capacity_total_nuclear=min(dummy_min,capacity_nuclear_cooling);

% Repairing Task

repair_rate_nuclear_storage=rebuild_rate(2)*(resource_for_nuclear(t,6,1)/(trans_demand_from_nuclear(1)));
repair_rate_nuclear_reactor=rebuild_rate(2)*(resource_for_nuclear(t,6,2)/(trans_demand_from_nuclear(2)));
repair_rate_nuclear_cooling=rebuild_rate(2)*(resource_for_nuclear(t,6,2)/(trans_demand_from_nuclear(2)));

capacity_nuclear_storage=capacity_nuclear_storage+repair_rate_nuclear_storage;
if capacity_nuclear_storage > 1
    capacity_nuclear_storage = 1;
end
capacity_nuclear_reactor=capacity_nuclear_reactor+repair_rate_nuclear_reactor;
if capacity_nuclear_reactor > 1
    capacity_nuclear_reactor = 1;
end
capacity_nuclear_cooling=capacity_nuclear_cooling+repair_rate_nuclear_cooling;
if capacity_nuclear_cooling > 1
    capacity_nuclear_cooling = 1;
end

% Fossil Fuel Power Plant (Physical)
% Fuel storage

delivery_rate=total_capacity_trans;
dummy_min=84000;dummy_max=85530;
unif_coal_for_fossil(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [84000, 85530] - Variability, When E(t)=84765
coal_inthe_fossil=delivery_rate*(capacity_fossil_storage*unif_coal_for_fossil(t));
dummy_min=28000;dummy_max=28384;
unif_pet_for_fossil(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [28000, 28384] - Variability, When E(t)=28192
pet_inthe_fossil=delivery_rate*(capacity_fossil_storage*unif_pet_for_fossil(t));
dummy_min=580.83;dummy_max=596.83;
unif_gas_for_fossil(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [580.83, 596.83] - Variability, When E(t)=588.83
natural_gas_inthe_fossil=delivery_rate*(capacity_fossil_storage*unif_gas_for_fossil(t));
dummy_min=70.3;dummy_max=80.3;
unif_othergas_for_fossil(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [70.3, 80.3] - Variability, When E(t)=75.3
othergas_inthe_fossil=delivery_rate*(capacity_fossil_storage*unif_othergas_for_fossil(t));

% Interdependency to other infrastructures
% fuel storage are affected by oil infra
demand(t,3) = (capacity_total_fossil*unif_coal_for_fossil(t)) +
(capacity_total_fossil*unif_pet_for_fossil(t)) + (capacity_total_fossil*unif_othergas_for_fossil(t));
demand(t,4)= capacity_total_fossil * unif_gas_for_fossil(t);

coal_inthe_fossil=coal_inthe_fossil*total_capacity_oil;
pet_inthe_fossil=pet_inthe_fossil*total_capacity_oil;
othergas_inthe_fossil=othergas_inthe_fossil*total_capacity_oil;
% fuel storage are affected by Natural Gas infra
natural_gas_inthe_fossil=natural_gas_inthe_fossil*total_capacity_gas;

demand(t,6)=demand(t,6)+((1.001-capacity_fossil_storage)*30);
demand(t,6)=demand(t,6)+(capacity_total_fossil*50);
trans_demand_from_fossil(t,1)=((1.001-capacity_fossil_storage)*30)+(capacity_total_fossil*50);

% Boiler
dummy_min=2400;dummy_max=2460;
unif_demand_water_fossil_boiler(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist [2400, 2460] - Variability, When E(t)=2430.8
demand(t,1)=demand(t,1)+(capacity_total_fossil*unif_demand_water_fossil_boiler(t));
% 0.7 gallons per kWh
water_demand_from_fossil(t,1)=(capacity_total_fossil* unif_demand_water_fossil_boiler(t));
% Transportation demand for repairing
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_fossil_boiler)*20);

```



```

trans_demand_from_fossil(t,2)=demand(t,6)-dummy;

% Generator
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_fossil_generator)*30);
trans_demand_from_fossil(t,3)=demand(t,6)-dummy;
% Calculating the progressing power
% progress_power_fossil=[coal petroleum naturalgas othergases]
dummy_min=125200;dummy_max=125364;
unif_progress_fossil_1(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=125282
dummy_min=15700;dummy_max=15766;
unif_progress_fossil_2(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=15733.61
dummy_min=183854;dummy_max=184054;
unif_progress_fossil_3(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=183954.2
dummy_min=74;dummy_max=76;
unif_progress_fossil_4(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=75.3
progress_power_fossil(t,1)=unif_progress_fossil_1(t) * (coal_inthe_fossil/84765) *
capacity_fossil_boiler * capacity_fossil_generator;
progress_power_fossil(t,2)=unif_progress_fossil_2(t) * (pet_inthe_fossil/28192) * capacity_fossil_boiler
* capacity_fossil_generator;
progress_power_fossil(t,3)=unif_progress_fossil_3(t) * (natural_gas_inthe_fossil/588.83) *
capacity_fossil_boiler * capacity_fossil_generator;
progress_power_fossil(t,4)=unif_progress_fossil_4(t) * (othergas_inthe_fossil/75.3) *
capacity_fossil_boiler * capacity_fossil_generator;

% Cooling Tower
% Calculate the power from fossil
sum_power_from_fossil=0;
for i=1:4
power_from_fossil(t,i)=capacity_fossil_cooling*progress_power_fossil(t,i);
sum_power_from_fossil=sum_power_from_fossil+power_from_fossil(t,i);
end
% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_fossil_cooling)*20);
trans_demand_from_fossil(t,4)=demand(t,6)-dummy;
% total capacity of fossil plant
dummy_min=min(capacity_fossil_storage, capacity_fossil_boiler);
dummy_min_2=min(dummy_min, capacity_fossil_generator);
capacity_total_fossil=min(dummy_min_2, capacity_fossil_cooling);

% Repairing Task
repair_rate_fossil_storage=rebuild_rate(2)*(resource_for_fossil(t,6,1)/(trans_demand_from_fossil(t,1)));
repair_rate_fossil_boiler=rebuild_rate(2)*(resource_for_fossil(t,6,2)/(trans_demand_from_fossil(t,2)));
repair_rate_fossil_generator=rebuild_rate(2)*(resource_for_fossil(t,6,3)/(trans_demand_from_fossil(t,3)));
repair_rate_fossil_cooling=rebuild_rate(2)*(resource_for_fossil(t,6,4)/(trans_demand_from_fossil(t,4)));
capacity_fossil_storage=capacity_fossil_storage+repair_rate_fossil_storage;
if capacity_fossil_storage > 1
capacity_fossil_storage = 1;
end
capacity_fossil_boiler=capacity_fossil_boiler+repair_rate_fossil_boiler;
if capacity_fossil_boiler > 1
capacity_fossil_boiler = 1;
end
capacity_fossil_generator=capacity_fossil_generator+ repair_rate_fossil_generator;
if capacity_fossil_generator > 1
capacity_fossil_generator = 1;
end
capacity_fossil_cooling=capacity_fossil_cooling+repair_rate_fossil_cooling;
if capacity_fossil_cooling > 1
capacity_fossil_cooling = 1;
end

% Geothermal Power Plant
% 1) underground pipe
dummy=demand(t,6);

```

```

demand(t,6)=demand(t,6)+((1.001-capacity_geothermal_pipe)*20);
trans_demand_from_geothermal(1)=demand(t,6)-dummy;
% 2) Geothermal Heat Pump
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_geothermal_pump)*20);
trans_demand_from_geothermal(2)=demand(t,6)-dummy;

% Need water for steam
dummy_min=490;dummy_max=510;
unif_need_water_geothermal_steam=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=500
demand(t,1)=demand(t,1)+(capacity_total_geothermal*unif_need_water_geothermal_steam);
water_demand_from_geothermal(1)=(capacity_total_geothermal*unif_need_water_geothermal_steam);
dummy_min=1660;dummy_max=1686;
unif_power_from_geothermal=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=1673
progress_power_geothermal=unif_power_from_geothermal * capacity_geothermal_pipe *
capacity_geothermal_pump;

% 3) Cooling Tower
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_geothermal_cooling)*20);
trans_demand_from_geothermal(3)=demand(t,6)-dummy;
% Need water for cooling
dummy_min=5;dummy_max=15;
unif_need_water_geothermal_cooling=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=10
demand(t,1)=demand(t,1)+(capacity_geothermal_cooling*unif_need_water_geothermal_cooling);
water_demand_from_geothermal(2)=(capacity_geothermal_cooling*unif_need_water_geothermal_cooling);
power_from_geothermal(t)=progress_power_geothermal*capacity_geothermal_cooling;

% total capacity of geothermal plant
dummy_min=min(capacity_geothermal_pipe,capacity_geothermal_pump);
dummy_min_2=min(dummy_min,capacity_geothermal_cooling);
capacity_total_geothermal=dummy_min_2;
% Repairing Task

repair_rate_geothermal_pipe=rebuild_rate(2)*(resource_for_geothermal(t,6,1)/(trans_demand_from_geothermal(1)
));
repair_rate_geothermal_pump=rebuild_rate(2)*(resource_for_geothermal(t,6,2)/(trans_demand_from_geothermal(2)
));
repair_rate_geothermal_cooling=rebuild_rate(2)*(resource_for_geothermal(t,6,3)/(trans_demand_from_geothermal
(3)));
capacity_geothermal_pipe=capacity_geothermal_pipe+repair_rate_geothermal_pipe;
if capacity_geothermal_pipe > 1
capacity_geothermal_pipe = 1;
end
capacity_geothermal_pump=capacity_geothermal_pump+repair_rate_geothermal_pump;
if capacity_geothermal_pump > 1
capacity_geothermal_pump = 1;
end
capacity_geothermal_cooling=capacity_geothermal_cooling+ repair_rate_fossil_generator;
if capacity_geothermal_cooling > 1
capacity_geothermal_cooling = 1;
end
capacity_fossil_cooling=capacity_fossil_cooling+repair_rate_geothermal_cooling;
if capacity_fossil_cooling > 1
capacity_fossil_cooling = 1;
end

% Hydroelectricity Power Plant
% 1) Dam
% Transportation demand for repairing
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_hydro_dam)*30);
trans_demand_from_hydro(1)=demand(t,6)-dummy;
% 2) Intake System
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_hydro_intake)*20);
trans_demand_from_hydro(2)=demand(t,6)-dummy;

```

```

% 3) Generator
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_hydro_generator)*20);
trans_demand_from_hydro(3)=demand(t,6)-dummy;
dummy_min=2400;dummy_max=2484;
unif_power_from_hydro(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=2442.3
power_from_hydro(t)=unif_power_from_hydro(t) * capacity_hydro_dam * capacity_hydro_intake *
capacity_hydro_generator;

% total capacity of hydro
dummy_min=min(capacity_hydro_dam,capacity_hydro_intake);
dummy_min_2=min(dummy_min,capacity_hydro_generator);
capacity_total_hydro=dummy_min_2;

% Repairing Task
repair_rate_hydro_dam=rebuild_rate(2)*(resource_for_hydro(t,6,1)/(trans_demand_from_hydro(1)));
repair_rate_hydro_intake=rebuild_rate(2)*(resource_for_hydro(t,6,2)/(trans_demand_from_hydro(2)));
repair_rate_hydro_generator=rebuild_rate(2)*(resource_for_hydro(t,6,3)/(trans_demand_from_hydro(3)));
capacity_hydro_dam=capacity_hydro_dam+repair_rate_hydro_dam;
if capacity_hydro_dam > 1
    capacity_hydro_dam = 1;
end
capacity_hydro_intake=capacity_hydro_intake+repair_rate_hydro_intake;
if capacity_hydro_intake > 1
    capacity_hydro_intake = 1;
end
capacity_hydro_generator=capacity_hydro_generator+ repair_rate_hydro_generator;
if capacity_hydro_generator > 1
    capacity_hydro_generator = 1;
end

% Combined Heat and Power (Physical)
% Fuel storage

delivery_rate=total_capacity_trans;
dummy_min=35;dummy_max=45;
unif_coal_for_chp(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=39.38
coal_inthe_chp=delivery_rate*(capacity_chp_storage*unif_coal_for_chp(t));
dummy_min=910;dummy_max=930;
unif_pet_for_chp(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=921.21
pet_inthe_chp=delivery_rate*(capacity_chp_storage*unif_pet_for_chp(t));
dummy_min=180;dummy_max=200;
unif_gas_for_chp(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=191.17
natural_gas_inthe_chp=delivery_rate*(capacity_chp_storage*unif_gas_for_chp(t));
dummy_min=35;dummy_max=49;
unif_othergas_for_chp(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=42.3
othergas_inthe_chp=delivery_rate*(capacity_chp_storage*unif_othergas_for_chp(t));

% fuel storage are affected by oil infra
coal_inthe_chp=coal_inthe_chp*total_capacity_oil;
pet_inthe_chp=pet_inthe_chp*total_capacity_oil;
othergas_inthe_chp=othergas_inthe_chp*total_capacity_oil;
% fuel storage are affected by Natural Gas infra
natural_gas_inthe_chp=natural_gas_inthe_chp*total_capacity_gas;

demand(t,3) = demand(t,3) + (capacity_total_fossil*unif_coal_for_chp(t)) +
(capacity_total_fossil*unif_pet_for_chp(t)) + (capacity_total_fossil*unif_othergas_for_chp(t));

demand(t,4)=demand(t,4)+capacity_total_fossil* unif_gas_for_chp(t);
demand(t,6)=demand(t,6)+(1.001-capacity_chp_storage)*30);
demand(t,6)=demand(t,6)+(capacity_total_chp*20);
% when total fossil plant is 100% : 10 transportation unit is needed to
% deliver the Fuel.
trans_demand_from_chp(t,1)=((1.001-capacity_chp_storage)*30)+(capacity_total_chp*20);

```

```

% Boiler
% Need Water for steam : http://www.sandia.gov/energy-water/West/Innis.pdf
dummy_min=520;dummy_max=580;
unif_needwater_for_chp_boiler(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=550
demand(t,1)=demand(t,1)+(capacity_total_chp*unif_needwater_for_chp_boiler(t));
% 0.7 gallons per kWh
water_demand_from_chp(t,1)=(capacity_total_chp*unif_needwater_for_chp_boiler(t));
% Transportation demand for repairing
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_chp_boiler)*20);
% 20 unit is needed
trans_demand_from_chp(t,2)=demand(t,6)-dummy;

% Generator
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_chp_generator)*20);
trans_demand_from_chp(t,3)=demand(t,6)-dummy;
% Calculating the progressing power
% progress_power_chp=[coal petroleum naturalgas othergases]
dummy_min=130;dummy_max=141;
unif_power_from_chp_1(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=136.59
progress_power_chp(t,1)=unif_power_from_chp_1(t) * (coal_inthe_chp/39.38) * capacity_chp_boiler *
capacity_chp_generator;
dummy_min=350;dummy_max=378;
unif_power_from_chp_2(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=364.74
progress_power_chp(t,2)=unif_power_from_chp_2(t) * (pet_inthe_chp/921.21) * capacity_chp_boiler *
capacity_chp_generator;
dummy_min=64900;dummy_max=65100;
unif_power_from_chp_3(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=65000
progress_power_chp(t,3)=unif_power_from_chp_3(t) * (natural_gas_inthe_chp/191.17) * capacity_chp_boiler
* capacity_chp_generator;
dummy_min=6650;dummy_max=6776;
unif_power_from_chp_4(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=6713.52
progress_power_chp(t,4)=unif_power_from_chp_4(t) * (othergas_inthe_chp/42.3) * capacity_chp_boiler *
capacity_chp_generator;

% Cooling Tower
% Calculate the power from CHP
sum_power_from_chp=0;
for i=1:4
power_from_chp(t,i)=capacity_chp_cooling*progress_power_chp(t,i);
sum_power_from_chp=sum_power_from_chp+power_from_chp(t,i);
end
% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_chp_cooling)*20);
trans_demand_from_chp(t,4)=demand(t,6)-dummy;
% total capacity of chp plant
dummy_min=min(capacity_chp_storage,capacity_chp_boiler);
dummy_min_2=min(dummy_min,capacity_chp_generator);
capacity_total_chp=min(dummy_min_2,capacity_chp_cooling);

% Repairing Task
repair_rate_chp_storage=rebuild_rate(2)*(resource_for_chp(t,6,1)/(trans_demand_from_chp(t,1)));
repair_rate_chp_boiler=rebuild_rate(2)*(resource_for_chp(t,6,2)/(trans_demand_from_chp(t,2)));
repair_rate_chp_generator=rebuild_rate(2)*(resource_for_chp(t,6,3)/(trans_demand_from_chp(t,3)));
repair_rate_chp_cooling=rebuild_rate(2)*(resource_for_chp(t,6,4)/(trans_demand_from_chp(t,4)));

capacity_chp_storage=capacity_chp_storage+repair_rate_chp_storage;
if capacity_chp_storage > 1
capacity_chp_storage = 1;
end
capacity_chp_boiler=capacity_chp_boiler+repair_rate_chp_boiler;
if capacity_chp_boiler > 1
capacity_chp_boiler = 1;

```

```

        end
        capacity_chp_generator=capacity_chp_generator+ repair_rate_chp_generator;
        if capacity_chp_generator > 1
            capacity_chp_generator = 1;
        end
        capacity_chp_cooling=capacity_chp_cooling+repair_rate_chp_cooling;
        if capacity_chp_cooling > 1
            capacity_chp_cooling = 1;
        end
    end

% Transmission Line=====
% Assumption: All power plants use same transmission line.

    capacity_power_transmission=mean(power_transmission_capacity);
    trans_count=0;
    for i=1:size(power_transmission_capacity(:,1),1)
        if power_transmission_capacity(i) < 0.95
            trans_count=trans_count+1;
        end
    end
    dummy=demand(t,6);
    demand(t,6)=demand(t,6)+(50 * (trans_count/size(power_transmission_capacity(:,1),1)));
    trans_demand_from_power_transmission(t)=demand(t,6)-dummy;

    if trans_demand_from_power_transmission(t) == 0
        trans_demand_from_power_transmission(t) = 0.001;
    end

repair_rate_power_transmission=rebuild_rate(2)*(resource_for_power_transmission(t)/(trans_demand_from_power_
transmission(t)));

% Repairing Task of power transmission line
    power_transmission_capacity=power_transmission_capacity+repair_rate_power_transmission;
    for i=1:size(power_transmission_capacity,1)
        if power_transmission_capacity(i) > 1
            power_transmission_capacity(i) = 1;
        end
    end

% integrate the power production from all plants
% power_matrix(t)=[nuclear fossil geothermal hydro CHP]
dummy_matrix=[power_from_nuclear(t) sum_power_from_fossil power_from_geothermal(t) power_from_hydro(t)
sum_power_from_chp];
sum_dummy=0;
for i=1:5
    dummy_matrix2(i)=dummy_matrix(i) * capacity_power_transmission;
    sum_dummy=sum_dummy+dummy_matrix2(i);
end
power_matrix=[power_matrix; dummy_matrix2];

total_capacity_power(t)=mean([capacity_total_nuclear capacity_total_fossil capacity_total_geothermal
capacity_total_hydro capacity_total_chp]);
% 1st method: total capacity of power is estimated by mean value of all
% sub powers

demand_from_power_to_water(t) = water_demand_from_nuclear(1) + water_demand_from_fossil(t,1) +
water_demand_from_geothermal(1) + water_demand_from_geothermal(2) + water_demand_from_chp(t,1);

dummy=0;
for i=1:4
    dummy=dummy + trans_demand_from_fossil(t,i) + trans_demand_from_chp(t,i);
end
dummy2=0;
for i=1:3
    dummy2=dummy2 + trans_demand_from_geothermal(i) + trans_demand_from_hydro(i);
end
demand_from_power_to_trans(t) = trans_demand_from_nuclear(1)+trans_demand_from_nuclear(2)+dummy+dummy2 +
trans_demand_from_power_transmission(t);

```

```

dummy_min=0.6;dummy_max=0.6294;
unif_supply_power(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.6147 (0.382 + 0.0347 + 0.198)

supply(t,2)= sum_dummy * unif_supply_power(t);
dummy_min=0.3;dummy_max=0.6;
rand_for_power=dummy_min+(dummy_max-dummy_min)*rand();
supply(t,2) = supply(t,2) - (supply(t,2) * (1 - (resource_for_power(t,1) /demand_from_power_to_water(t)))
* rand_for_power);

end % Big Loop within Power Sub-Model End

%=====
%===== Oil Infrastructure Sub Model =====
%=====
if (total_capacity_oil ~1.2) % Big Loop within Oil Sub-Model

% Coal Industry - Mines
dummy_min=11450;dummy_max=11550;
unif_coal_in_state(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=11506.8
coal_in_state(t)=capacity_oil_mines * unif_coal_in_state(t);
dummy_min=73200;dummy_max=73300;
unif_coal_out_state(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=73258.4
coal_from_others(t)=total_capacity_trans * unif_coal_out_state(t);
% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_oil_mines)*20);
trans_demand_from_oil(t,1)=demand(t,6)-dummy;
% demand for power
dummy_min=1450;dummy_max=1550;
unif_demand_power_from_mine(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=1500
demand(t,2)=demand(t,2)+(capacity_oil_mines * unif_demand_power_from_mine(t));
power_demand_from_oil(t,1)=(capacity_oil_mines * unif_demand_power_from_mine(t));
% source_storage
coal_inthe_storage=capacity_oil_source_storage * (coal_in_state(t)+coal_from_others(t));
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_oil_source_storage)*20);
trans_demand_from_oil(t,2)=demand(t,6)-dummy;

% supply(t,3,1)=coal_inthe_storage;
coal_matrix=[ coal_matrix; coal_inthe_storage];

% Oil Wells
dummy_min=206500;dummy_max=207500;
unif_crude_oil(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=207000
crude_oil = capacity_oil_wells * unif_crude_oil(t);
% 207000 Barrels / day
% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_oil_wells)*50);
trans_demand_from_oil(t,3)=demand(t,6)-dummy;
% demand for Water
dummy_min=0.78;dummy_max=0.82;
unif_demand_water_from_oilwells(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.8
demand(t,1)=demand(t,1)+((crude_oil * unif_demand_water_from_oilwells(t) * 42) / 1000000);
% 0.8 gallon per crude oil * 1,000,000 = Million Gallons / Day
water_demand_from_oil(t,1)=(crude_oil * unif_demand_water_from_oilwells(t) * 42 / 1000000);

% Gathering Pipeline
% Assumption: crude oil uses the same pipeline whatever it's gathering
% process or transmission process
% Assumptio#2: Unif(Mean=70%) of crude oil is delivered by pipelilne

```

```

dummy_min=0.65;dummy_max=0.75;
unif_ratio_oil_by_pipe(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.7
unif_ratio_oil_by_port(t)=1-unif_ratio_oil_by_pipe(t);

crude_oil_by_pipeline=(unif_ratio_oil_by_pipe(t) * crude_oil * capacity_oil_pipe);
% demand for transportation
trans_count=0;
for i=1:size(oil_pipeline_capacity(:,1),1)
    if oil_pipeline_capacity(i) < 0.95
        trans_count=trans_count+1;
    end
end
dummy=demand(t,6);
demand(t,6)=demand(t,6)+(50 * (trans_count/size(oil_pipeline_capacity(:,1),1)));
trans_demand_from_oil(t,4)=demand(t,6)-dummy;
if trans_demand_from_oil(t,4) == 0
    trans_demand_from_oil(t,4) = 0.001;
end

% Ports
% Assumption: Unif(Mean=30%) of crude oil is delivered by ports
crude_oil_by_port=(unif_ratio_oil_by_port(t) * crude_oil * capacity_oil_port);

% demand for transportation
trans_count=0;
for i=1:size(oil_port_capacity(:,1),1)
    if oil_port_capacity(i) < 0.95
        trans_count=trans_count+1;
    end
end
dummy=demand(t,6);
demand(t,6)=demand(t,6)+(30 * (trans_count/size(oil_port_capacity(:,1),1)));
trans_demand_from_oil(t,5)=demand(t,6)-dummy;
if trans_demand_from_oil(t,5) == 0
    trans_demand_from_oil(t,5) = 0.001;
end

% Refinery Storage
crude_oil_in_state=(crude_oil_by_pipeline + crude_oil_by_port) * capacity_oil_refinery_storage;
% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_oil_refinery_storage)*20);
trans_demand_from_oil(t,6)=demand(t,6)-dummy;

% Crude Oil is imported by various source
% Crude oil from OCS
dummy_min=444550;dummy_max=445550;
unif_crude_oil_from_OCS(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=445050
crude_oil_from_others(t,1)= unif_crude_oil_from_OCS(t) * capacity_oil_pipe *
capacity_oil_refinery_storage;
% Crude oil from Foreign
dummy_min=984820;dummy_max=985820;
unif_crude_oil_from_foreign(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=985320
crude_oil_from_others(t,2)= unif_crude_oil_from_foreign(t) * total_capacity_trans *
capacity_oil_refinery_storage;
% Crude oil from Other states
dummy_min=97200;dummy_max=97380;
unif_crude_oil_from_other(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=97290
crude_oil_from_others(t,3)= unif_crude_oil_from_other(t) * total_capacity_trans *
capacity_oil_refinery_storage;

sum=0;
for i=1:3
    sum=sum+crude_oil_from_others(t,i);
end
crude_oil_refinery(t) = crude_oil_in_state + sum;

```

```

% Refinery
% product_oil = [ gasoline diesel kerosene fuel oil LPG asphalt]
% gasoline 19.5 / Diesel Fuel oil 9.2 / Kerosene (jet) 4.3
% Fuel oil 2.3 / LPG 1.9 / Asphalt 1.3

% Randomized the Production Ratio
dummy_min=19.4;dummy_max=19.6;
unif_production_ratio_1(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=19.5
dummy_min=9.1;dummy_max=9.3;
unif_production_ratio_2(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=9.2
dummy_min=4.2;dummy_max=4.4;
unif_production_ratio_3(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=4.3
dummy_min=2.2;dummy_max=2.4;
unif_production_ratio_4(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=2.3
dummy_min=1.8;dummy_max=2;
unif_production_ratio_5(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=1.9
dummy_min=1.2;dummy_max=1.3;
unif_production_ratio_6(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=1.3

product_oil(t,1) = (crude_oil_refinery(t) * unif_production_ratio_1(t) * capacity_oil_refinery)/42;
product_oil(t,2) = (crude_oil_refinery(t) * unif_production_ratio_2(t) * capacity_oil_refinery)/42;
product_oil(t,3) = (crude_oil_refinery(t) * unif_production_ratio_3(t) * capacity_oil_refinery)/42;
product_oil(t,4) = (crude_oil_refinery(t) * unif_production_ratio_4(t) * capacity_oil_refinery)/42;
product_oil(t,5) = (crude_oil_refinery(t) * unif_production_ratio_5(t) * capacity_oil_refinery)/42;
product_oil(t,6) = (crude_oil_refinery(t) * unif_production_ratio_6(t) * capacity_oil_refinery)/42;
% IOT make Barrels from Gallons, 42 is divided.
% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_oil_refinery)*30);
trans_demand_from_oil(t,7)=demand(t,6)-dummy;
% demand for Water
sum=0;
for i=1:6
    sum=sum+product_oil(t,i);
end
dummy_min=78;dummy_max=82;
unif_demand_water_from_oil_refinery(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=80
demand(t,1)=demand(t,1)+((crude_oil * unif_demand_water_from_oil_refinery(t) * 42) / 1000000);
% 80 gallon per product(gallons) / 1,000,000 = Million Gallons / Day
water_demand_from_oil(t,2)=(crude_oil * unif_demand_water_from_oil_refinery(t) * 42 / 1000000);
% demand for power
dummy_min=590;dummy_max=610;
unif_demand_power_from_oil_refinery(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=600
demand(t,2)=demand(t,2)+(crude_oil_in_state * unif_demand_power_from_oil_refinery(t) / 1000);
power_demand_from_oil(t,2)=(crude_oil_in_state * unif_demand_power_from_oil_refinery(t) / 1000);
% 600 kWh per Barrels

% Terminal storage
% To get the terminal storage, 70% is delivered by pipeline, 30% is
% delivered by transportation
dummy_min=0.60;dummy_max=0.80;
unif_ratio_oil_by_pipe_to_storage(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.7
unif_ratio_oil_by_port_to_storage(t)=1-unif_ratio_oil_by_pipe_to_storage(t);

for i=1:6
    product_oil_pipeline(t,i)=product_oil(t,i) * unif_ratio_oil_by_pipe_to_storage(t);
%    product_oil_pipeline(t,i)=product_oil(t,i) * 0.7 * capacity_oil_pipe;
end
for i=1:6

```



```

product_oil_trans(t,i)=product_oil(t,i) * unif_ratio_oil_by_port_to_storage(t);
% product_oil_trans(t,i)=product_oil(t,i) * 0.3 * total_capacity_trans;
end

dummy_min=0.28;dummy_max=0.32;
unif_ratio_oil_for_state_use(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.30 (30%)
for i=1:6
final_product_oil(t,i) = (product_oil_pipeline(t,i) + product_oil_trans(t,i)) * capacity_oil_terminal *
unif_ratio_oil_for_state_use(t);
% Only 35% of total product would be used for state.
end

% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_oil_terminal)*20);
trans_demand_from_oil(t,8)=demand(t,6)-dummy;

sum=0;
for i=1:6
sum=sum+final_product_oil(t,i);
end
supply(t,3)= coal_inthe_storage + sum;
demand_from_oil_to_water(t) = water_demand_from_oil(t,1) + water_demand_from_oil(t,2);
demand_from_oil_to_power(t) = power_demand_from_oil(t,1) + power_demand_from_oil(t,2);
demand_from_oil_to_trans(t)=0;
for i=1:8
demand_from_oil_to_trans(t) = demand_from_oil_to_trans(t) + trans_demand_from_oil(t,i);
end

dummy_min=0.3;dummy_max=0.6;
rand_for_oil=dummy_min+(dummy_max-dummy_min)*rand();

% supply(t,3) = supply(t,3) * (resource_for_oil(t,1) / demand_from_oil_to_water(t)) *
(resource_for_oil(t,2) / demand_from_oil_to_power(t));
supply(t,3) = supply(t,3) - (supply(t,3) * (1 - (resource_for_oil(t,1) /demand_from_oil_to_water(t)) *
(resource_for_oil(t,2) / demand_from_oil_to_power(t))) * rand_for_oil);

for i=1:6
final_product_oil(t,i) = final_product_oil(t,i) * (resource_for_oil(t,1) / demand_from_oil_to_water(t))
* (resource_for_oil(t,2) / demand_from_oil_to_power(t));
end

% Repairing Task
repair_rate_oil_mines=rebuild_rate(3)*(resource_for_oil(t,6,1)/(trans_demand_from_oil(t,1)));
repair_rate_oil_source_storage=rebuild_rate(3)*(resource_for_oil(t,6,2)/(trans_demand_from_oil(t,2)));
repair_rate_oil_wells=rebuild_rate(3)*(resource_for_oil(t,6,3)/(trans_demand_from_oil(t,3)));
repair_rate_oil_refinery_storage=rebuild_rate(3)*(resource_for_oil(t,6,6)/(trans_demand_from_oil(t,6)));
repair_rate_oil_refinery = rebuild_rate(3)*(resource_for_oil(t,6,7)/(trans_demand_from_oil(t,7)));
repair_rate_oil_terminal = rebuild_rate(3)*(resource_for_oil(t,6,8)/(trans_demand_from_oil(t,8)));

capacity_oil_refinery=capacity_oil_refinery+repair_rate_oil_refinery;
if capacity_oil_refinery > 1
capacity_oil_refinery = 1;
end
capacity_oil_terminal=capacity_oil_terminal+repair_rate_oil_terminal;
if capacity_oil_terminal > 1
capacity_oil_terminal = 1;
end

capacity_oil_mines=capacity_oil_mines+repair_rate_oil_mines;
if capacity_oil_mines > 1
capacity_oil_mines = 1;
end
capacity_oil_source_storage=capacity_oil_source_storage+repair_rate_oil_source_storage;
if capacity_oil_source_storage > 1
capacity_oil_source_storage = 1;
end

```

```

        end
        capacity_oil_wells=capacity_oil_wells + repair_rate_oil_wells;
        if capacity_oil_wells > 1
            capacity_oil_wells = 1;
        end
        capacity_oil_refinery_storage=capacity_oil_refinery_storage + repair_rate_oil_refinery_storage;
        if capacity_oil_refinery_storage > 1
            capacity_oil_refinery_storage = 1;
        end

        capacity_oil_pipe=mean(oil_pipeline_capacity);
        repair_rate_oil_pipe=rebuild_rate(3)*(resource_for_oil(t,6,4)/(trans_demand_from_oil(t,4)));
        oil_pipeline_capacity=oil_pipeline_capacity+repair_rate_oil_pipe;
        for i=1:size(oil_pipeline_capacity,1)
            if oil_pipeline_capacity(i) > 1
                oil_pipeline_capacity(i) = 1;
            end
        end
        capacity_oil_port=mean(oil_port_capacity);
        repair_rate_oil_port=rebuild_rate(3)*(resource_for_oil(t,6,5)/(trans_demand_from_oil(t,5)));
        oil_port_capacity=oil_port_capacity+repair_rate_oil_port;
        for i=1:size(oil_port_capacity,1)
            if oil_port_capacity(i) > 1
                oil_port_capacity(i) = 1;
            end
        end

        % total capacity
        total_capacity_oil=mean([capacity_oil_mines capacity_oil_source_storage capacity_oil_wells
        capacity_oil_refinery_storage capacity_oil_pipe capacity_oil_port]);

    end % End of Big Loop within OIL Sub-Model

    %=====
    %===== Natural Gas Infrastructure Sub Model =====
    %=====
    if (total_capacity_gas ~1.2) % Big Loop within Oil Sub-Model

        % Gas Wells
        % Raw Gas Withdrawals
        dummy_min=3450;dummy_max=3650;
        unif_rawgas(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=3550.82
        raw_gas = capacity_gas_wells * unif_rawgas(t);
        % 3550.82 Mcf / day
        % demand for transportation
        dummy=demand(t,6);
        demand(t,6)=demand(t,6)+((1.001-capacity_gas_wells)*50);
        trans_demand_from_gas(t,1)=demand(t,6)-dummy;
        % Power demand for rigging the gas
        dummy_min=900;dummy_max=960;
        unif_demand_power_from_gaswells(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=928
        demand(t,2)=demand(t,2)+(capacity_gas_wells * unif_demand_power_from_gaswells(t));
        % 928 is modified parameter (MWh / Day)
        power_demand_from_gas(t,1)=(capacity_gas_wells * unif_demand_power_from_gaswells(t));

        % Gathering Pipeline
        dummy_min=0.0300;dummy_max=0.0350; % Loss Rate by Pipeline
        unif_loss_ratio_gas_pipe(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=0.0325
        raw_gas = (raw_gas * capacity_gas_pipe);
        raw_gas = raw_gas - (raw_gas * unif_loss_ratio_gas_pipe(t) );
        % 0.0325 is loss by pipeline

        % demand for transportation
        trans_count=0;
        for i=1:size(oil_pipeline_capacity(:,1),1)
            if oil_pipeline_capacity(i) < 0.95
                trans_count=trans_count+1;
            end
        end
    end

```

```

        end
    end
    dummy=demand(t,6);
    demand(t,6)=demand(t,6)+(50 * (trans_count/size(gas_pipeline_capacity(:,1),1)));
    trans_demand_from_gas(t,2)=demand(t,6)-dummy;
    if trans_demand_from_gas(t,2) == 0
        trans_demand_from_gas(t,2) = 0.001;
    end

% Treatment Plant
dummy_min=0.0611;dummy_max=0.0811; % Loss Rate by Treatment Plant
unif_loss_ratio_gas_treat(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.0711
natural_gas = raw_gas - (unif_loss_ratio_gas_treat(t) * raw_gas );
% 0.0711 is loss by lease fuel and plant fuel (self-used gas)

% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_gas_treat)*30);
trans_demand_from_gas(t,3)=demand(t,6)-dummy;
% Power demand for treating the gas
dummy_min=54500;dummy_max=55500;
unif_demand_power_from_gas_treat(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=55000
demand(t,2)=demand(t,2)+(capacity_gas_treat * unif_demand_power_from_gas_treat(t));
% 55000 is modified parameter (MWh / Day)
power_demand_from_gas(t,2)=(capacity_gas_wells * unif_demand_power_from_gas_treat(t));
% Water demand for treating the gas
dummy_min=270;dummy_max=330;
unif_demand_water_from_gas_treat(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=300
demand(t,1)=demand(t,1)+(capacity_gas_treat * unif_demand_water_from_gas_treat(t));
% 300 is modified parameter (MegaGallons / Day)
water_demand_from_gas(t,1)=(capacity_gas_wells * unif_demand_water_from_gas_treat(t));

% Gas Storage
natural_gas = natural_gas * capacity_gas_storage;

% demand for transportation
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_gas_storage)*20);
trans_demand_from_gas(t,4)=demand(t,6)-dummy;

% Transportation or pipeline
dummy_min=0.6;dummy_max=0.8;
unif_ratio_natural_gas_pipetrans(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.7
unif_ratio_natural_gas_pipetrans_2(t)=1 - unif_ratio_natural_gas_pipetrans(t);
if capacity_gas_pipe >= total_capacity_trans
    trans_ratio = [unif_ratio_natural_gas_pipetrans_2(t) unif_ratio_natural_gas_pipetrans(t) ];
else trans_ratio=[unif_ratio_natural_gas_pipetrans(t) unif_ratio_natural_gas_pipetrans_2(t)];
end
gas_by_transportation = natural_gas * trans_ratio(1) * total_capacity_trans;
gas_by_pipeline = natural_gas * trans_ratio(2);

supply(t,4) = gas_by_transportation + gas_by_pipeline;

demand_from_gas_to_water(t) = water_demand_from_gas(t,1);
demand_from_gas_to_power(t) = power_demand_from_gas(t,1) + power_demand_from_gas(t,2);
dummy_min=0.24;dummy_max=0.29;
unif_supply_ratio_used_for_gas(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=0.2474
% 0.3074 is latest used value

supply(t,4) = supply(t,4) * unif_supply_ratio_used_for_gas(t);
dummy_min=0.3;dummy_max=0.6;
rand_for_gas=dummy_min+(dummy_max-dummy_min)*rand();

```

```

supply(t,4) = supply(t,4) - (supply(t,4) * (1 - (resource_for_gas(t,1) / demand_from_gas_to_water(t))
* (resource_for_gas(t,2) / demand_from_gas_to_power(t))) * rand_for_gas);

demand_from_gas_to_trans(t) = trans_demand_from_gas(t,1) + trans_demand_from_gas(t,2) +
trans_demand_from_gas(t,3) + trans_demand_from_gas(t,4);

% Repairing Task
repair_rate_gas_wells=rebuild_rate(4)*(resource_for_gas(t,6,1)/(trans_demand_from_gas(t,1)));
repair_rate_gas_treat=rebuild_rate(4)*(resource_for_gas(t,6,3)/(trans_demand_from_gas(t,3)));
repair_rate_gas_storage=rebuild_rate(4)*(resource_for_gas(t,6,4)/(trans_demand_from_gas(t,4)));

capacity_gas_wells=capacity_gas_wells+repair_rate_gas_wells;
if capacity_gas_wells > 1
    capacity_gas_wells = 1;
end
capacity_gas_treat=capacity_gas_treat+repair_rate_gas_treat;
if capacity_gas_treat > 1
    capacity_gas_treat = 1;
end
capacity_gas_storage=capacity_gas_storage + repair_rate_gas_storage;
if capacity_gas_storage > 1
    capacity_gas_storage = 1;
end

capacity_gas_pipe=mean(gas_pipeline_capacity);
repair_rate_gas_pipe=rebuild_rate(4)*(resource_for_gas(t,6,2)/(trans_demand_from_gas(t,2)));
gas_pipeline_capacity=gas_pipeline_capacity+repair_rate_gas_pipe;
for i=1:size(gas_pipeline_capacity,1)
    if gas_pipeline_capacity(i) > 1
        gas_pipeline_capacity(i) = 1;
    end
end

% total capacity
total_capacity_gas=mean([capacity_gas_wells capacity_gas_pipe capacity_gas_treat capacity_gas_storage]);

end % End of Big Loop within gas Sub-Model

%=====
%===== Transportation Infrastructure Sub Model =====
%=====
if (total_capacity_trans ~1.2) % Big Loop within trans Sub-Model

% demand for transportation itself
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_trans_signal)*50);
trans_demand_from_trans(t,1)=demand(t,6)-dummy;

% Power demand
dummy_min=8600;dummy_max=8696;
unif_demand_power_from_trans(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=8648.7
demand(t,2)=demand(t,2)+(capacity_trans_signal * unif_demand_power_from_trans(t));
% 8648.7 is modified parameter (MWh / Day)
power_demand_from_trans(t,1)=(capacity_trans_signal * unif_demand_power_from_trans(t));
demand_from_trans_to_power(t) = power_demand_from_trans(t,1);

% demand for transportation itself
capacity_trans_road = mean(trans_road_capacity);
trans_count=0;
for i=1:size(trans_road_capacity(:,1),1)
    if trans_road_capacity(i) < 0.95
        trans_count=trans_count+1;
    end
end
dummy=demand(t,6);
demand(t,6)=demand(t,6)+(50 * (trans_count/size(trans_road_capacity(:,1),1)));
trans_demand_from_trans(t,2)=demand(t,6)-dummy;
if trans_demand_from_trans(t,2) == 0
    trans_demand_from_trans(t,2) = 0.001;
end

```

```

% demand for restoring the asphalt
% demand(t,3,7)=(1.001-capacity_trans_road)* 18700);
dummy_min=17000;dummy_max=18700;
unif_demand_asphalt(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=18700
demand(t,3)=demand(t,3) + ((1.001-capacity_trans_road)* unif_demand_asphalt(t));
% 18700 is dummy
demand_from_trans_to_oil(t)=((1.001-capacity_trans_road)* unif_demand_asphalt(t));

% demand for Gasoline
% demand(t,3,2)=(capacity_trans_road * 281882.25);
dummy_min=220000;dummy_max=251882;
unif_demand_gasoline(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=251882.25
demand(t,3)=demand(t,3) +(capacity_trans_road * unif_demand_gasoline(t));
demand_from_trans_to_oil(t)=demand_from_trans_to_oil(t)+(capacity_trans_road *
unif_demand_gasoline(t));

% demand for Diesel Fuel
% demand(t,3,3)=(capacity_trans_road * 130000);
dummy_min=80000;dummy_max=100000;
unif_demand_diesel(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=100000
demand(t,3)=demand(t,3) + (capacity_trans_road * unif_demand_diesel(t));
demand_from_trans_to_oil(t)=demand_from_trans_to_oil(t)+(capacity_trans_road *
unif_demand_diesel(t));
% demand for LPG
% demand(t,3,6)=(capacity_trans_road * 27465.45);
dummy_min=25000;dummy_max=27465;
unif_demand_LPG(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=27465
demand(t,3)=demand(t,3) + (capacity_trans_road * unif_demand_LPG(t));
demand_from_trans_to_oil(t)=demand_from_trans_to_oil(t)+(capacity_trans_road * unif_demand_LPG(t));

% Rail
% demand for transportation itself
capacity_trans_rail = mean(trans_rail_capacity);
trans_count=0;
for i=1:size(trans_rail_capacity(:,1),1)
    if trans_rail_capacity(i) < 0.95
        trans_count=trans_count+1;
    end
end
dummy=demand(t,6);
demand(t,6)=demand(t,6)+(50 * (trans_count/size(trans_rail_capacity(:,1),1)));
trans_demand_from_trans(t,3)=demand(t,6)-dummy;
if trans_demand_from_trans(t,3) == 0
    trans_demand_from_trans(t,3) = 0.001;
end

% Bridges
% demand for transportation itself
capacity_trans_bridges = mean(trans_bridges_capacity);
trans_count=0;
for i=1:size(trans_bridges_capacity(:,1),1)
    if trans_bridges_capacity(i) < 0.95
        trans_count=trans_count+1;
    end
end
dummy=demand(t,6);
demand(t,6)=demand(t,6)+(50 * (trans_count/size(trans_bridges_capacity(:,1),1)));
trans_demand_from_trans(t,4)=demand(t,6)-dummy;
if trans_demand_from_trans(t,4) == 0
    trans_demand_from_trans(t,4) = 0.001;
end

% AirPort
% demand for transportation itself
dummy=demand(t,6);
demand(t,6)=demand(t,6)+((1.001-capacity_trans_airport)*50);

```

```

trans_demand_from_trans(t,5)=demand(t,6)-dummy;

dummy_min=52000;dummy_max=62158;
unif_demand_jet_fuel(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=62158.65
demand(t,3)=demand(t,3)+ (capacity_trans_airport * unif_demand_jet_fuel(t));
% demand(t,3,4)=capacity_trans_airport * 62158.65;
% Jet Fuel
demand_from_trans_to_oil(t)=demand_from_trans_to_oil(t)+(capacity_trans_airport *
unif_demand_jet_fuel(t));

% total capacity
total_capacity_trans=mean([capacity_trans_signal capacity_trans_road capacity_trans_rail
capacity_trans_airport capacity_trans_bridges ]);

dummy_min=480;dummy_max=520;
unif_supply_trans(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=500
supply(t,6) = unif_supply_trans(t) * total_capacity_trans;
%supply(t,6) = unif_supply_trans(t) * total_capacity_trans * (resource_for_trans(t,3)
/demand_from_trans_to_oil(t));
dummy_min=0.05;dummy_max=0.2;
rand_for_trans=dummy_min+(dummy_max-dummy_min)*rand();
supply(t,6) = supply(t,6) - (supply(t,6) * (1 - (resource_for_trans(t,3) / demand_from_trans_to_oil(t))) *
rand_for_trans);

demand_from_trans_to_power(t) = power_demand_from_trans(t,1);
demand_from_trans_to_trans(t) = 0;
for i=1:5
demand_from_trans_to_trans(t) = demand_from_trans_to_trans(t) + trans_demand_from_trans(t,i);
end

% Repairing Task
repair_rate_trans_signal=rebuild_rate(6)*(resource_for_trans(t,6,1)/(trans_demand_from_trans(t,1)));
repair_rate_trans_airport=rebuild_rate(6)*(resource_for_trans(t,6,5)/(trans_demand_from_trans(t,5)));

capacity_trans_signal=capacity_trans_signal+repair_rate_trans_signal;
if capacity_trans_signal > 1
capacity_trans_signal = 1;
end
capacity_trans_airport=capacity_trans_airport+repair_rate_trans_airport;
if capacity_trans_airport > 1
capacity_trans_airport = 1;
end

repair_rate_trans_road=rebuild_rate(6)*(resource_for_trans(t,6,2)/(trans_demand_from_trans(t,2)));
trans_road_capacity=trans_road_capacity + repair_rate_trans_road;
for i=1:size(trans_road_capacity,1)
if trans_road_capacity(i) > 1
trans_road_capacity(i) = 1;
end
end

repair_rate_trans_rail=rebuild_rate(6)*(resource_for_trans(t,6,3)/(trans_demand_from_trans(t,3)));
trans_rail_capacity=trans_rail_capacity + repair_rate_trans_rail;
for i=1:size(trans_rail_capacity,1)
if trans_rail_capacity(i) > 1
trans_rail_capacity(i) = 1;
end
end

repair_rate_trans_bridges=rebuild_rate(6)*(resource_for_trans(t,6,4)/(trans_demand_from_trans(t,4)));
trans_bridges_capacity=trans_bridges_capacity + repair_rate_trans_bridges;
for i=1:size(trans_bridges_capacity,1)
if trans_bridges_capacity(i) > 1
trans_bridges_capacity(i) = 1;
end
end

end % End of Big Loop within trans Sub-Model

```

```

%=====
%===== Telecommunication Infrastructure Sub Model =====
%=====
if (total_capacity_tele ~=1.2) % Big Loop within trans Sub-Model
% Wireless Communication
% Service Station
    % demand for transportation
    dummy=demand(t,6);
    demand(t,6)=demand(t,6)+((1.001-capacity_tele_service_station)*30);
    trans_demand_from_tele(t,1)=demand(t,6)-dummy;
    if t >= 10
        % demand for power
        dummy_min=4548;dummy_max=4748;
        unif_demand_power_from_tele(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=4648.67
        demand(t,2)=demand(t,2) + (capacity_tele_service_station*unif_demand_power_from_tele(t));
        % 4648.7 is modified parameter (MWh / Day)
        power_demand_from_tele(t,1)=(capacity_tele_service_station * unif_demand_power_from_tele(t));
    end
% Back-up Power
    if t < 10 % assumption: back-up power is available within 10 days.
        dummy_min=4548;dummy_max=4748;
        unif_demand_power_from_tele(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=4648.67
        power_from_backup(1) = capacity_tele_service_station * unif_demand_power_from_tele(t);
        power_demand_from_tele(t,1) = 0;
    end

% Local Tower
    % demand for transportation
    dummy=demand(t,6);
    demand(t,6)=demand(t,6)+((1.001-capacity_tele_local_tower)*50);
    trans_demand_from_tele(t,2)=demand(t,6)-dummy;
% Output of Wireless
    dummy_min=95;dummy_max=105;
    unif_bandwidth(t)=dummy_min+(dummy_max-dummy_min)*rand();
    % Uniform Dist - Variability, When E(t)=100
    bandwidth(t) = mean([capacity_tele_service_station capacity_tele_local_tower]) * unif_bandwidth(t);
% 100 is dummy value

% Wire Communication
% Control Tower
    % demand for transportation
    dummy=demand(t,6);
    demand(t,6)=demand(t,6)+((1.001-capacity_tele_control_tower)*30);
    trans_demand_from_tele(t,3)=demand(t,6)-dummy;
    % demand for power
    if t >= 10
        dummy_min=3900;dummy_max=4100;
        unif_demand_power_from_tele2(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=4000
        demand(t,2)=demand(t,2) + (capacity_tele_control_tower * unif_demand_power_from_tele2(t));
        % 4,000 is modified parameter (MWh / Day)
        power_demand_from_tele(t,2)=(capacity_tele_control_tower * unif_demand_power_from_tele2(t));
    end
% Back-up Power
    if t < 10 % assumption: back-up power is available within 10 days.
        dummy_min=3900;dummy_max=4100;
        unif_demand_power_from_tele2(t)=dummy_min+(dummy_max-dummy_min)*rand();
        % Uniform Dist - Variability, When E(t)=4000
        power_from_backup(2) = capacity_tele_control_tower * unif_demand_power_from_tele2(t);
        power_demand_from_tele(t,2) = 0;
    end
% Communication line
    % demand for transportation
    dummy=demand(t,6);
    demand(t,6)=demand(t,6)+((1.001-capacity_tele_com_line)*50);
    trans_demand_from_tele(t,4)=demand(t,6)-dummy;

```

```

% Output of Wire com
dummy_min=95;dummy_max=105;
unif_service(t)=dummy_min+(dummy_max-dummy_min)*rand();
% Uniform Dist - Variability, When E(t)=100
tele_service(t) = mean([capacity_tele_control_tower capacity_tele_com_line]) * unif_service(t);
% 100 is dummy value

% Total TeleCom Output
if bandwidth(t) > 90 | tele_service(t) > 90
% If, At least one of two (wireless, wire) is in the good condition, then
% overall repair circumstance will be enhanced.
% Increase the Repair Rate.
if runonce_tele == 1
rebuild_constant = rebuild_constant + 0.01;
runonce_tele = 2;
end
end
if bandwidth(t) < 50 & tele_service(t) < 50
if runonce_tele2 == 1
rebuild_constant = rebuild_constant - 0.01;
runonce_tele2 = 2;
end
end

demand_from_tele_to_power(t) = power_demand_from_tele(t,1) + power_demand_from_tele(t,2);
demand_from_tele_to_trans(t) = trans_demand_from_tele(t,1) + trans_demand_from_tele(t,2) +
trans_demand_from_tele(t,3) + trans_demand_from_tele(t,4);

% end
supply(t,5) = bandwidth(t) + tele_service(t);
dummy_min=0.1;dummy_max=0.3;
rand_for_tele=dummy_min+(dummy_max-dummy_min)*rand();
if t >= 10
supply(t,5) = supply(t,5) - (supply(t,5) * (1 - (resource_for_tele(t,2) /
demand_from_tele_to_power(t))) * rand_for_tele);
end

% Dummy Demand
demand(t,5) = 200 - (rand() * 5);

% total capacity
total_capacity_tele=mean([capacity_tele_service_station capacity_tele_local_tower
capacity_tele_control_tower capacity_tele_com_line]);

% Repairing Task

repair_rate_tele_service_station=rebuild_rate(5)*(resource_for_tele(t,6,1)/(trans_demand_from_tele(t,1)));
repair_rate_tele_local_tower=rebuild_rate(5)*(resource_for_tele(t,6,2)/(trans_demand_from_tele(t,2)));
repair_rate_tele_control_tower=rebuild_rate(5)*(resource_for_tele(t,6,3)/(trans_demand_from_tele(t,3)));
repair_rate_tele_com_line=rebuild_rate(5)*(resource_for_tele(t,6,4)/(trans_demand_from_tele(t,4)));

capacity_tele_service_station=capacity_tele_service_station+repair_rate_tele_service_station;
if capacity_tele_service_station > 1
capacity_tele_service_station = 1;
end
capacity_tele_local_tower=capacity_tele_local_tower+repair_rate_tele_local_tower;
if capacity_tele_local_tower > 1
capacity_tele_local_tower = 1;
end
capacity_tele_control_tower=capacity_tele_control_tower+repair_rate_tele_control_tower;
if capacity_tele_control_tower > 1
capacity_tele_control_tower = 1;
end
capacity_tele_com_line=capacity_tele_com_line+repair_rate_tele_com_line;
if capacity_tele_com_line > 1
capacity_tele_com_line = 1;
end
end

```



```

end % End of Big Loop within trans Sub-Model

% Demand Collector
% integrate demand

% Water
demand_from_water(t,1:6) = 0;
demand_from_water(t,2) = demand_from_water_to_power(t);
%demand_from_water(t,3:5) = 0;
demand_from_water(t,6) = trans_demand_from_water(t,1) + trans_demand_from_water(t,2) +
trans_demand_from_water(t,3);
demand(t,4)= demand(t,4) + 0.397; % 0.397 is trans

% demand and supply

for i=1:6
    demand_supply(t,i)=demand(t,i)-supply(t,i);
end

% Priority
if t == 1
    for i=1:6
        initial_score(i) = 100 - (initial_priority(i) * 10);
        now_score(t,i) = initial_score(i);
    end
    score = [1 initial_score(1); 2 initial_score(2); 3 initial_score(3); 4 initial_score(4); 5
initial_score(5); 6 initial_score(6)];
end

if t > 1
    for i=1:6
        now_score(t,i) = 100 - (priority(i) * 10);
    end
    score = [1 now_score(t,1); 2 now_score(t,2); 3 now_score(t,3); 4 now_score(t,4); 5 now_score(t,5); 6
now_score(t,6)];
end

% If one of infra is repaired by 95% then decrease its score.
if total_capacity_water > 0.95
    score(1,2) = score(1,2) * (0.6);
end
if total_capacity_power(t) > 0.95
    score(2,2) = score(2,2) * (0.6);
end
if total_capacity_oil > 0.95
    score(3,2) = score(3,2) * (0.6);
end
if total_capacity_gas > 0.95
    score(4,2) = score(4,2) * (0.6);
end
if total_capacity_tele > 0.95
    score(5,2) = score(5,2) * (0.6);
end
if total_capacity_trans > 0.95
    score(6,2) = score(6,2) * (0.6);
end
% By the ( demand - supply ), score is affected
if t > 5
    for i=1:6
        diff(i) = demand_supply(t,i) - demand_supply(t-1,i);
        if diff(i) > 0
            a=a+1;
        end
        if a > 5
            score(i,2) = score(i,2) + 11;
            a=0;
        end
    end
end

```

```

end

for i=1:6
score_history(i)=score(i,2);
end
score_matrix = [score_matrix; score_history];

% Assign priority with related to score
sort_score=sortrows(score,2);
for i=6:-1:1
priority(sort_score(i,1))=7-i;
end
priority_cum=[priority_cum; priority];

% Distribution Center
% at first, by score, resource is allocated to infra
% secondly, resource of each infra is allocated into sub infra.
sum_score=0;
for i=1:6
sum_score=sum_score+score(i,2);
end
for i=1:6
allocation_rate(t,i) = score(i,2) / sum_score;
end

% Water at time t allocation to the customers
% Who needs water? power, oil, gas
if demand (t,1) <= supply(t,1)
resource_for_power(t+1,1) = demand_from_power_to_water(t);
resource_for_oil(t+1,1) = demand_from_oil_to_water(t);
resource_for_gas(t+1,1) = demand_from_gas_to_water(t);
end
if demand(t,1) > supply(t,1)
dummy = demand(t,1) - supply(t,1);
% Assumption: In order to make realistic approach, weighted rate (score) will be introduced
weighted_score(1) = score(2,2)^3;
weighted_score(2) = score(3,2)^3;
weighted_score(3) = score(4,2)^3;
% Score Rate
sum = weighted_score(1) + weighted_score(2) + weighted_score(3);
weighted_score_rate(1) = weighted_score(1) / sum;
weighted_score_rate(2) = weighted_score(2) / sum;
weighted_score_rate(3) = weighted_score(3) / sum;
% Supply * Score Rate
for i=1:3
dummy(i) = weighted_score_rate(i) * supply(t,1);
end
% (Above number * demand rate)
demand_rate(1) = demand_from_power_to_water(t) / demand (t,1);
demand_rate(2) = demand_from_oil_to_water(t) / demand (t,1);
demand_rate(3) = demand_from_gas_to_water(t) / demand (t,1);
for i=1:3
dummy2(i) = dummy(i) * demand_rate(i);
end
% Constant = supply / sum(demand rate)
sum = dummy2(1) + dummy2(2) + dummy2(3);
if sum == 0
sum = 0.5;
end

constant = supply(t,1) / sum;
% dummy2 * constant
resource_for_power(t+1,1) = dummy2(1) * constant;
if resource_for_power(t+1,1) > demand_from_power_to_water(t)
resource_for_power(t+1,1) = demand_from_power_to_water(t);
end
resource_for_oil(t+1,1) = dummy2(2) * constant;
if resource_for_oil(t+1,1) > demand_from_oil_to_water(t)
resource_for_oil(t+1,1) = demand_from_oil_to_water(t);

```

```

        end
        resource_for_gas(t+1,1) = dummy2(3) * constant;
        if resource_for_gas(t+1,1) > demand_from_gas_to_water(t)
            resource_for_gas(t+1,1) = demand_from_gas_to_water(t);
        end
    end

% Power allocation to the customers
% Who needs power? water, oil, gas, tele, trans
if demand (t,2) <= supply(t,2)
    resource_for_water(t+1,2) = demand_from_water_to_power(t);
    resource_for_oil(t+1,2) = demand_from_oil_to_power(t);
    resource_for_gas(t+1,2) = demand_from_gas_to_power(t);
    resource_for_tele(t+1,2) = demand_from_tele_to_power(t);
    resource_for_trans(t+1,2) = demand_from_trans_to_power(t);
end
if demand(t,2) > supply(t,2)
    dummy = demand(t,2) - supply(t,2);
    % Assumption: In order to make realistic approach, weighted rate (score) will be introduced
    weighted_score(1) = score(1,2)^3;
    weighted_score(2) = score(3,2)^3;
    weighted_score(3) = score(4,2)^3;
    weighted_score(4) = score(5,2)^3;
    weighted_score(5) = score(6,2)^3;

    % Score Rate
    sum = weighted_score(1) + weighted_score(2) + weighted_score(3) + weighted_score(4) +
weighted_score(5);
    for i=1:5
        weighted_score_rate(i) = weighted_score(i) / sum;
    end
    % Supply * Score Rate
    for i=1:5
        dummy(i) = weighted_score_rate(i) * supply(t,2);
    end
    % (Above number * demand rate)
    demand_rate(1) = demand_from_water_to_power(t) / demand (t,2);
    demand_rate(2) = demand_from_oil_to_power(t) / demand (t,2);
    demand_rate(3) = demand_from_gas_to_power(t) / demand (t,2);
    demand_rate(4) = demand_from_tele_to_power(t) / demand (t,2);
    demand_rate(5) = demand_from_trans_to_power(t) / demand (t,2);

    for i=1:5
        dummy2(i) = dummy(i) * demand_rate(i);
    end
    % Constant = supply / sum(demand rate)
    sum = dummy2(1) + dummy2(2) + dummy2(3)+ dummy2(4)+ dummy2(5);
    if sum == 0
        sum = 0.5;
    end
    constant = supply(t,2) / sum;

    % dummy2 * constant
    resource_for_water(t+1,2) = dummy2(1) * constant;
    if resource_for_water(t+1,2) > demand_from_water_to_power(t)
        resource_for_water(t+1,2) = demand_from_water_to_power(t);
    end
    resource_for_oil(t+1,2) = dummy2(2) * constant;
    if resource_for_oil(t+1,2) > demand_from_oil_to_power(t)
        resource_for_oil(t+1,2) = demand_from_oil_to_power(t);
    end
    resource_for_gas(t+1,2) = dummy2(3) * constant;
    if resource_for_gas(t+1,2) > demand_from_gas_to_power(t)
        resource_for_gas(t+1,2) = demand_from_gas_to_power(t);
    end
    resource_for_tele(t+1,2) = dummy2(4) * constant;
    if resource_for_tele(t+1,2) > demand_from_tele_to_power(t)
        resource_for_tele(t+1,2) = demand_from_tele_to_power(t);
    end

```

```

        end
        resource_for_trans(t+1,2) = dummy2(5) * constant;
        if resource_for_trans(t+1,2) > demand_from_trans_to_power(t)
            resource_for_trans(t+1,2) = demand_from_trans_to_power(t);
        end
    end

% Oil allocation to the customers
% Who needs oil? power, tele, trans
    resource_for_power(t+1,3) = coal_inthe_storage + final_product_oil(t,4) + (0.003 *
final_product_oil(t,5));
    resource_for_trans(t+1,3) = final_product_oil(t,3) + final_product_oil(t,1) + final_product_oil(t,2) +
final_product_oil(t,6) + final_product_oil(t,5);

% Gas allocation to the customers
% Who needs gas? power, trans
    resource_for_power(t+1,4) = supply(t,4) * 0.24734837;
    resource_for_trans(t+1,4) = supply(t,4) * 0.0001249;

% Trans Allocation
if demand (t,6) <= supply(t,6)
    resource_for_water(t+1,6) = demand_from_water_to_trans(t);
    for i=1:3
        resource_for_water(t+1,6,i) = trans_demand_from_water(t,i);
    end
    resource_for_power(t+1,6) = demand_from_power_to_trans(t);
    for i=1:2
        resource_for_nuclear(t+1,6,i) = trans_demand_from_nuclear(i);
    end
    for i=1:3
        resource_for_geothermal(t+1,6,i) = trans_demand_from_geothermal(i);
        resource_for_hydro(t+1,6,i) = trans_demand_from_hydro(i);
    end
    for i=1:4
        resource_for_fossil(t+1,6,i) = trans_demand_from_fossil(t,i);
        resource_for_chp(t+1,6,i) = trans_demand_from_chp(t,i);
    end
    resource_for_power_transmission(t+1) = trans_demand_from_power_transmission(t);
    resource_for_oil(t+1,6) = demand_from_oil_to_trans(t);
    for i=1:8
        resource_for_oil(t+1,6,i) = trans_demand_from_oil(t,i);
    end
    resource_for_gas(t+1,6) = demand_from_gas_to_trans(t);
    for i=1:4
        resource_for_gas(t+1,6,i) = trans_demand_from_gas(t,i);
    end
    resource_for_tele(t+1,6) = demand_from_tele_to_trans(t);
    for i=1:4
        resource_for_tele(t+1,6,i) = trans_demand_from_tele(t,i);
    end
    resource_for_trans(t+1,6) = demand_from_trans_to_trans(t);
    for i=1:5
        resource_for_trans(t+1,6,i) = trans_demand_from_trans(t,i);
    end
end

if demand(t,6) > supply(t,6)
    dummy = demand(t,6) - supply(t,6);
    % Assumption: In order to make realistic approach, weighted rate (score) will be introduced
    weighted_score(1) = score(1,2)^3;
    weighted_score(2) = score(2,2)^3;
    weighted_score(3) = score(3,2)^3;
    weighted_score(4) = score(4,2)^3;
    weighted_score(5) = score(5,2)^3;
    weighted_score(6) = score(6,2)^3;
    % Score Rate
    sum=0;
    for i=1:6
        sum = sum + weighted_score(i);
    end
end

```

```

end
for i=1:6
    weighted_score_rate(i) = weighted_score(i) / sum;
end
% Supply * Score Rate
for i=1:6
    dummy(i) = weighted_score_rate(i) * supply(t,6);
end
% (Above number * demand rate)
demand_rate(1) = demand_from_water_to_trans(t) / demand (t,6);
demand_rate(2) = demand_from_power_to_trans(t) / demand (t,6);
demand_rate(3) = demand_from_oil_to_trans(t) / demand (t,6);
demand_rate(4) = demand_from_gas_to_trans(t) / demand (t,6);
demand_rate(5) = demand_from_tele_to_trans(t) / demand (t,6);
demand_rate(6) = demand_from_trans_to_trans(t) / demand (t,6);
for i=1:6
    dummy2(i) = dummy(i) * demand_rate(i);
end
% Constant = supply / sum(demand rate)
sum =0;
for i=1:6
    sum = sum + dummy2(i);
end
if sum == 0
    sum = 0.5;
end

constant = supply(t,6) / sum;
% dummy2 * constant
resource_for_water(t+1,6) = dummy2(1) * constant;
    if resource_for_water(t+1,6) > demand_from_water_to_trans(t)
        resource_for_water(t+1,6) = demand_from_water_to_trans(t);
    end
    resource_for_water(t+1,6,1) = resource_for_water(t+1,6) * (5/11);
    resource_for_water(t+1,6,2) = resource_for_water(t+1,6) * (3/11);
    resource_for_water(t+1,6,3) = resource_for_water(t+1,6) * (3/11);
    for i=1:3
        if resource_for_water(t+1,6,i) > trans_demand_from_water(t,i)
            resource_for_water(t+1,6,i) = trans_demand_from_water(t,i);
        end
    end
end

resource_for_power(t+1,6) = dummy2(2) * constant;
    if resource_for_power(t+1,6) > demand_from_power_to_trans(t)
        resource_for_power(t+1,6) = demand_from_power_to_trans(t);
    end
    resource_for_nuclear(t+1,6,1) = resource_for_power(t+1,6) * (20/390);
    resource_for_nuclear(t+1,6,2) = resource_for_power(t+1,6) * (30/390);
    for i=1:2
        if resource_for_nuclear(t+1,6,i) > trans_demand_from_nuclear(i)
            resource_for_nuclear(t+1,6,i) = trans_demand_from_nuclear(i);
        end
    end
end
for i=1:3
    resource_for_geothermal(t+1,6,i) = resource_for_power(t+1,6) * (20/390);
    if resource_for_geothermal(t+1,6,i) > trans_demand_from_geothermal(i)
        resource_for_geothermal(t+1,6,i) = trans_demand_from_geothermal(i);
    end
end

resource_for_hydro(t+1,6,1) = resource_for_power(t+1,6) * (30/390);
resource_for_hydro(t+1,6,2) = resource_for_power(t+1,6) * (20/390);
resource_for_hydro(t+1,6,3) = resource_for_power(t+1,6) * (20/390);
for i=1:3
    if resource_for_hydro(t+1,6,i) > trans_demand_from_hydro(i)
        resource_for_hydro(t+1,6,i) = trans_demand_from_hydro(i);
    end
end

resource_for_fossil(t+1,6,1) = resource_for_power(t+1,6) * (50/390);
resource_for_fossil(t+1,6,2) = resource_for_power(t+1,6) * (20/390);
resource_for_fossil(t+1,6,3) = resource_for_power(t+1,6) * (30/390);

```

```

resource_for_fossil(t+1,6,4) = resource_for_power(t+1,6) * (20/390);
for i=1:4
    if resource_for_fossil(t+1,6,i) > trans_demand_from_fossil(t,i)
        resource_for_fossil(t+1,6,i) = trans_demand_from_fossil(t,i);
    end
end
resource_for_chp(t+1,6,1) = resource_for_power(t+1,6) * (30/390);
resource_for_chp(t+1,6,2) = resource_for_power(t+1,6) * (20/390);
resource_for_chp(t+1,6,3) = resource_for_power(t+1,6) * (20/390);
resource_for_chp(t+1,6,4) = resource_for_power(t+1,6) * (20/390);
for i=1:4
    if resource_for_chp(t+1,6,i) > trans_demand_from_chp(t,i)
        resource_for_chp(t+1,6,i) = trans_demand_from_chp(t,i);
    end
end
resource_for_power_transmission(t+1) = resource_for_power(t+1,6) * (50/390);
if resource_for_power_transmission(t+1) > trans_demand_from_power_transmission(t)
    resource_for_power_transmission(t+1) = trans_demand_from_power_transmission(t);
end

resource_for_oil(t+1,6) = dummy2(3) * constant;
if resource_for_oil(t+1,6) > demand_from_oil_to_trans(t)
    resource_for_oil(t+1,6) = demand_from_oil_to_trans(t);
end
resource_for_oil(t+1,6,1) = resource_for_oil(t+1,6) * (20/240);
resource_for_oil(t+1,6,2) = resource_for_oil(t+1,6) * (20/240);
resource_for_oil(t+1,6,3) = resource_for_oil(t+1,6) * (50/240);
resource_for_oil(t+1,6,4) = resource_for_oil(t+1,6) * (50/240);
resource_for_oil(t+1,6,5) = resource_for_oil(t+1,6) * (30/240);
resource_for_oil(t+1,6,6) = resource_for_oil(t+1,6) * (20/240);
resource_for_oil(t+1,6,7) = resource_for_oil(t+1,6) * (30/240);
resource_for_oil(t+1,6,8) = resource_for_oil(t+1,6) * (20/240);
for i=1:8
    if resource_for_oil(t+1,6,i) > trans_demand_from_oil(t,i)
        resource_for_oil(t+1,6,i) = trans_demand_from_oil(t,i);
    end
end
resource_for_gas(t+1,6) = dummy2(4) * constant;
if resource_for_gas(t+1,6) > demand_from_gas_to_trans(t)
    resource_for_gas(t+1,6) = demand_from_gas_to_trans(t);
end
resource_for_gas(t+1,6,1) = resource_for_gas(t+1,6) * (50/150);
resource_for_gas(t+1,6,2) = resource_for_gas(t+1,6) * (50/150);
resource_for_gas(t+1,6,3) = resource_for_gas(t+1,6) * (30/150);
resource_for_gas(t+1,6,4) = resource_for_gas(t+1,6) * (20/150);
for i=1:4
    if resource_for_gas(t+1,6,i) > trans_demand_from_gas(t,i)
        resource_for_gas(t+1,6,i) = trans_demand_from_gas(t,i);
    end
end
resource_for_tele(t+1,6) = dummy2(5) * constant;
if resource_for_tele(t+1,6) > demand_from_tele_to_trans(t)
    resource_for_tele(t+1,6) = demand_from_tele_to_trans(t);
end
resource_for_tele(t+1,6,1) = resource_for_tele(t+1,6) * (30/160);
resource_for_tele(t+1,6,2) = resource_for_tele(t+1,6) * (50/160);
resource_for_tele(t+1,6,3) = resource_for_tele(t+1,6) * (30/160);
resource_for_tele(t+1,6,4) = resource_for_tele(t+1,6) * (50/160);
for i=1:4
    if resource_for_tele(t+1,6,i) > trans_demand_from_tele(t,i)
        resource_for_tele(t+1,6,i) = trans_demand_from_tele(t,i);
    end
end
resource_for_trans(t+1,6) = dummy2(6) * constant;
if resource_for_trans(t+1,6) > demand_from_trans_to_trans(t)
    resource_for_trans(t+1,6) = demand_from_trans_to_trans(t);
end
resource_for_trans(t+1,6,1) = resource_for_trans(t+1,6) * (50/200);
resource_for_trans(t+1,6,2) = resource_for_trans(t+1,6) * (50/200);

```

```

        resource_for_trans(t+1,6,3) = resource_for_trans(t+1,6) * (50/200);
        resource_for_trans(t+1,6,4) = resource_for_trans(t+1,6) * (50/200);
        for i=1:4
            if resource_for_trans(t+1,6,i) > trans_demand_from_trans(t,i)
                resource_for_trans(t+1,6,i) = trans_demand_from_trans(t,i);
            end
        end
    end
end

% Rebuilding rate renew by priority
for i=1:6
    switch priority(i)
        case 1
            rebuild_rate(i)=rebuild_rate(i) + 0.002;
        case 2
            rebuild_rate(i)=rebuild_rate(i) + 0.001;
        case 3
            rebuild_rate(i)=rebuild_rate(i) + 0.0005;
        case 4
            rebuild_rate(i)=rebuild_rate(i) - 0.0005;
        case 5
            rebuild_rate(i)=rebuild_rate(i) - 0.001;
        case 6
            rebuild_rate(i)=rebuild_rate(i) - 0.002;
        for i=1:6
            if rebuild_rate(i) < 0
                rebuild_rate(i) = 0;
            end
        end
    end

    rebuild_rate_cum=[rebuild_rate_cum; rebuild_rate];
end
end

    total_current_condition=[];
    total_current_condition=[total_capacity_water total_capacity_power(t) total_capacity_oil
total_capacity_gas total_capacity_tele total_capacity_trans];
    total_current_condition_cum=[total_current_condition_cum; total_current_condition];
    rebuild_total=mean(total_current_condition);

    t=t+1; % day count

end % Most Big Loop End

% =====
% ===== Output Analysis (Graph, Table) =====

% Total Current Capacity Graph
figure
plot(total_current_condition_cum,'lineWidth',2')
title('Total Current Capacity Graph','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('Percentage','fontsize',12)
axis([-inf inf 0 1.1])
h=legend('Water','Power','Oil','Gas','Tele','Trans',4);

% Change of Score Graph
figure
plot(score_matrix,'lineWidth',2')
title('Change of Score by times','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('Score','fontsize',12)
axis([-inf inf -inf inf])
h=legend('Water','Power','Oil','Gas','Tele','Trans',3);

% Supply and Demand
figure
plot([demand(:,1),supply(:,1)],'LineWidth',2)
title('Water Infrastructure Demand / Supply','fontsize',14)
xlabel('Days','fontsize',12)

```

```

ylabel('Millions Barrels', 'fontsize', 12)
axis([2 inf -inf inf])
h=legend('Demand', 'Supply', 4);

figure
plot([demand(:, 2), supply(:, 2)], 'LineWidth', 2)
title('Power Infrastructure Demand / Supply', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('Millions Watt / hrs', 'fontsize', 12)
h=legend('Demand', 'Supply', 4);

figure
plot([demand(:, 3), supply(:, 3)], 'LineWidth', 2)
title('Oil Infrastructure Demand / Supply', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('Barrels', 'fontsize', 12)
h=legend('Demand', 'Supply', 4);

figure
plot([demand(:, 4), supply(:, 4)], 'LineWidth', 2)
title('Natural Gas Infrastructure Demand / Supply', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('Millions Cubic per Feet', 'fontsize', 12)
h=legend('Demand', 'Supply', 4);

figure
plot([demand(:, 5), supply(:, 5)], 'LineWidth', 2)
title('Telecommunication Infrastructure Demand / Supply', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('Bandwidth + Service', 'fontsize', 12)
h=legend('Demand', 'Supply', 4);

figure
plot([demand(:, 6), supply(:, 6)], 'LineWidth', 2)
title('Transportation Infrastructure Demand / Supply', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('Unit', 'fontsize', 12)
h=legend('Demand', 'Supply', 4);

% Power Demand from all infrastructure
figure
set(gca, 'nextplot', 'add');
plot([demand_from_water_to_power(1, :)], 'lineWidth', 2');
plot([demand_from_oil_to_power(1, :)], 'r', 'lineWidth', 2');
plot(demand_from_gas_to_power, 'k', 'lineWidth', 2');
plot(demand_from_tele_to_power, 'g', 'lineWidth', 2');
plot(demand_from_trans_to_power, 'c', 'lineWidth', 2');
title('Power Demand from all infrastructures', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('MW/hrs', 'fontsize', 12)
h=legend('Water', 'Oil', 'gas', 'tele', 'trans', 2);

% Water Demand from all infrastructure
figure
set(gca, 'nextplot', 'add');
plot(demand_from_power_to_water, 'lineWidth', 2');
plot(demand_from_oil_to_water, 'r', 'lineWidth', 2');
plot(demand_from_gas_to_water, 'g', 'lineWidth', 2');
title('Water Demand from all infrastructures', 'fontsize', 14)
xlabel('Days', 'fontsize', 12)
ylabel('Millions Barrels', 'fontsize', 12)
h=legend('Power', 'Oil', 'Gas', 2);

% Trans Demand from all infrastructure
figure
set(gca, 'nextplot', 'add');
plot(demand_from_water_to_trans, 'lineWidth', 2');
plot(demand_from_power_to_trans, 'r', 'lineWidth', 2');
plot(demand_from_oil_to_trans, 'g', 'lineWidth', 2');
plot(demand_from_gas_to_trans, 'k', 'lineWidth', 2');

```



```

plot(demand_from_tele_to_trans,'c','lineWidth',2');
plot(demand_from_trans_to_trans,'y','lineWidth',2');
title('Transportation Demand from all infrastructures','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('Unit','fontsize',12)
h=legend('Water','Power','Oil','Gas','Tele','Trans',2);

% Oil Production by Source
figure
pie3(final_product_oil(t-1,:));
title('Oil Productions by Source','fontsize',14)
% h=legend('Gasoline','Diesel','Kerosene','Fuel oil','LPG','Asphalt',2);
% '—','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','g','MarkerSize',1)

% Rebuilding Rate
figure
plot(rebuild_rate_cum,'lineWidth',2')
title('Rebuilding Rate','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('Rate','fontsize',12)
h=legend('Water','Power','Oil','Gas','Tele','Trans',2);

% Power Allocation to Water
figure
set(gca,'nextplot','add');
plot(resource_for_water(:,2),'lineWidth',2');
plot(demand_from_water_to_power,'r','lineWidth',2');
title('Power Allocation to Water','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('MMW / hrs','fontsize',12)
h=legend('Resource','Demand',2);

% Power Allocation to oil
figure
set(gca,'nextplot','add');
plot(resource_for_oil(:,2),'lineWidth',2');
plot(demand_from_oil_to_power,'r','lineWidth',2');
title('Power Allocation to Oil','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('MMW / hrs','fontsize',12)
h=legend('Resource','Demand',2);

% Power Allocation to gas
figure
set(gca,'nextplot','add');
plot(resource_for_gas(:,2),'lineWidth',2');
plot(demand_from_gas_to_power,'r','lineWidth',2');
title('Power Allocation to Gas','fontsize',14)
xlabel('Days','fontsize',12)
ylabel('MMW / hrs','fontsize',12)
h=legend('Resource','Demand',2);

```

Appendix C. MATLAB code for optimization model

```
% =====  
% ===== Rebuilding Simulation Model with Optimization =====  
% ===== SIM area: Louisiana =====  
% ===== Must simulate with withoutgraph3.m =====  
% =====  
clear all;  
bb = 1;  
best = 200;  
aa = 1;  
tt = 500; % Initial temperature  
rate_t = 90; % Cooling rate  
itry = 0; % Iterations within inner-loop  
  
initial_priority = [ 1 2 3 4 5 6];  
best_sol = initial_priority;  
a = 0;  
current_matrix = [];  
current_priority_matrix = [];  
  
while tt >= 1  
  
    if aa == 5 | aa == 6  
  
        swap_priority = current_solution;  
        number_swap = ceil(rand * (2));  
        if number_swap < 1  
            number_swap = 1;  
        end  
  
        for i = 1:number_swap  
            step = ceil(rand * 6);  
            if step < 1  
                step = 1;  
            end  
            step2 = ceil(rand * 6);  
            if step2 < 1  
                step2 = 1;  
            end  
            dummy = swap_priority(step);  
            swap_priority(step) = swap_priority(step2);  
            swap_priority(step2) = dummy;  
        end  
  
        initial_priority = swap_priority;  
        aa = 6;  
        bb = 5;  
    end  
  
    total_iter = 0;  
    endtime = [];  
  
    while total_iter < 64  
        t = 1;  
  
        % *****  
        % This Part is same as Appendix B  
        % *****  
  
        total_iter = total_iter + 1;  
        endtime = [endtime; t];  
  
    end  
    mean_duration = mean(endtime)  
  
    if bb == 1  
        current = mean_duration;
```

```

current_solution = initial_priority;
end

if bb == 1
aa = 5
end

if aa == 6
diff=abs(mean_duration - current);

if mean_duration < current

current = mean_duration
current_solution = swap_priority
if itry >= 10
tt = tt * rate_t
itry=0;
end
if mean_duration < best
best = mean_duration
best_sol = current_solution
end
itry = itry + 1;
end

if mean_duration > current

r = rand();
if r <= exp(-(diff)/tt);
current_solution = swap_priority
tt = tt * rate_t;
current = mean_duration
itry=itry+1;
end

end
end
current_matrix=[current_matrix; current];
current_priority_matrix=[current_priority_matrix; current_solution];

end

% ===== Graph and Output =====
figure
plot(current_matrix,'lineWidth',2)
title('Optimization of Best Duration','fontsize',14)
xlabel('Iterations','fontsize',12)
ylabel('Days','fontsize',12)

worst=max([current_matrix]);
worst_sol=find(current_matrix==worst);

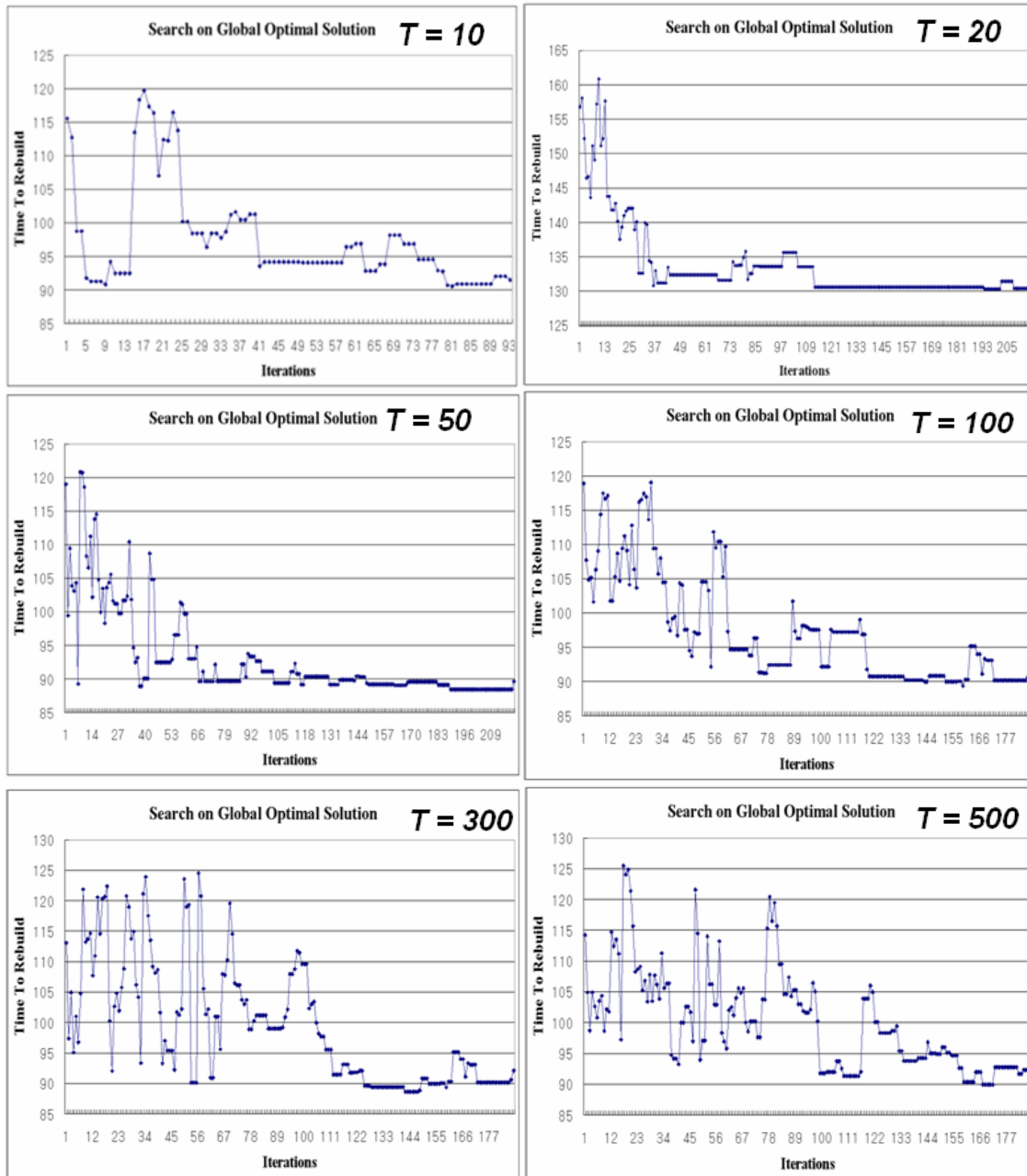
```

Appendix D. Incident matrix of infrastructure interdependency

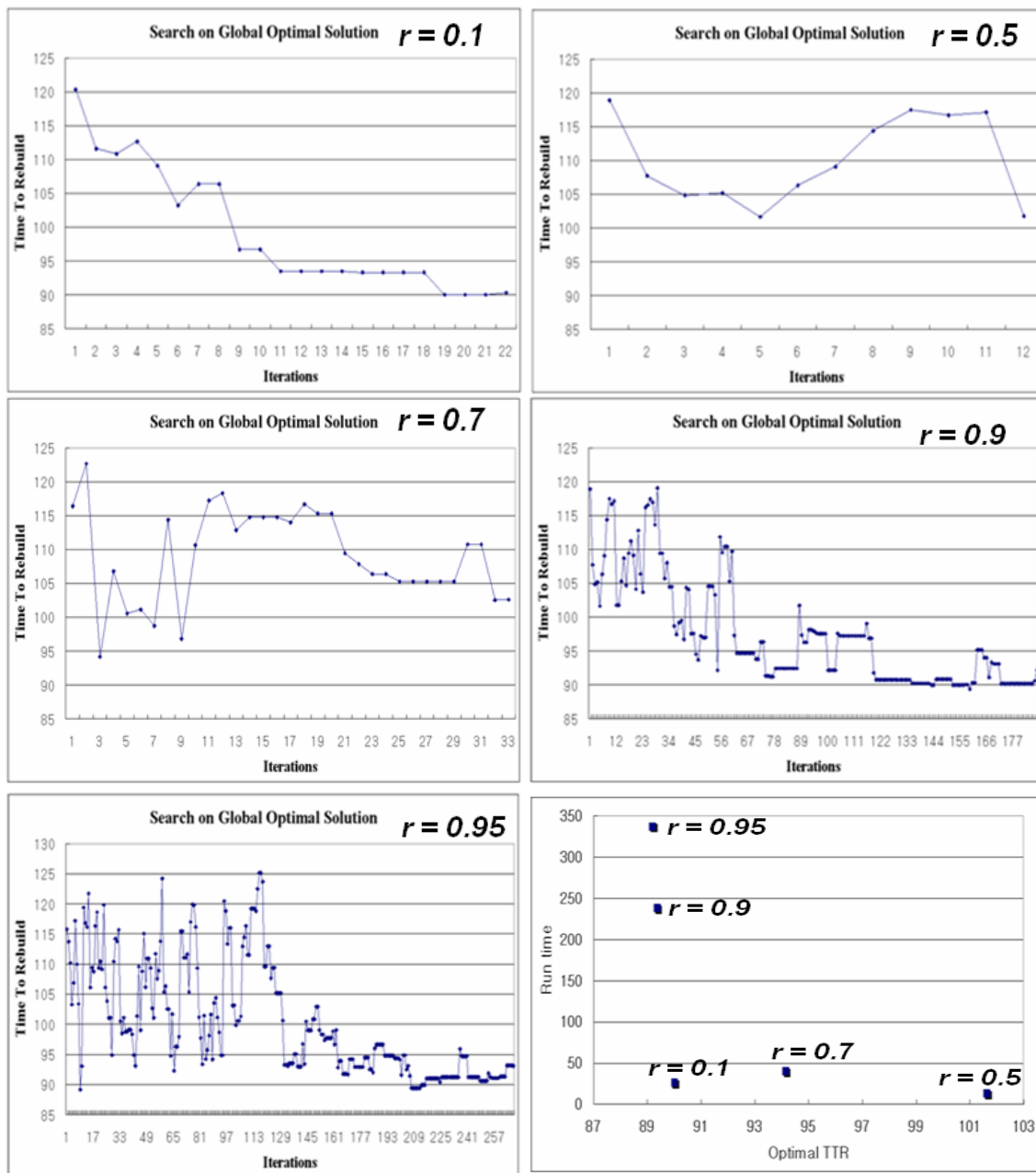
INCIDENT MATRIX in terms of PHYSICAL FLOW for INFRASTRUCTURE INTERDEPENDENCY		PHYSICAL FLOW														
		WATER	Nuclear	Fossil fuel	Geothermal	Hydroelectric	CHP	trans	OIL	Natural Gas	TeleCommunication	Transportation				
Interdependency	water wells	WATER														
	treatment plant	WATER														
WATER	wastewater	WATER														
	fuel storage	WATER														
POWER	Nuclear reactor	Nuclear														
	cooling	Nuclear														
	fuel storage	Fossil fuel														
	Boiler	Fossil fuel														
	Generator	Fossil fuel														
	Cooling	Fossil fuel														
	under pipe	Geo														
	heat pump	Geo														
	Normal cooling	Normal														
	dam	Hydro														
	intake system	Hydro														
elec generator	elec															
fuel storage	CHP															
Boiler	CHP															
Generator	CHP															
Cooling	CHP															
transmission line	trans															
coal mines	OIL															
oil wells	OIL															
pipeline	OIL															
ports	OIL															
refinery storage	OIL															
refinery	OIL															
terminal storage	OIL															
gas wells	Natural Gas															
pipeline	Natural Gas															
treatment plant	Natural Gas															
gas storage	Natural Gas															
pipeline	Natural Gas															
Service Station	TeleComm															
Local Tower	TeleComm															
Control Tower	TeleComm															
Comm line	TeleComm															
Road	Transportation															
Rail	Transportation															
Air ports	Transportation															
Signal System	Transportation															

Appendix E. Experiment results to find temperature setting (SA)

Initial temperature T (others are fixed: $r = 0.9$, $T_{final} = 1$)



Cooling rate r (others are fixed: $T = 100$, $T_{final} = 1$)



Bibliography

- Averill M. Law. *Simulation Modeling and Analysis* (4th edition). New York: McGraw-Hill, 2007
- Billy Ball, "Rebuilding Electrical Infrastructure along the Gulf Coast: A Case Study," *National academy of Engineering, Volume 36* (Spring 2006)
- Climate Change Technologies, "Combined Heat and Power," January 2000
[http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BPLD4/\\$File/combinedheatandpower.pdf](http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BPLD4/$File/combinedheatandpower.pdf)
- David McGee, "Cogeneration: Its place in the future of electricity in Louisiana," Louisiana Department of Natural Resources, April 2006
- Department of Homeland Security (DHS), "Hurricane Katrina: What Government Is Doing," <http://www.dhs.gov/interweb/assetlibrary/katrina.htm> (2006)
- Donald D. Dudenhoeffer, May R. Permann, and Elliot M. Sussman. "A parallel simulation framework for infrastructure modeling and analysis," *Proceeding of 2002 Winter Simulation Conference*, 2:1971-1977 (December 2002)
- Eleanor Soltau, "Putting Case management to the Ultimate test: Rebuilding New Orleans after Katrina, Part 1," *The Case manager*, 17:56-59 (2006)
- Energy Information Administration (EIA), "State Louisiana Energy Profile," Online at http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=LA
- Energy Information Administration (EIA), "Changes in U.S. Natural Gas Transportation Infrastructure in 2004," June 2005
- Energy Information Administration (EIA), "The Changing Structure of the Electric Power Industry 2000: An Update," October 2000
- Energy Information Administration (EIA), "Electric Power Annual 2004," November 2005 http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html
- Fred Freme. "U.S. Coal Supply and Demand: 2005 Review," Energy Information Administration (EIA), 2005

Guofei Jiang, "SIMP: A Simple Infrastructure Management Protocol for Infrastructure Monitoring and Management," *Proceeding of 2002 IEEE workshop on Information Assurance United States Military Academy*, West Point, NY June 2002

Hyeung-sik J.Min, Walter Beyeler, Theresa Brown, Young jun son, and Albert T.Jones. "Toward modeling and simulation of critical national infrastructure interdependencies," *IIE Transactions*, 39:57-71 (2007).

James Ellison. "Modeling the US Natural Gas Network," Sandia National Laboratories

James Peerenboom, Ronald Fisher, and Ronald Whitfield. "Recovering from Disruptions of Interdependent Critical Infrastructures," *prepared for CRIS/DRM/IIIT/NSF Workshop on Mitigating the Vulnerability of Critical Infrastructure to Catastrophic Failures*, Virginia, September 2001

Jeffrey Hunker, "Policy challenges in building dependability in global infrastructures," *Proceedings of Compsec 2002*, London, October 2002

John D. Sterman. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. New York: McGraw-Hill, 2000

Louisiana Geological Survey (LGS), "Louisiana Industry Petroleum Facts," Feb 2000
<http://www.lgs.lsu.edu/pubs/2oilgasfacts.pdf>

Munaf Aamir, Diana Damyanova, Mark W. Nichols, Micheal J. Radzicki, and Esra Unluaslan. "Rebuilding New Orleans: An Agent-Based Modeling Approach,"

Pengcheng Zhang, "Dynamic Game Theoretic Model of Multi-Layer Infrastructure Networks," *Proceeding of 10th International Conference on Travel Behavior Research*, Lucerne, August 2003

Roger Smith. "Complexities of Simulating Domestic Infrastructure Protection," Titan Systems Corporation, *Proceedings of Simulation Interoperability Workshop*, (Fall 2002)

Saifur Rahman, "Critical Infrastructure Dependency: A View from the United States," *Proceeding of European Critical Infrastructure Protection Workshop*, Frankfurt Germany, September 2003

SEDA Renewable Energy & Cogeneration, "Hydro Power," September 2006
http://www.seda.nsw.gov.au/ren_hydropower_body.asp

Steven M. Rinaldi., Peerenboom, J. and Kelly, T. “Identifying, understanding, and analyzing critical infrastructure interdependencies,” *IEEE Control System Magazine*, 21:11-25 (2001)

Steven M. Rinaldi. “Modeling and Simulating Critical Infrastructures and Their Interdependencies,” *Proceedings of the 37th Hawaii International Conference on System Sciences*. Big Island. HI, 2004.

Susan S. Hutson, Nancy L. Barber, Joan F. Kenny, Kristin S. Linsey, Deborah S. Lumia, and Molly A. Maupin. “Estimated Use of Water in the United States in 2000,” U.S. Geological Survey, Feb 2005

The Urban Land Institute (ULI), “A Strategy for Rebuilding New Orleans, Louisiana,” http://law.wustl.edu/landuselaw/Articles/ULI_Draft_New_Orleans%20Report.pdf

U.S. Department of Transportation, “Status of Transportation-Related Recovery Efforts,” <http://www.nhtsa.dot.gov/USDOTReliefSite/>

U.S. Department of Transportation, “Louisiana Transportation Profile,” 2002 http://www.bts.gov/publications/state_transportation_profiles/louisiana/index.html

Wenjum Zhang. “Models that Simulate Critical Infrastructure Networks,” *Report of Joint Infrastructure interdependencies Research Program Symposium*. Ontario, 10 November 2005 http://www.psepc.gc.ca/prg/em/jiirp/_fl/report-en.pdf

William Wimbish, Jeffrey Sterling. “The National Infrastructure Simulation and Analysis Center,” *Issue paper of Center for Strategic Leadership U.S. Army War College*, Volume 06-03, August 2003

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 074-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.				
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (DD-MM-YYYY) 23-03-2007		2. REPORT TYPE Master's Thesis		3. DATES COVERED (From - To) March 2006 - March 2007
4. TITLE AND SUBTITLE CRITICAL INFRASTRUCTURE REBUILD PRIORITIZATION USING SIMULATION OPTIMIZATION			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Namsuk Cho., Captain., ROK Army			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way, Building 641 WPAFB OH 45433-7765			8. PERFORMING ORGANIZATION REPORT NUMBER AFIT/GOR/ENS/07-04	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) None			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.				
13. SUPPLEMENTARY NOTES				
14. ABSTRACT This thesis examines the importance of a critical infrastructure rebuild strategy following a terrorist attack or natural disaster such as Hurricane Katrina. Critical infrastructures are very complex and dependent systems in which their re-establishment is an essential part of the rebuilding process. A rebuild simulation model consisting of three layers (physical, information, and spatial) captures the dependency between the six critical infrastructures modeled. We employ a simulation optimization approach to evaluate rebuild prioritization combinations with a goal of minimizing the time needed to achieve an acceptable rebuild level. We use a simulated annealing heuristic as an optimization technique that works in concert with the rebuild simulation model. We test our approach with three disaster scenarios and find that the initial rebuild strategy greatly impacts the time to recover. With respect to the scenarios tested, we recommend a rebuild strategy and areas for further investigation that may be of use to disaster and emergency management organizations.				
15. SUBJECT TERMS Critical infrastructure rebuild modeling, Simulation optimization, Simulated annealing				
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT			c. THIS PAGE
U	U	UU	177	19b. TELEPHONE NUMBER (Include area code) (937) 255-3636 (emailname@afit.edu)

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

