An Agent-Based Model of the effect of Cyclone Vardah on Chennai's Electricity Grid

A project report

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MASTER OF ARTS

Submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **An Agent Based Model of the effect of Cyclone Vardah on Chennai's Electricity Grid** submitted by **N Chandrasekhar Ramanujan (HS12H014)**, to the Department of Humanities and Social Sciences, Indian Institute of Technology Madras, Chennai in partial fulfillment of requirements for the award of the degree of Masters of Arts (Development Studies), is a bona fide record of the research work done by him under my supervision. The contents of the thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or Diploma.

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Abstract:

KEYWORDS: Agent Based Modeling, Disaster Management, Emergence, Energy Studies

This project applies agent-based modelling (ABM) to understand the effect of cyclone Vardah on Chennai's electricity grid.

The first part of the project focuses on an Agent-Based model of the collapse of Chennai's electricity grid due to Cyclone Vardah. It finds that the cascading power failures caused in part by Cyclone Vardah are responsible for the complete collapse of the grid inside two hours. Further, this project finds that the speed and intensity of the collapse depends on which part of the grid is struck first by the cyclone. It also finds that certain parts of the grid, when attacked, lead to rapid collapses in overall power supply. This could not have been determined from seeing the individual parts of the grid. Therefore it concludes that this is an emergent phenomenon of the model.

Next, this project discusses the features of a bottom-up model that simulates a socio-technical system comprising energy producers, consumers, power-lines, decision makers, and disaster response authorities. Such a model should be able to provide some understanding of any emergent patterns caused due to the interaction of the various agents inside the simulation environment.

This project then discusses the possible uses of these models as disaster management simulation tool that can be used by policy-makers to plan for various possible scenarios.

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The Thesis

Introduction

Context

Our national security, economic prosperity, and societal well-being depend on what Steven Rinaldi calls “critical infrastructures” (Rinaldi 2004). Given how important it is that they continue to operate securely and reliably, policymakers need to understand the behavior of these infrastructures, especially when they come under stress.

The electricity supply can arguably be said to be the most important of these critical infrastructures. It is required for most household activities, for telecommunications networks to function, entertainment needs, economic productivity, and mass transport. Our banking and digital payment systems as well cannot operate in the absence of electricity.

Electricity is the critical infrastructure most vulnerable to disruption from all kinds of failure modes, from terrorist attacks and excessive consumer demand to damage caused due to extreme weather events.

On 12 December 2016, one such extreme weather event, later designated as cyclone Vardah hit Chennai. The city was lashed by winds that blew at speeds of up to 140 kilometers per hour. (Punit, 2016). About 20,000 people were evacuated and 18 people were killed. Power and telephone lines were uprooted and many localities were left without power for several days.

Given Chennai’s location and its proximity to various ocean currents and weather systems in the wider Bay of Bengal area, cyclones of similar or greater magnitude are more likely than not to occur again in the future (Ranga Rao et al. 2012), with similar disruptions to the electric system, and concurrent knock-on effects on industries, services, payment & telecom systems etc.

Conceptual Motivation

In the social sciences, there is a growing interest in trying to use some form of assemblage theory to understand the connections between individual entities/ actors and their emergent collective formations. (Hoffman et al 2016, Canniford & Badje 2016)

If we could develop a tool that could help policymakers understand possible threats to the electricity grid from various disruption vectors, then we would go a long way in ensuring that power outages of the scale that we witnessed during Vardah (and all too many times before: Phailin, Thane and Chennai rains) are not repeated again.

Chapterisation

Chapter 1 is a literature review of concepts that are salient to this thesis, and aims to build a grounding to build the thesis on. It begins with a brief overview of complex systems and agent-based models. Then it gives a brief overview of disaster response simulations. Then it discusses the theoretical concepts that underpin this thesis, placing them under the broad rubrics of Socio Technical Systems theory, Assemblage Theory, and Emergence Theory.

Chapter 2 discusses the events of Dec 12-15 2016, and attempts to answer the question; What happened during Cyclone Vardah? Then it attempts to put Cyclone Vardah in context by examining the literature on cyclones, and comparing it to other similar disasters. It then discusses the impact of Cyclone Vardah on Chennai's electricity grid, and again refers to the literature to talk about the effect that cyclones normally have on electricity grids.

Chapter 3 discusses a simple agent based model of the collapse of Chennai's grid due to Cyclone Vardah. It focuses the construction and the results obtained from the model. It then focuses on where future iterations of the model may be taken

Chapter 4 describes a simple agent based model of the response to the disruption caused by Cyclone Vardah to the electricity grid in Mylapore, Chennai. This model seeks to comprise energy producers, consumers, power lines, decision makers, and first responders. This chapter seeks to encompass all aspects of the modeling process, from problem formulation and actor identification to software implementation, data analysis and model validation.

Chapter 5 intends to discuss the usage of the model as a tool to support decision making by policymakers. It refers to the literature again to describe possible scenarios in which the model may be used. Then the chapter discusses the benefits and learnings obtained from applying systems thinking to this problem.

Chapter 1: Literature Review

Introduction to Complex Systems, Agent Based Models and Emergence

A model is "a simplified representation of reality" (Varian 2016, 4) which seeks to approximate an event or a system. A simulation in turn, is an activity that allows for repeated observations of a model under various parameters.
Complex systems feature a lot of components which interact with each other. The aggregated activities of these components can be said to be non-linear.

This means that summation of the activity of individual components cannot be used to derive the activity of the system. The whole is literally more than the sum of its parts. Complex systems can be found everywhere on earth, including Earth's climate, social and economic organisations etc.

An Agent-Based Model is a computational model which simulates the actions of, and the interactions between discrete autonomous agents. This is done in order to assess their effect on the system as a whole. These agents have specified attributes and behaviours and could be individuals such as people, cars etc. These agents create patterns in time and space that could not have been foreseen earlier.

This is due to the concept of **emergence**. When a system as a whole displays a particular pattern which is not immediately obvious from the rules at a micro level, the behaviour is described as emergent. (Sawyer 2005)

This overall behaviour is by definition not explicitly nor implicitly built into the model. By contrast, conventional top-down modelling techniques (eg Dynamic General Equilibrium models) assume macroscopic behavior by definition. The bottom-up, agent-based approach does not make these sorts of assumptions and hence the model can give greater insight into causality!

Disaster Response Simulations in Theory

Disaster Response is the second stage of the series of preventative, reactive, and mitigative measures known as "The Disaster Management Cycle" (Vasilescu et al. 2008). It can be characterised as an "aggregate of decisions and measures" (businessdictionary.com) which aim to restrict the effects of a disaster or any similar calamitous event.

The aims of these various measures include avoiding further casualties and property damage, the restoration of order (or more broadly, normal system functionality), and to restore critical services, and help the community recover.

Such efforts would therefore require "Information exchange, coordination between the participating entities, allocation of available resources and decision making" (Filippoupolitis et. al. 2008, 1) in order to be optimally implemented.
Simulations, with their ability to quickly (and cheaply) model a range of possible situations, are therefore well-suited for this task.

Jain and McLean classify disaster modeling and simulation tools into 5 types, 2 of which directly lend themselves to disaster response simulations. Those 2 are:

- Emergency Response Planning Tools: Which "allow evaluation of alternative strategies to respond to a disaster event" (Jain and McLean 2003, 3). They can either allow the operator to input the various possible impacts of disaster events, or they themselves have the capacity to model the impacts of various disasters.

  Many of these models use Geographical Information Systems (GIS) in order to give the user a spatial understanding of the disaster and overlay onto a map. These can be used to identify populations and critical infrastructures that are immediately vulnerable, or liable to be affected subsequently. This kind of tool is used by decision makers. It presents the overall scenario and is intended to evaluate how the user makes high level decisions at a macro level. These high level decisions can include how, where and when response units are deployed.

Harald Rohracher explains that such simulations become useful in scenario planning exercises because they

> "help to generate and integrate knowledge about complex future states and developments of the system and its contexts, discuss interrelationships, uncertainties or inconsistencies.. (and) also contribute to building competence of the actors involved, facilitate and organise team work (e.g. enable negotiating different viewpoints) or counsel decision makers. (Rohracher 2008, 153)

Examples include the DRILLSIM project (Balasubramanian et al. 2016) which aims to simulate a hazardous materials situation over a large city.

- <u>Simulation Tools For Emergency Response Training</u> are tools which are used primarily for training and education purposes.

  They work in two possible ways; the first being to imitate the effect possible situations and present them to responders in order to "improve their capabilities for emergency response." (Jain and McLean 2003, ibid.). Such simulations operate at an individual level, using technologies such as virtual and augmented reality that allow a responder to act as if he or she is present at the site of the disaster in real time.

  Examples of such tools include BioSimMER, a virtual reality environment that trains first responders in responding to Bio-Warfare scenarios (Stansfield et al. 1998). Hsu et al. discuss how the New York City Office of Emergency Management built a virtual replica of New York City that was buffeted by

Earthquakes. Trainees assume the role of paramedics, police officers etc. who are tasked to restore order and provide first aid in the immediate aftermath. (Hsu et al. 2013)

Socio Technical Systems as applied to the electricity grid

When we think about the electricity grid, we are tempted to see it only in terms of electrons passing through wires. This is not the case. The electricity grid as we know it today is a system constituted of a "constellation" of actors, machinery, and political influences all working together in various ways. This way of thinking has been codified using the "socio-technical systems" framework.

Socio-technical systems have been defined by Neville Stanton as

> "A descriptive term given to any practical instantiation of social and technical elements engaged in purposeful, interacting and goal-directed behaviour" (Stanton et al. 2009, 114)

They go on to note the key features of these systems as follows, highlighting that Socio-Technical Systems:

- Are "characterized by communication and processing of information" (p.115)
- Recognise that "artifacts as well as people can communicate, hold and process information"
- Act over time, hence they can be described as dynamic in nature

Edward Cohen-Rosenthal further points out that socio technical systems theory recognises the fact that such systems (here defined as organisations, infrastructures etc) are bounded, and that any interactions or transactions "occur within the system (and its sub-systems) and between the wider context and dynamics of the environment" (Cohen-Rosenthal 1997, 10)

Harald Rohracher describes energy systems as,

> "Socio-technical arrangements with a strong interrelation of technological and social elements such as institutions, regulations, cultural values, social practices as well as interests, expectations and relationships of the actors involved." (Rohracher 2008, 144)

He further elaborates this definition later on, defining energy systems as "socio-technical configurations" where:

> "institutional arrangements (e.g. regulation, norms), social practices and actor constellations (such as user–producer relations and interactions, intermediary organisations, public authorities) mutually depend on each other, and are embedded into broader contexts of cultural values, socio-economic trends (globalisation, individualisation, etc.). (ibid. 147)

In *Networks of Power* Thomas Hughes examines explicitly "electrical" systems, postulating that the way they manifested was not any inevitable fact of mechanical or scientific necessity. Instead, they were shaped by the prevailing political and geographical forces of the day. (Hughes 1993)

There are differences in which the grid evolved between various cities based on factors such as the structures of the governments which exercised jurisdiction over them. He gives two major examples of Chicago and London. In Chicago, because of pre-existing relationships and goodwill between industrial business and local politicians, a single unified system developed quickly.

Meanwhile in London, development slowed a little because of how the government there was stratified into multiple wards. Because of that, the electrical system was run by many companies, and there was no technological standardization of any kind.

In India, the electricity infrastructure system comprises of a network known as a "grid". This grid connects power stations, and other sources of power such as solar farms, wind farms etc with consumers.

As Min 2016 points out, India's power grid is "among the most intricate in the world" (p 40), with "4 million transformers along some 4.5 million miles of transmission and distribution lines" (ibid)

I follow on Hughes' description of electrical grid as a system which consists of various technological "artifacts" which are interconnected and interdependent on each other. Further, his incorporation of local, regional, and national level political structures, perceived (and manufactured) societal need, and geographical features as units of analysis are very useful for the modeling that I plan to do.

The various components of the electrical grid as a technical system include overhead lines and underground cables which carry electricity, substations where overhead lines and underground cables are connected, transformers which connect the various components of the network which are operated at different voltages, metering equipment, centralized control centres and control systems, etc.

The components of the electricity grid as a social system include consumers, utility employees, call centre operators, policy makers and local media/journalists.

According to the electricity grid act of 2003, the transmission network and distribution network have been split into two different entities, TANGEDCO and TANTRANSCO.

TANGEDCO is the Tamil Nadu Generation and Distribution Company. It comprises of the power stations and power plants as well as the low voltage parts of the grid system which transmit lesser amounts of power from the transmission system to consumers. TANTRANSCO stands for the Tamil Nadu Transmission Company. It handles that part of the grid which operates at high voltages in order to transmit large amounts of electricity over long distances between power stations and load centers.

Assemblage Theory and the Electricity Grid

Donna Hoffman describes assemblage theory as:

> “a non-human-centric comprehensive theory of social complexity from the neo-realist school of philosophy which explains the processes by which the identity of a whole, a whole that is more than the sum of its parts, emerges from the on-going interaction among its heterogeneous parts” (Hoffman et al 2016, 4)

This theory stands is useful because of its unique perspective on how the world works. It argues that heterogeneous components of a system of any kind come together to combine a kind of gestalt entity that is called an assemblage. The scope of an assemblage ranges from the individual (our personalities as an assemblage made up of emotions,) to the collective (political institutions, societies etc)

Jane Bennett applies Assemblage theory to the study of the electricity grid, in a chapter of her book “Vibrant Matter” that studies of the great North American blackout of 2004 and outlines the various actors and “actants” whose emergent interactions led to it. These include the workers in various power plants, to the decisions of the Federal Electricity Regulatory Commission. (Bennett 2009)

Chapter 2: Cyclone Vardah in Context

<u>What happened during Cyclone Vardah?</u>

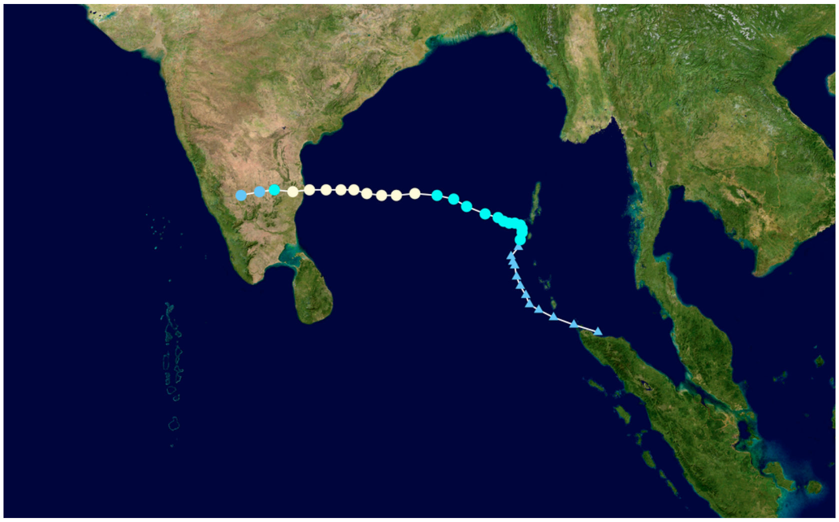


Fig 2.1: The path of Cyclone Vardah. Source: Public Imagery from NASA TERRA satellite, 2016

Cyclone Vardah originated as a low-pressure area near Sumatra and from there proceeded to move west towards the Bay of Bengal, gathering strength as it did so. It was finally classified as a cyclone by the Indian Meteorological Department on Dec 8 2016, and made landfall on Dec 12, 2016.

As to its effect on the electricity grid, 3400 electricity poles fell due to cyclone Vardah, and 30 transformers shut down due to lack of supply (Press Statement by POSOCO, 13 December 2016)

3 units of the North Chennai Thermal Power Station (NCTPS) tripped because of heavy winds while 2 220MW units at Madras Atomic Power Station (MAPS) also stopped operating on Dec 12. However, the death toll was relatively marginal, with 18 people killed due to Vardah-related incidents. The government worked to evacuate over 20,000 people from the coast and low-lying areas in preparation against the disaster. (Punit 2016)

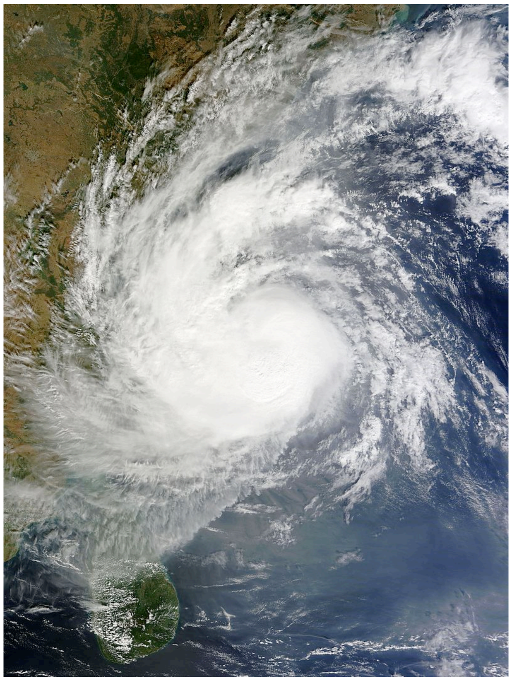


Fig. 2.2: Satellite image of Cyclone Vardah over Chennai. Source: Public Imagery from NASA TERRA satellite, 2016

Cyclone Vardah in Context

What is a cyclone? Shannon Doocy and her colleaguues define tropical cyclones/typhoons/hurricanes as "a non-frontal storm system that is characterized by a low pressure center, spiral rain bands and strong winds" (Doocy et al 2013, 1).

These inflict damage to the built environment and citizens via three major forces, namely high speed winds, (155 mph to kmph), storm surges where the sea level rises as much as 10 metres and lastly, floods due to the extreme precipitation events that normally accompany cyclones.

Vardah was not particularly unique as cyclones go, in terms of its origin and physical characteristics. But in order to understand why it did so much damage, we need to refer to the literature. Irene Ayala states that the impact of natural disasters such as Vardah is greater in developing countries due to two factors, the first of which is the relationship between the geographical location and the geological/geomorphical settings of the affected areas. This means that developing countries are much more likely to be situated in areas vulnerable to seismicity, volcanic activity, and flooding (Ayala 2002).

The second reason that she states for the disproportionate impact of disasters is tied into the economic and historical contexts of these countries; without institutions and state entities capable enough to plan for and coordinate against natural disasters, their vulnerability in turn increases.

S. Raghavan and S. Rajesh contradict this. They claim that economic and demographic characteristics are more significant in determining vulnerability to tropical cyclone damage than than any meteorological or geological factors. (Raghavan & Rajesh 2003)

They build upon existing work that attributes the cause of increasing hurricane damages to economic inflation, population growth, and the "increased wealth of people in the coastal areas" (Pielke & Landsea 1998). They then quote that work again when they summarise this phenomenon as "Coastal residents today have more to lose"

Impact of Cyclone Vardah on the electricity grid

Mathaios Panteli and Pierluigi Mancarella characterise cyclones, storms and other extreme weather events as "one of the main causes of wide-area electrical disturbances worldwide" (Panteli & Mancarella 2015, 260). A lot of work has been done on the effect of the weather on the electricity grid and the reliability of the power supply. The larger consensus is that "extreme weather events have a significant influence on the reliability and operation of electrical components, and in turn on the resilience of the entire power infrastructure" (ibid).

David Ward summarises the potential threats to electricity infrastructure from extreme weather events by highlighting specific problem areas:

1. High speed winds during storms and hurricanes lead to faults (defined here as "any unplanned event that causes a circuit or an item of equipment in a network to be switched out of service: (Ward 2013, 105) and debris/trees being thrown against overhead transmission and distribution lines!

2. Water from rain-related precipitation does not normally pose a danger to overhead transmission lines. However this can damage equipment found in substations that can include control cubicles and the switching equipment found therein.
3. However, when rain, strong winds, and lightning are combined, together they can pose a threat to overhead lines.[1]

How do you plan for it? The TNEB's response to the cyclone was reactive. I was told that the sheer intensity of the cyclone meant that the damage was unpredictable. The TNEB's standard operating procedure was reactive in nature; it used to wait for the damage to occur, and then respond. In this, it had surprisingly a lot in common with other electricity utilities around the world (Ward 2013)

In my interview with Mr John, an engineer for the Tamil Nadu Electricty Board, I was able to put together a coherent account of the disaster relief efforts during the cyclone.

During cyclone Vardah, no capital equipment (i.e machinery used to produce and treat electricity, like generators and transformers) was damaged. Instead the bulk of the damage happened to the transmission lines, especially the extra high voltage (230 kV) lines. The towers that housed these were hardest hit, with 61 of them collapsing. In addition to collapse, their conductors snapped and the insulators were damaged, slowing repair work.

The impact on the utility, he told me, was largely from the transmission side. There was no effect on the generation capability, as without transmission capability, there was no load to generate for. As power plants cannot generate electricity without a grid capable of carrying the load (a process known as "feeding the load" the power plants shut down.

There are three kinds of power lines operated by TANTRANSCO, the electrical power transmission system operator owned by the Tamil Nadu government. They operate at 400 kV, 230 kV and 110 kV respectively. There was no major damage to the 400 kV lines.

[1] This phenomenon, where the individual actants by themselves do not have an effect on the system, but together create feedback loops that propel it out of equilibrium, may be a topic of interest to complexity scientists as well!

Only one feeder line (which connects consumers to a substation) was damaged.

The bulk of the damage to the transmission system happened to the 230 kV and 110 kV lines. Further, the distribution system (which is the last mile component of the electricity grid that actually touches consumers), specifically the 33 kV lines bore the brunt of the cyclone damage. Around 14 to 16 transmission system poles/towers had been affected by the cyclone as opposed to about a 1000 distribution poles.

As a result, access to consumers was disrupted for anything between 36 hours to 5 days, in some outlying areas, extending up to a week.

<u>Relief Measures undertaken by TNEB</u>

The cyclone hit Chennai on Monday, December 12. However, the TNEB could only start to ascertain the situation, and come to know the real effect of the damage on the morning of Tuesday, December 13. Given the damage to the infrastructure, the TNEB had to bring in manpower from other districts to restore the transmission system. The primary way in which they did this was via a line patrol where a TNEB team was sent along with a local representative (such a municipal ward councilor)

My interview with Engineer John of the TNEB gave me a detailed overview of the response to the disaster, as well as an example of one of these line patrols worked.
The 230 kV lines were carried by large towers made of steel. If the patrol ascertained that there was damage to the tower, due to which the line was disrupted, the action they would take would depend on how the tower got damaged. If the top cone alone, which carried the conductors and insulators which attached the line to the tower, was damaged, then it was a relatively easy 2-day fix by contractors. However if the tower itself had been uprooted from the ground then that would be a different story. They would need to build an entirely new tower on an adjacent location, since the downed towers were not easily moved.

Towards that end, the TNEB kept a stock of quick setting concrete and other construction materials on hand. They also got spare towers on a loan basis from adjoining districts. Another factor that determined how easy it would be to restore transmission towers was the nature of the terrain; if the failure happened over hilly terrain or a water body, the difficulties involved in fixing the tower were compounded.

The engineer gave me another example; especially in Chennai, the electricity board needs to get permission from landowners before they can place an electricity pole or tower on someone's property. As a result, a large number of towers were placed on canals, lakes etc which were technically government property. This would come back to haunt the TNEB later. Engineer John's team ran into great difficulty in fixing an electricity tower that had collapsed in a canal near the Perungudi lake in South Chennai. They needed to pull the wire on top of the tower taut into the insulator in order to get the downed line to carry an electric load. However, as this downed tower was in the middle of the canal, they had no way of applying enough leverage to accomplish their goal. In the end, they improvised by commandeering a boat from a local fisherman, installing pulley on it, and running a rope from the top of the tower through the pulley on the boat, and towards TNEB staffers on shore, who could then apply even force. It took two days for the TNEB to restore that single tower alone.

For the first two days, the TNEB had a communication problem. The telecom towers were down because there was no electricity. However, their prior experience of the Chennai Rains in 2015 had given them experience of the communications going off. They were able to procure walkie talkies and give them to the Junior Engineers in order to coordinate between substations.

The TNEB worked to restore electricity first to the Poes Garden area where the majority of politicians and bureaucrats lived. Then, working with the ward councilors and various other local politicians, they coordinated repair efforts across the whole of Chennai.

Chapter 3: Cyclone Vardah – A Model of Electricity Grid Collapse

Problem Formulation and Actor Identification

The modeling process cannot be initiated without a problem that we need to solve. Most problems manifest as a gap in our knowledge of how a real-world system functions, the ways in which it can behave, or the way in which it responds to particular interventions. (Nikolic et al 2013). We need to keep the ultimate objective of the modeling exercise in mind as we proceed. Said objective being, as Richard Hamming puts it, “insights” as opposed to “numbers”. (Hamming 1962)

Models, especially Agent-Based ones, are tools that we (academicians, policymakers) can use in order to better understand the dynamics of complex systems and their component subsystems, to discern larger patterns in their operation that were previously invisible to us (emergence), and to explore possible futures/what-if scenarios.

To that end, we need to answer several questions before we begin developing the model. What is the problem? Whose problem are we addressing? What all actors are involved in this problem? What is our role?

Problem Definition

Electrical Grids can be broadly characterised as networks whose edges carry electricity from producer nodes to consumer nodes. Edges can be disrupted due to any number of causes. Disrupted edges shift their loads to nearby edges, and those nearby edges end up pushed beyond their capacity, becoming overloaded.

This sets of a chain reaction, like the ripple of water on the surface of a pond, until the system reaches a state where “substantially all the elements… are compromised and/or the system becomes functionally disconnected from the source of its load” (Kaboli and Oraee 2016, p.305).

In this case, the aim of the simulation is to create a model of the cascading collapse of Chennai's power grid due to a cyclone or similar such extreme weather event.

Outlining Role of Actors

The main problem owner is the Tamil Nadu Electricity Board, which governs the functioning of the power grid.

Role of Modeler

What the modeler does is gather knowledge from the literature, field excursions, and interviews with domain experts, and system stakeholders and relevant actors in order to create the model.

System Identification and Decomposition

The next step after formulating the problem is to decide the boundaries of the system as well as what it is composed of.

Inventory of Physical and Social Entities in the System

This phase seeks to set out in explicit terms who the physical and social entities in the system are, and what the links between them are.

The electricity transmission system of Chennai is represented by a set of nodes that are connected by edges. The nodes can behave either as sources of electricity (i.e they are stand-ins for the actual power plants) or sinks (acting as proxies for sources of power demand, represented by substations and feeders). The electricity is carried from the source nodes to to the sink nodes via edges. The edges have a specific capacity of load that they can carry, and once that is exceeded they are more vulnerable to failure due to overload.

These edges are also vulnerable due to possible damage from Cyclone-related incidents (trees falling on lines, collapse due to high windspeed etc.)

Identifying the External World

The external world in this case is largely the Chennai metropolitan area, comprising of the various infrastructures within it (sourced from TNEB Grid Map).

Concept Formalisation and Model Narrative

At each tick of the simulation (roughly equivalent to one minute in real time), before cyclone Vardah hits, the grid is in equilibrium; energy demanded is equal to energy supplied. There is a random chance that, first; Cyclone Vardah makes Landfall and affects a part of the grid, and second; a random edge of the network will collapse due to Vardah-related damage. The locations of the various nodes are represented by a GIS overlay over the simulation display, and with the help of the TNEB's grid map. There were 100 nodes to represent Chennai's electrical grid.

Once cyclone Vardah makes landfall, the first condition is rendered false and only the second condition holds.

After a random edge falls to Vardah, neighbouring edges end up carrying more load and are susceptible to failure. The At the end of every tick, the power supply, i.e the amount of current that the undamaged parts of the current carry, is calculated by the model.

A visual explanation of the model's functioning, and the pseudocode demonstrating the model's architecture may be found on the following pages (Figs 3.1 and 3.2)

Software Implementation

This model has been implemented using Netlogo, which is an object-oriented programming language developed especially for Agent-Based Modelling. (Wilensky 1999) It uses aids for visualization, GIS overlay and data analysis. There are no specific hardware requirements. The model is designed to be run on any personal computer. It is based on the "Power Grid" model by Thomas Reith (modelingcommons.org, 2016)

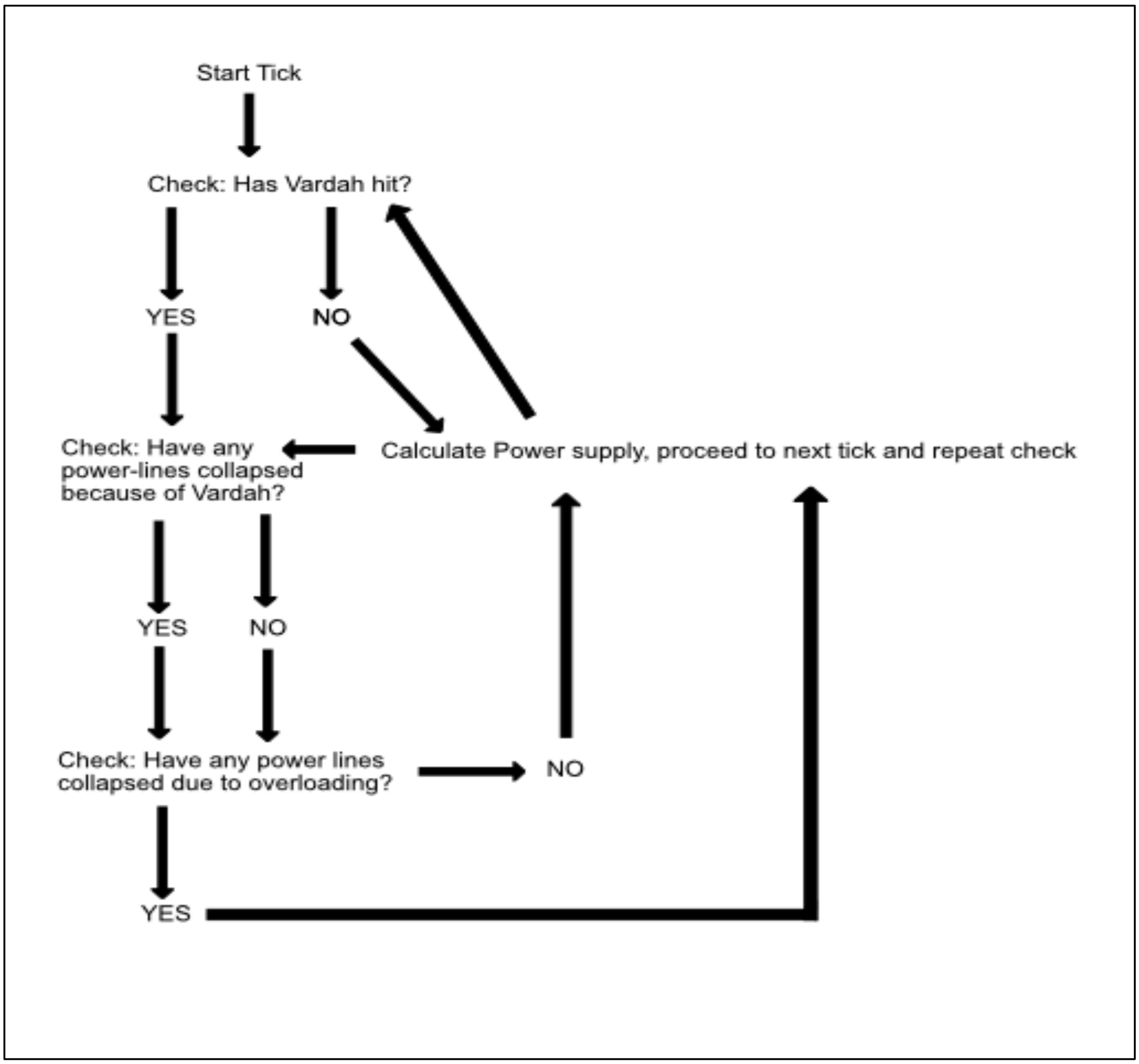


Fig 3.1 – Flowchart showing the sequence of actions during one tick of the simulation

```
Initialise Simulation

Load Chennai-Map-Overlay
Load pre-saved-grid

Pre saved grid consists of 100 nodes connected to each other by 350 edges.

At every tick, report-power-supply

Power-supply = value of energy carried by functional edges

Start-tick

      check if random-Cyclone-Vardah-has-made-landfall = true
       if random-Cyclone-Vardah-has-made-landfall = false
end-tick

if Cyclone-Vardah-has-made-landfall = true
                     report Vardah-started = true

      then,

      at-every-tick check if random?edge fails-due-to-Vardah

      at-every-tick check if any?edge-overloaded

      edge-overloaded if any?edge reports carrying load> 4*capacity-of-edge

      if edge-overloaded then kill-edge
```

Fig 3.2 - Grid Model Pseudocode

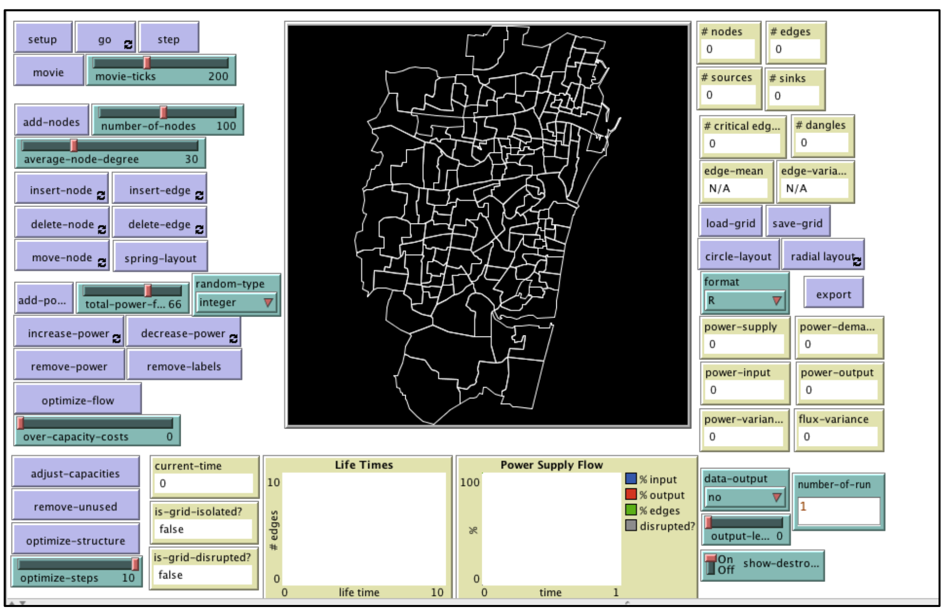


Fig 3.3 – The simulation interface before the grid is overlaid and the simulation is initialized. Note the vector map of Chennai's various wards as a visual aid (ArcGIS.com)

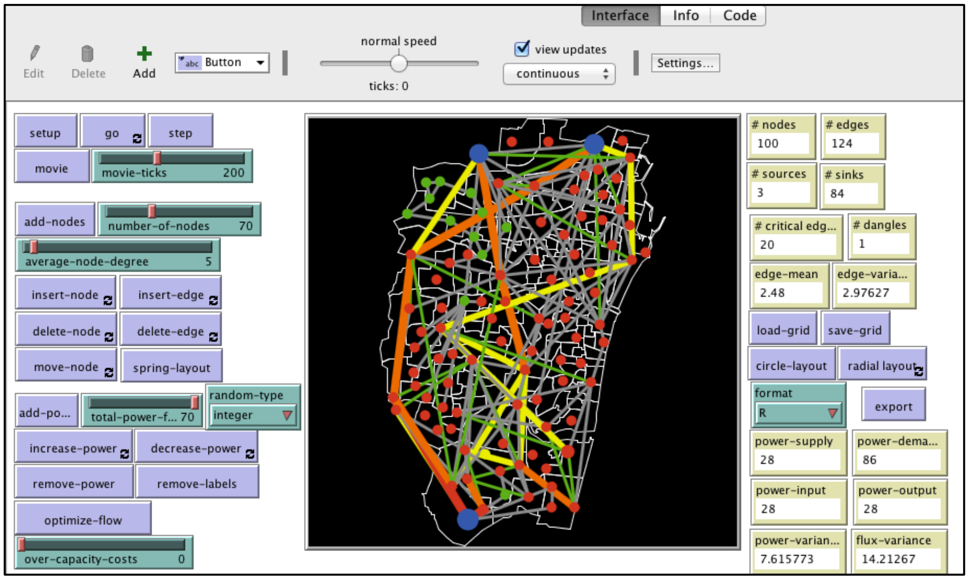


Fig. 3.4: *The simulation while it is running. The colour denotes how overloaded a particular edge is. Red (not shown here) means that an edge is critically overloaded and about to collapse.*

<u>Experimentation, Analysis, and Results</u>

A Monte Carlo experiment was run. The simulation was run one hundred times in NetLogo's "BehaviourSpace" environment. Each iteration varied randomly based on which part of the grid was first to fall to the effect of the cyclone.

The electricity grid collapsed completely (i.e the grid was completely disconnected from the source of the load) in anything between 85 and 102 minutes. The time taken before fifty percent of the grid could collapse ranged between 54 and 74 minutes, depending on where the cyclone hit.

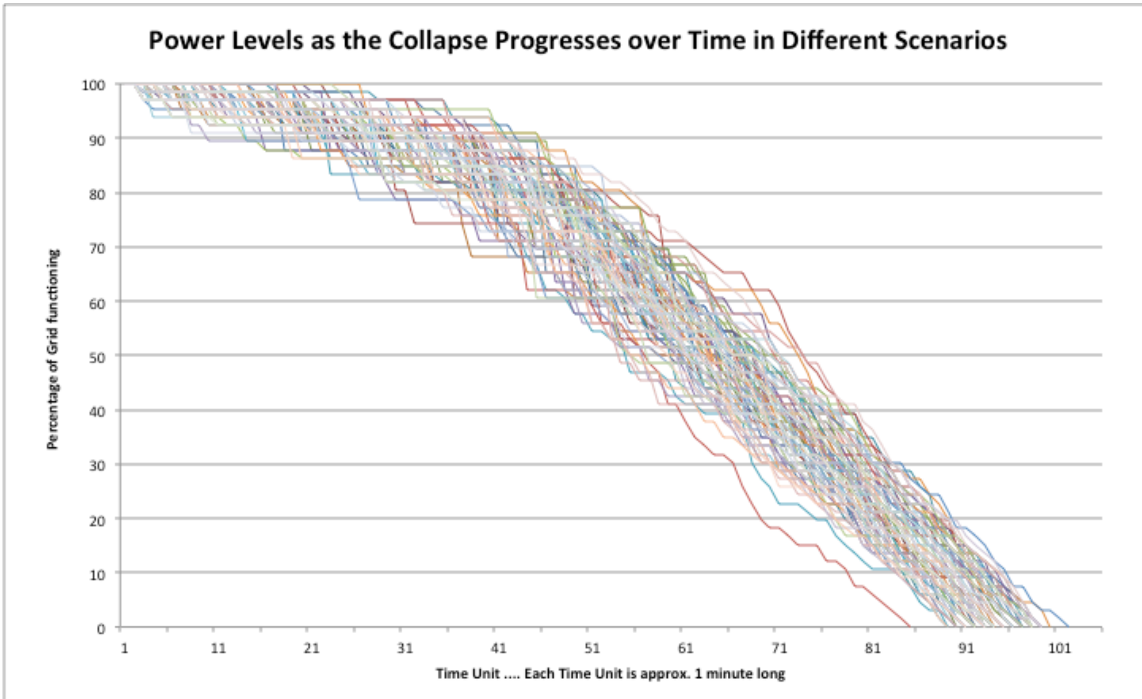


Fig 3.5: Chart showing how the percentage of grid functioning (i.e amount of current in the grid) comes down over time in all runs of the Monte Carlo Simulation

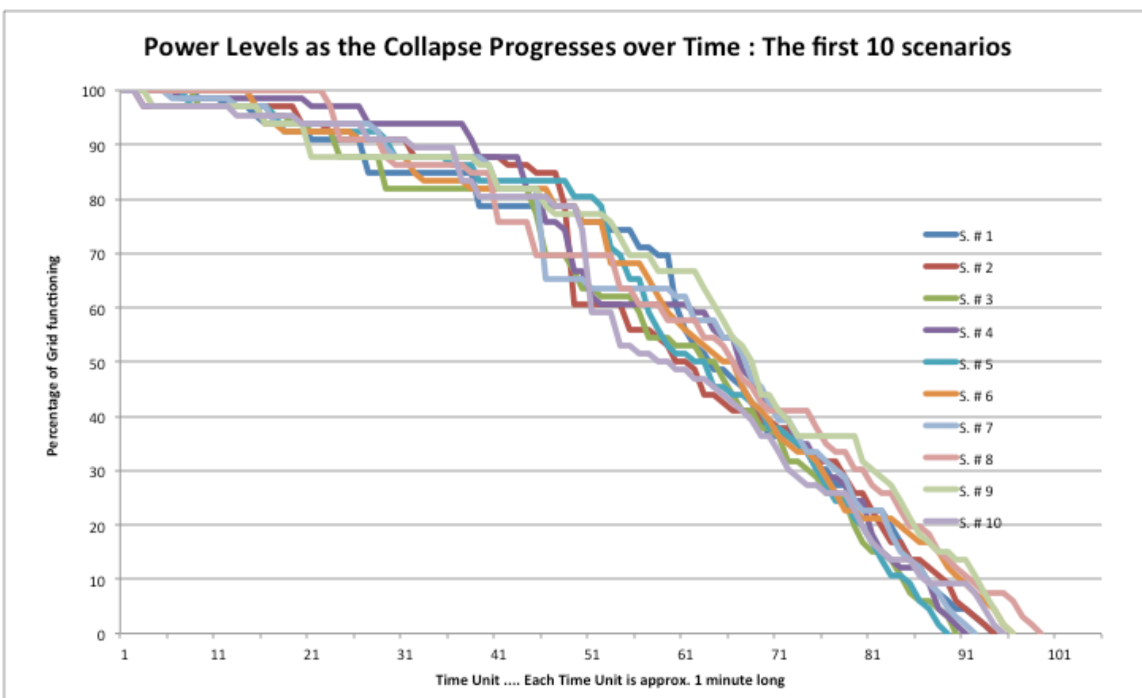


Fig 3.6: Chart showing first 10 runs of the Monte Carlo Simulation

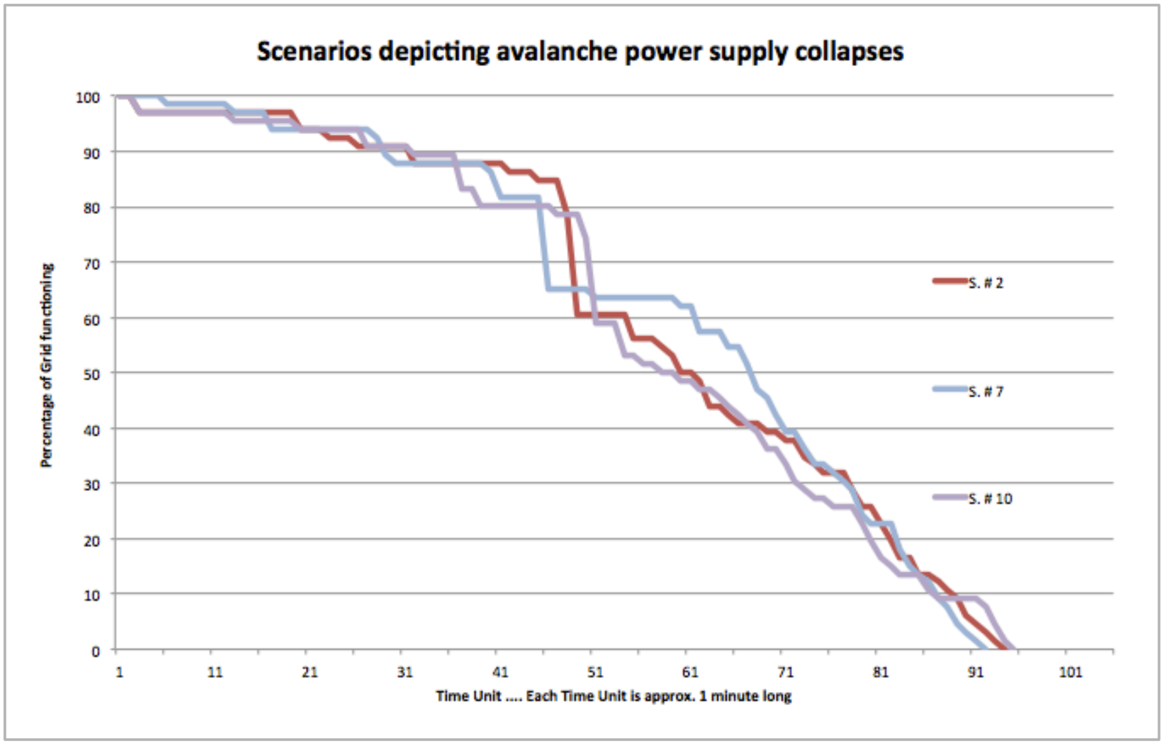


Fig 3.7: Charts showing examples of iterations where Avalanche collapses are present

The results of the experiments reveal two emergent patterns.

First, we see differences in collapse patterns based on which part of the grid the cyclone struck. This difference is important, since based on which part of the grid is hit first, the grid might take up to twenty more minutes before it can collapse completely, allowing first responders to take emergency measures as needed.

Second, in several iterations of the simulation, we see that the power supply in the grid falls off suddenly and precipitously. This is also known as an “abrupt” cascade failure (Pahwa et al. 2013). The reason for these avalanche collapses seem to be that important “hub” nodes which held the grid together, were hit by the twin effects of the cyclone and the overloads. They then ended up getting isolated from the rest of the network, leading to a sudden drop in power demanded, which in turn meant the power supplied went down too.

Scope for Further Work

More dimensions of the electricity grid may be modeled in later iterations of this simulation. The model as it currently is works as constant power-drawal load, adjusting properties such as resistance and voltage to ensure that the amount of power (i.e the product of voltage and current) in the system is constant. There are other ways of modeling loads, depending on which the network behaviour will change. This demands further investigation.

Another limitation of this simulation is that actual power grids have mechanisms that work to isolate certain parts of the grids, such as overload relays. Such mechanisms end up reducing the probability of a grid collapse, by isolating faults and reducing the amount of load on the system.and slows down the speed of the collapse. I plan to implement these in post-thesis iterations of this simulation.

The simulation as it stands currently however, is valuable in and of itself since, by analyzing the so called "avalanche" failures, we can see which parts of the grid are especially vulnerable and recommend measures to protect them.

Lastly, the collapse of the grid has only been analysed in macro, temporal terms. More granularity will be helpful. The GIS part of the simulation needs further study so that we can understand which neighbourhoods and localities are vulnerable to electrical blackouts due to the effect of the cyclone. Contingent on more meterological information, we can also model the movement of the cyclone and its associated wind speeds/rain more precisely.

Chapter 4: Cyclone Vardah: Emergency Response Model Framework

Problem Formulation

Problem Definition

Following from Joshua Epstein's argument that Agent Based Modelling operates from within a Generative Science perspective (Epstein 1999), we are to build a description of the system from the bottom up. We first need to identify the pattern that is of interest to us. Then we need to identify who "owns" the problem, who the other actors involved in the system are, and our role in the process of developing the model.

So what is the Problem? What is the exact paucity of insight that we as modelers wish to address?

As I pointed out earlier, there is clearly a gap in the literature. There have been (non agent based) models of the impact of extreme weather events on the electricity grid, there have been various agent based models of electricity grids and electricity markets, but there has, so far been no model I could find of the disaster response to the collapse of the electricity grid as a socio-technical system.

Within the context, the aim of this modeling exercise is to gain further insights into the dynamics of disaster response mobilization and operations, with specific reference to the Tamil Nadu electricity board in Chennai.

It aims to further understand, as Andrew Bollinger puts it, if and "how micro-level adjustments—modifications in the behaviour of actors and in the properties of physical goods in the system" (Bollinger 2013, 223)

Lastly, it wishes to see how the relationships between the actors and any external compulsions they operate under, lead to changes in observed patterns of response "at the emergent system level" (ibid.)

Initial Hypothesis

The initial hypothesis is that the difference between the behavior that we can currently see in the system and the behavior that we would like to see in the system is that the current method of assigning repair priorities depending on the relative political power of the affected areas does not work.

Limited TNEB resources are diverted from localities which would benefit more from immediate assistance and instead are routed towards restoring power to those housing residents having higher amounts of social and political capital.

This hypothesis is supported by the literature, especially Brian Min's work on the electoral impact of electricity provision and distribution (Min 2016). The decision-making process in such cases also tends to be less transparent (Withanaarachchi & Setunge 2014) and this disparity of attention affects poor neighbourhoods disproportionately (Lee 2012)

Outlining Role of Actors

The main problem owner is the Tamil Nadu Electricity Board. Its job is to fix the the damage caused by cyclone Vardah. It does this through the actors "Line Patrols" and "Flying Squads" whose activities are coordinated by the "Load Dispatch Center".

The secondary actor is the residential consumer who requests the TNEB to fit the electrical fault. His request gets placed in a queue and assigned a priority by the load dispatch center.

What the modeler does is gather knowledge from the literature, field excursions, and interviews with domain experts, and system stakeholders and relevant actors in order to create the model.

System Identification and Decomposition

The next step after formulating the problem is to decide the boundaries of the system as well as what it is composed of.

Inventory of Physical and Social Entities in the System

This phase seeks to set out in explicit terms who the physical and social entities in the system are, and what the links between them are. As explained earlier, the response to the "disaster" that was Cyclone Vardah is a complex socio-technical system.

The actors in the "social" part of the system are represented as agents in this model. The main actors are the line patrols of the Tamil Nadu Electricity board. The actions of the flying squads are regulated by the Load Dispatch Center which assign priorities and instruct each squad on where to go. Next are the "consumers" who live in various neighbourhoods, with differing degrees of political clout. Based on how important the area a consumer lives in is, the load dispatch center assigns priorities to repair.

The following, though comprise the "technical" components or the physical subsystem: the substations, power lines and poles/towers. Based on the location and accessibility of the pole/tower, repair times may differ.

Structuring of Agents and Interactions

The main agent, the "Line Patrol" travels around the simulation "universe", ascertaining the extent of damage caused post-cyclone, repairing electrical faults.

They make decisions about which part of the grid to fix based on the instructions that they receive from the Load Dispatch Center.

Their behavior depends on which state they are currently operating at. If they are in the "reconnaissance" state, they wander around the "environment" looking for faults to repair.

If they are in the "following orders" state, they go where the Load Dispatch Center tells them to.

The Load Dispatch Center has two states, either choosing to assign repair priorities based on the political clout of areas that submit complaints, or based on which repair is most urgently needed.

The customers who submit complaints when an electrical fault pops up possess "political clout" based on which neighbourhood they live in.

Identifying the External World

The external world in this case is the area that comes under the "Mylapore" feeder station which steps down the current from 230 to 33 KV, and the 33 to 11 KV substations which come under it within the Mylapore Locality, namely the "Luz" and Ammaiyappan Lane sub stations (Source: Grid Map of Chennai supplied by the TNEB), Together, they serve 163,781 voters (extrapolated from 2016 election results for the Mylapore Assembly Constituency)

4.3 Concept Formalisation and Model Narrative

This simulation is intended to take off from where the previous one ended; with a damaged electrical power grid, with a variety of agents operating in the immediate aftermath. There are a variety of ways in which the line patrol can behave, and based on that, the time taken to restore the grid will also fluctuate.

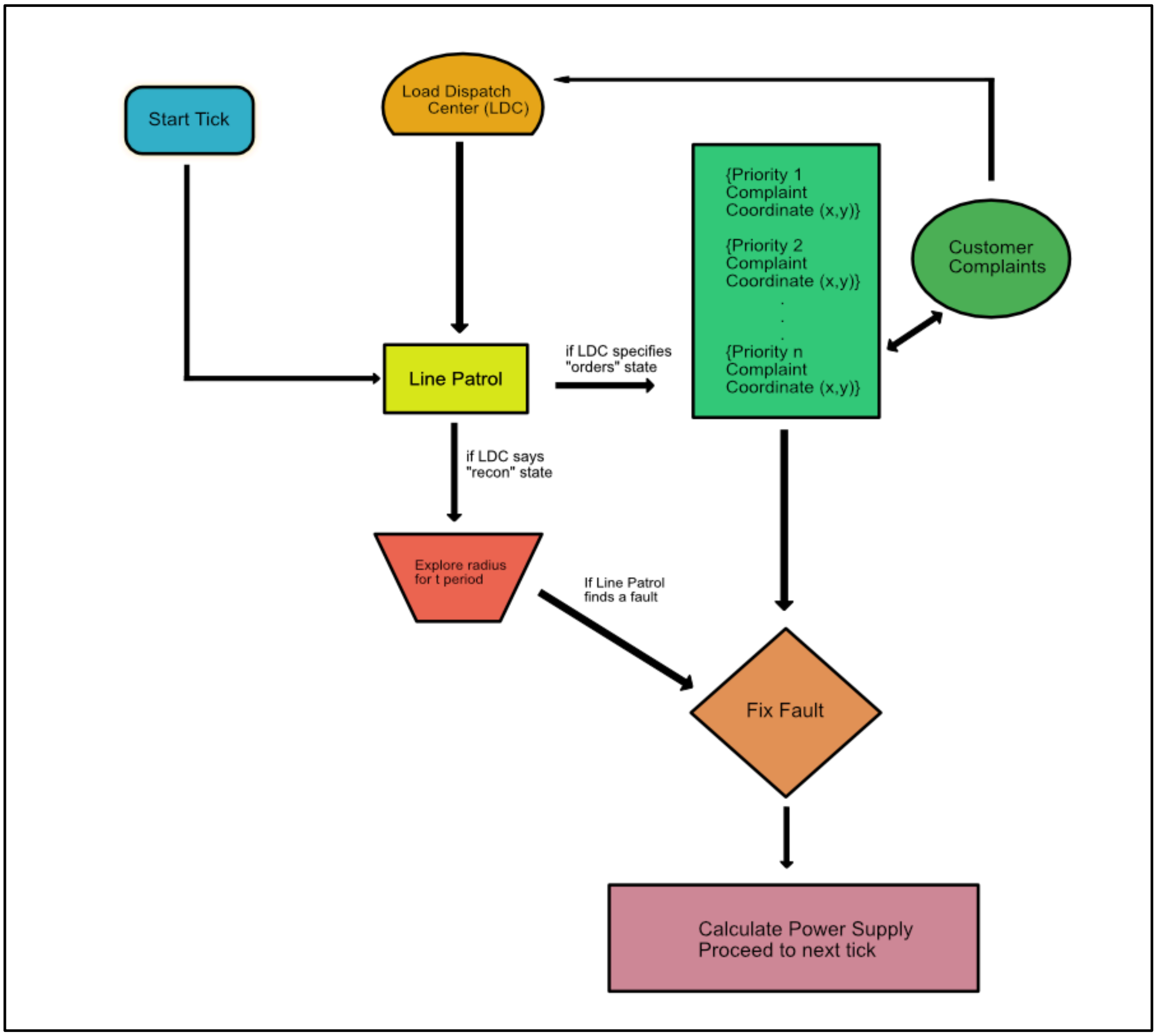


Fig. 4.1: – Flowchart showing the sequence of actions during one tick of the simulation

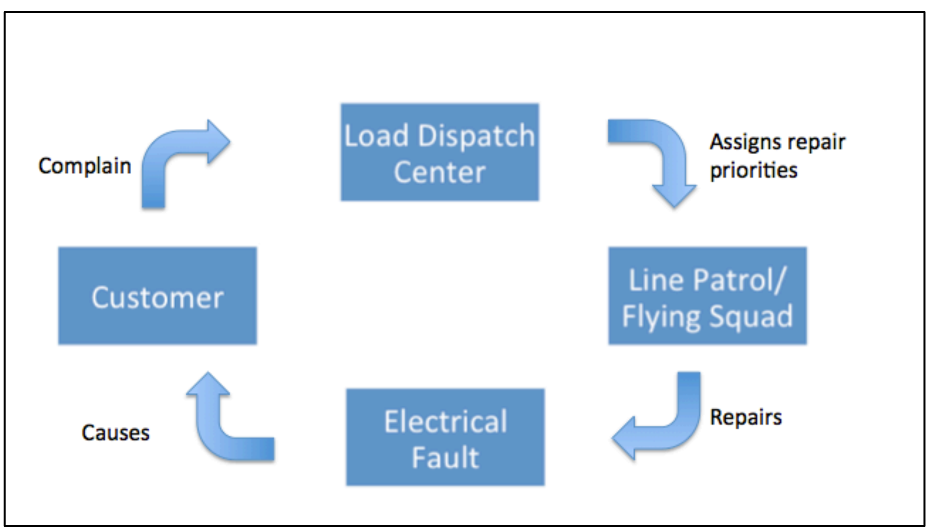


Fig. 4.2: The framework of the Disaster Response Simulation

```
 Initialise Simulation

 Load Chennai-Map-Overlay
 Load pre-saved-grid

 Pre saved grid consists of 100 customer nodes connected to each other by 350 edges.

 At every tick,

Start-tick

   Check if
      load-dispatch-centre-priority = (0,1)
      Any-customer-has-electricity= (0,1)

customer owns:
    has-electricity
    complaint-coordinates
    political-power

     end-tick

  if load-dispatch-centre-priority = 0
        then line-patrol searches for (specified amount of time)

  if load-dispatch-centre-priority = 1
   Line-patrol goes to $complaint-coordinates (x,y)
```

Fig 4.3: Disaster Response Model Pseudocode

4.4: Moving Forward and Scope for Further Work

This framework serves as the basis from which a larger simulation exercise may be undertaken. To be incorporated in later iterations of this simulation are various kinds of faults that can be encountered by the line patrol (for example, cutting down a tree that has fallen on a power line is significantly less difficult than replacing a fallen transmission tower that was built on a canal).

Chapter 5: Conclusion

In the grid-collapse simulation, the electricity grid collapsed wholesale within 100-odd minutes, buffeted as it was by the cyclone's effects, as well as the knock-on cascading failures due to overload.

We have also observed emergent behavior in the manner in which the grid collapsed, as well as certain "avalanche" points where large portions of the grid collapsed all at once.

The emergency-response simulation, in turn helps provide a valuable framework that helps think about how post-disaster recovery can be better handled. It brings into focus the role that high-level decision-making actors (in this case the Load-Dispatch Centre) play in helping/or hindering recovery efforts, since it is very possible that they may redirect resources to where influential people are, and not where they are most needed.

These simulations would help policymakers grasp the principles of what makes these complex sociotechnical systems function, and thus serve a decision support and scenario planning functions (a known use case for ABMs as outlined in the literature review)

Eric Bonabeau describes Agent Based Modeling as a "mindset more than a technology" (Bonabeau 2002, 7280). The modeler thinks about the system not in terms of larger macro-level patterns on "top" of the system, (as system dynamics practitioners would tend to do) but instead describes the system from the viewpoint of its constituent units.

While skeptics may decry this thinking as missing the forest for the trees (Schieritz 2003) they would be better served by realizing Agent Based Modeling's fundamental mission, viz. "the search for principles underlying the dynamics of complex systems" (ibid. 24) is compatible with certain principles of disaster response and vulnerability analysis.

Fundamentally, these simulations produce scenarios. Some are disturbing, but they could very well happen. After all, scenarios are, as Cynthia Selin puts it, “stories describing different but equally plausible futures that are developed using methods that systematically gather perceptions about certainties and uncertainties” (Selin 2006, 1).

Tim Harford describes scenarios as serving to “highlight hidden connections and make distant consequences seem real”, and to help us “face up to uncomfortable prospects and think clearly about possiblities”. (Harford 2016)

More importantly, the exercises in this thesis help us move from what Harford calls ‘sterile’ questions, for eg. “What will happen?” to ‘fertile’ questions such as “What will we do if it does”?

Works Cited

Rinaldi, S. M. (2004, January). Modeling and simulating critical infrastructures and their interdependencies. In *System sciences, 2004. Proceedings of the 37th annual Hawaii international conference on* (pp. 8-pp). IEEE.

Punit, I. S. (2016, December 12). The wrath of Cyclone Vardah, in numbers. Retrieved June 15, 2017, from https://qz.com/860841/cyclone-vardah-death-and-damage-caused-by-the-storm-hitting-chennai-in-india/

Rao, V. R., Subramanian, B. R., Mohan, R., Kannan, R., Mageswaran, T., Arumugam, T., & Rajan, B. (2013). Storm surge vulnerability along Chennai–Cuddalore coast due to a severe cyclone THANE. *Natural hazards*, *68*(2), 453-465.

Hoffman, D. L., & Novak, T. P. (2016). Consumer and Object Experience in the Internet of Things: An Assemblage Theory Approach.

Canniford, R. & Bajdes, D. (2016), "Assembling Consumption," in *Assembling consumption: Researching actors, networks and markets*. Canniford, R. ed. Routledge.

Varian, H. R. (2016). How to build an economic model in your spare time. *The American Economist*, *61*(1), 81-90.

Sawyer, R. K. (2005). *Social emergence: Societies as complex systems*. Cambridge University Press.

Vasilescu, L., Khan, A., & Khan, H. (2008). Disaster management cycle–a theoretical approach. *Management & Marketing-Craiova*, (1), 43-50.

disaster response. Businessdictionary.com. Retrieved June 17, 2017, from Businessdictionary.com website: http://www.businessdictionary.com/definition/disaster-response.html

Filippoupolitis, A., Hey, L., Loukas, G., Gelenbe, E., & Timotheou, S. (2008, February). Emergency response simulation using wireless sensor networks. In *Proceedings of the 1st international conference on Ambient media and systems* (p. 21). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

Jain, S., & McLean, C. (2003, December). Simulation for emergency response: a framework for modeling and simulation for emergency response. In *Proceedings of the 35th conference on Winter simulation: driving innovation* (pp. 1068-1076). Winter Simulation Conference.

Rohracher, H. (2008). Energy systems in transition: contributions from social sciences. *International Journal of Environmental Technology and Management*, *9*(2-3), 144-161.

Hughes, T. P. (1993). *Networks of power: electrification in Western society, 1880-1930*. JHU Press.

Balasubramanian, V., D. Massaguer, S. Mehrotra, and N. Venkatasubramanian. "DrillSim:" A Simulation Framework for Emergency Response Drills", ISI'06." *Lecture Notes In Computer Science, Springer* (2006).

Stansfield, S., Sobel, A., & Shawver, D. (1998, November). BioSimMER: A virtual reality simulator for training first responders in a BW scenario. In *Proceedings of the 1998 Scientific Conference on Chemical and Biological Defense Research, Aberdeen Proving Ground, MD*.

Hsu, E. B., Li, Y., Bayram, J. D., Levinson, D., Yang, S., & Monahan, C. (2013). State of virtual reality based disaster preparedness and response training. *PLOS Currents Disasters*.

Stanton, N. A., Salmon, P., Jenkins, D., & Walker, G. (2009). *Human factors in the design and evaluation of central control room operations*. CRC Press.

Cohen-Rosenthal, E. (1997). Sociotechnical systems and unions: Nicety or necessity. *Human Relations*, *50*(5), 585-604.

Min, B. (2015). *Power and the Vote: Elections and Electricity in the Developing World*. Cambridge University Press.

Bennett, J. (2009). *Vibrant matter: A political ecology of things*. Duke University Press.

Doocy, S., Dick, A., Daniels, A., Kirsch, TD. The Human Impact of Tropical Cyclones: a Historical Review of Events 1980-2009 and Systematic Literature Review. *PLoS currents Disasters*. *2013 Apr 16 . Edition 1.*

Alcántara-Ayala, I. (2002). Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. *Geomorphology*, *47*(2), 107-124.

Raghavan, S., & Rajesh, S. (2003). Trends in tropical cyclone impact: A study in Andhra Pradesh, India. *Bulletin of the American Meteorological Society*, *84*(5), 635-644.

Pielke Jr, R. A., & Landsea, C. W. (1998). Normalized hurricane damages in the United States: 1925–95. *Weather and Forecasting*, *13*(3), 621-631.

Panteli, M., & Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, *127*, 259-270.

Ward, David M. "The effect of weather on grid systems and the reliability of electricity supply." *Climatic change* 121, no. 1 (2013): 103-113.

Van Dam, K. H., Nikolic, I., & Lukszo, Z. (Eds.). (2012). *Agent-based modelling of socio-technical systems* (Vol. 9). Springer Science & Business Media.

Hamming, R. W. (1962). Numerical analysis for scientists and engineers. *Dover Publications.*

Kaboli, S., & Oraee, H. (2016). Reliability in Power Electronics and Electrical Machines: Industrial Applications and Performance Models (pp. 1-481). Hershey, PA: IGI Global. doi:10.4018/978-1-4666-9429-3

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Epstein, J. M. (1999). Agent‐based computational models and generative social science. *Complexity*, *4*(5), 41-60.

Bollinger, L. A., Davis, C. B., & Nikolic, I. (2013). An agent-based model of a mobile phone production, consumption and recycling network. In *Agent-Based Modelling of Socio-Technical Systems* (pp. 221-243). Springer Netherlands.

Withanaarachchi, J., & Setunge, S. (2014). Influence of decision making during disasters and how it impacts a community. In R. R. Rapp & W.Harland (Eds.), *The Proceedings* of the *10th International conference of the international institute for infrastructure resilience and reconstruction* (pp. 176-188). Indiana: Purdue University.

Lee, D. (2012). *The impact of natural disasters on neighborhood change: longitudinal data analysis* (Doctoral dissertation, Georgia Institute of Technology).

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, *99*(suppl 3), 7280-7287.

Schieritz, N., & Milling, P. M. (2003). Modeling the forest or modeling the trees: A comparison of system dynamics and agent-based simulation. In *in Proceedings of the 21st International Conference of the System Dynamics Society*.

Selin, C. (2006). Trust and the illusive force of scenarios. *Futures*, *38*(1), 1-14.

Harford, T (2016, July 13). Brexit and the power of wishful thinking, *The Financial Times* Retrieved May 29th 2017,

Appendix 1 – Model Code

(Note: This appendix contains only the code for the simulation file. The grayed out parts is the documentation for explanatory purposes. The shapefiles and grid files required to actually run the simulation may be found on [https://github.com/NChandrasekharR/MA-Thesis-2017 /](https://github.com/NChandrasekharR/MA-Thesis-2017/) Please further note that this is only compatible with Netlogo versions 6.0 or higher)

```
extensions [vid gis nw] ;extensions that Netlogo is using to run
this model

breed [nodes node] ;NetLogo allows you to define different "breeds"
of turtles and breeds of links. Once you have defined breeds, you
can go on and make the different breeds behave differently. For
example, you could have breeds called sheep and wolves, and have the
wolves try to eat the sheep or you could have link breeds called
streets and sidewalks where foot traffic is routed on sidewalks and
car traffic is routed on streets.

undirected-link-breed [edges edge]

breed [fires fire]

nodes-own [
  key
  available-power
  actual-power
  search-parent
  search-costs-from-start
]

edges-own [
  capacity
  load
  life-time
]

fires-own [ ;fire appears to show that an edge (i.e a power line)
has been disrupted in the simulation display
  fire-key1
  fire-key2
  fire-capacity
  fire-load
  fire-life-time
]

globals [cyclone-1 cyclone-2 mouse-first-node mouse-second-node
search-open-node-list search-closed-node-list current-time is-grid-
disrupted? is-grid-isolated? initial-number-of-edges _recording-
save-file-name projection dataset chennai-dataset patch-area-sqkm]
;If a variable is a global variable, there is only one value for the
```

```
variable, and every agent can access it. You can think of global
variables as belonging to the observer.

to setup-globals
  set-default-shape nodes "circle"
  set-default-shape fires "fire"
  set mouse-first-node nobody
  set mouse-second-node nobody
  set current-time 0
  set is-grid-disrupted? false
  set is-grid-isolated? false
  set initial-number-of-edges 0
end

to startup
  setup
  let file "grid.dat" ;a map of the network reconstructed from the
GRID MAP provided by TNEB
  if file-exists? file [ read-grid-data-from-file file ]
end

to setup
  clear-all
  setup-globals
  reset-ticks
  setup-fire

set projection "WGS_84_Geographic"

set chennai-dataset gis:load-dataset
"/Users/balanarayanaswamy/wards.shp";edit file path with your
computers' as required

 gis:set-world-envelope (gis:envelope-of chennai-dataset)

  gis:set-drawing-color white
  gis:draw chennai-dataset 1

  reset-ticks

end

to go
;  beep
;  user-message "The procedure 'go' is not implemented yet!"
;  stop
  if is-grid-isolated? or count edges = 0 or count nodes = 0 [ stop
]
  if ticks > 0
  [ go-cyclone-related-failure-of-a-edge ]
   set initial-number-of-edges count edges
    numerize-nodes
```

```
  optimize-flow
  go-calculate-life-time-of-edges
  if data-output != "no" [ write-data-to-files ]
  tick
end

;; ============ Simulate network dynamics ================

to go-cyclone-related-failure-of-a-edge


  min-one-of edges with [life-time > 0 ] [
    ask min-one-of edges with [life-time > 0 ] [life-time] [
      if output-level = 1 [ show "selected!" ]
      set current-time current-time + life-time
      go-create-fire-at-destroyed-edge
      die
  ]
end ;Procedure by which the first node to be hit by Vardah is chosen


to go-calculate-life-time-of-edges
  ask edges [
    ifelse load > 0
      [ set life-time random-exponential capacity / load ]
      [ set life-time -1 ]
  ]
end

to go-create-fire-at-destroyed-edge
  let x 0.5 * ( [xcor] of end1 + [xcor] of end2)
  let y 0.5 * ( [ycor] of end1 + [ycor] of end2)
  let key1 [key] of end1
  let key2 [key] of end2
  ask one-of fires [
    set xcor x
    set ycor y
    ifelse show-destroyed [ show-turtle ][ hide-turtle ]
    set fire-key1 key1
    set fire-key2 key2
    set fire-capacity [capacity] of myself
    set fire-load [load] of myself
  ]
end

to setup-fire
  create-fires 1 [
    set size 2
    set color white
    hide-turtle
    set fire-key1 -1
    set fire-key2 -1
```

```
    set fire-capacity -1
    set fire-load -1
  ]
end

;; ============= Draw nodes and edges ======================

to draw-structure
  ask nodes [ draw-node ]
  ask edges [ draw-edge ]
end

to draw-node
  ifelse actual-power != 0 [ set size 1 + log abs actual-power 10 ]
[ set size 1 ]
  let power available-power
  ifelse is-dangling? [ set color yellow ] [ set color green ]
  ifelse power > 0 [ set color blue ] [set label "transformer"] ;
the "source" node in Chennai's grid
  ifelse power < 0 [ set color red ][set label "powerplant"]  ;the
"sink" node in Chennai's grid
end

to-report is-dangling?
  report count edges with [end1 = myself or end2 = myself] < 2
end

to draw-edge
  ifelse load > 0
  [
    set color green
    set thickness (1 - exp (- 0.5 * load))
    if load > capacity
    [
      ifelse load > 2 * capacity
      [
        ifelse load > 4 * capacity
        [ set color red ]
        [ set color orange ]
      ]
      [ set color yellow ]
    ]
  ]
  [
     set color grey
     set thickness (1 - exp (- 0.5 * capacity))
  ]
end

to numerize-nodes
  if any? nodes with [key < 0] [
    let counter 0
```

```
    ask nodes [
      set counter counter + 1
      set key counter
    ]
  ]
end

to-report edge-mean
  report mean [count my-edges] of nodes
end

to-report edge-variance
  report standard-deviation [count my-edges] of nodes
end

;;============== Design the net-structure ===================

to add-nodes
  setup-nodes
  setup-spatially-clustered-network
  draw-structure
end

to setup-nodes
  create-nodes number-of-nodes  [
    ; for visual reasons, we don't put any nodes *too* close to the
edges
    setxy (random-xcor * 0.95) (random-ycor * 0.95)
    setup-node
  ]
end

to setup-node
    set available-power 0
    set actual-power 0
    set key -1
end

to setup-spatially-clustered-network
  let number-of-edges (average-node-degree * count nodes) / 2
  while [count edges < number-of-edges ]
  [
    ask one-of nodes [
      let choice ( min-one-of
        ( other nodes with [not edge-neighbor? myself] )
        [distance myself] )
      if choice != nobody [
        create-edge-with choice [
          set capacity 1
          set load 0
        ]
      ]
```

```
    ]
  ]
end

to add-power
  let total-power total-power-flux
  while [total-power > 0] [
    let power 1
    if random-type = "float" [ set power power +   random-float 2 ]
    if random-type = "integer" [ set power power +   random 2 ]
    if power > total-power [ set power total-power ]
    set total-power total-power - power
    ask one-of nodes with [available-power <= 0] [
      set available-power available-power - power
    ]
    ask one-of nodes with [available-power >= 0] [
      set available-power available-power + power
    ]
  ]
  draw-structure
end

to remove-power
  ask nodes [
    set available-power 0
    set actual-power 0
    draw-node
  ]
  ask edges [
    set load 0
    set capacity 1
    draw-edge
  ]
end

to-report edge-level
  let value 100.
  if initial-number-of-edges > 0 [
    set value 100.0 * count edges / initial-number-of-edges
  ]
  report value
end

to-report disrupted-level
  let value 0
  if is-grid-disrupted? [ set value 100 ]
  report value
end

;;============= Editing the nodes and edges =========

to-report select-nearest-node
```

```
  report one-of nodes with-min [distancexy mouse-xcor mouse-ycor]
end

to insert-node
  if mouse-down? and mouse-inside? [
    create-nodes 1 [
      setxy mouse-xcor mouse-ycor
      setup-node
      draw-node
    ]
    stop
  ]
end

to delete-node
  if mouse-down? and mouse-inside? [
    ask select-nearest-node [ die ]
    draw-structure
    stop
  ]
end

to move-node
  if mouse-down? and mouse-inside? [
    ask select-nearest-node [ setxy mouse-xcor mouse-ycor ]
    if not mouse-down? [ stop ]
  ]
end

to set-selected
  set size size * 2
end

to set-unselected
  set size size * 0.5
end

to insert-edge
  if mouse-first-node = nobody [
     if mouse-down? and mouse-inside? [
       set mouse-first-node select-nearest-node
       ask mouse-first-node [ set-selected ]
     ]
  ]
  if mouse-second-node = nobody or mouse-second-node = mouse-first-
node [
    if mouse-down? and mouse-inside? [ set mouse-second-node select-
nearest-node ]
  ]
  if mouse-first-node != nobody and mouse-second-node != nobody
  and mouse-second-node != mouse-first-node [
    ask mouse-first-node [
```

```
      set-unselected
      create-edge-with mouse-second-node [
          set capacity 1
          set load 0
        ]
    ]
    draw-structure
    set mouse-first-node nobody
    set mouse-second-node nobody
    stop
  ]
end

to-report edges-between [node1 node2]
  report edges with [end1 = node1 and end2 = node2]
end

to delete-edge
  if mouse-first-node = nobody [
     if mouse-down? and mouse-inside? [
       set mouse-first-node select-nearest-node
       ask mouse-first-node [ set-selected ]
     ]
  ]
  if mouse-second-node = nobody or mouse-second-node = mouse-first-
node [
    if mouse-down? and mouse-inside? [ set mouse-second-node select-
nearest-node ] ]
  let found-edges edges-between mouse-first-node mouse-second-node
  if any? found-edges [
    ask one-of found-edges [ die ]
    ask mouse-first-node [ set-unselected ]
    set mouse-first-node nobody
    set mouse-second-node nobody
    draw-structure
    stop
  ]
end

to increase-power
  if mouse-down? and mouse-inside? [
    ask select-nearest-node [
      set available-power available-power + 1
      draw-node
    ]
    stop
  ]
end

to decrease-power
  if mouse-down? and mouse-inside? [
    ask select-nearest-node [
```

```
      set available-power available-power - 1
      draw-node
    ]
    stop
  ]
end

to radial-layout
  if mouse-down? and mouse-inside? [
    layout-radial nodes edges select-nearest-node
    stop
  ]
end

to spring-layout
  let spring-force 1
  let spring-length world-width / (sqrt count nodes)
  let repulsion-force 1
  repeat 30 [ layout-spring nodes edges spring-force spring-length
repulsion-force ]
end

to circle-layout
  let radius 0.4 * min (list world-width world-height)
  let node-set max-n-of 3 nodes [count edge-neighbors ]
  repeat 10 [ layout-tutte node-set edges radius ]
end

;;============= Save and load net-structure ===================

to write-data-to-files
  if data-output = "each" or data-output = "all" [
    let file-name (word "grid-sim-" ticks)
    let network-file (word file-name ".dat")
    if is-string? network-file [
      if file-exists? network-file [ file-delete network-file ]
      write-grid-data-to-file network-file
    ]
  ]
  if data-output = "for R" or data-output = "all" [ write-data-to-R-
files ]
end

to write-data-to-R-files
  numerize-nodes
  let file-name (word "grid-nodes-R-" number-of-run ".dat")
  if ticks = 0 and file-exists? file-name [ file-delete file-name ]
  file-open file-name
  if ticks = 0 [ file-print "key current-time xcor ycor available-
power actual-power" ]
  ask nodes [
    file-write key
```

```
    file-write current-time
    file-write xcor
    file-write ycor
    file-write available-power
    file-write actual-power
    file-print " "
  ]
  file-close
  set file-name (word "grid-edges-R-" number-of-run ".dat")
  if ticks = 0 and file-exists? file-name [ file-delete file-name ]
  file-open file-name
  if ticks = 0 [ file-print "key1 key2 current-time capacity load
life-time deleted?" ]
  ask fires [
    if fire-key1 >= 0 [
      file-write fire-key1
      file-write fire-key2
      file-write current-time
      file-write fire-capacity
      file-write fire-load
      file-write fire-life-time
      file-print " 1 "
    ]
  ]
  ask edges [
    file-write [key] of end1
    file-write [key] of end2
    file-write current-time
    file-write capacity
    file-write load
    file-write life-time
    file-print " 0 "
  ]
  file-close
end

to-report check-file-name [file-name file-tag]
  if is-string? file-name [
    let found substring file-name (length file-name - length file-
tag) length file-name
    if found != file-tag [ set file-name (word file-name file-tag)
]
  ]
  report file-name
end

to save-grid
  let network-file check-file-name user-new-file ".dat"
  if is-string? network-file [
    if file-exists? network-file [ file-delete network-file ]
    write-grid-data-to-file network-file
  ]
```

```
end

to write-grid-data-to-file [network-file]
  numerize-nodes
  file-open network-file
  file-print count nodes
  file-print "* node data key label x y available-power actual-
power"
  foreach sort-on [key] nodes  [ [?1] ->
    ask ?1 [
      if empty? label [ set label (word key)]
      file-write key
      file-write label
      file-write xcor
      file-write ycor
      file-write available-power
      file-write actual-power
      file-print " "
    ]
  ]
  file-print "* edge data key1 key2 capacity load"
  ask edges [
    file-write [key] of end1
    file-write [key] of end2
    file-write capacity
    file-write load
    file-print " "
  ]
  file-close
end

to load-grid
  setup
  let network-file user-file
  if is-string? network-file and file-exists? network-file [
    read-grid-data-from-file network-file
  ]
end

to read-grid-data-from-file [network-file]
  file-open network-file
  let counter file-read
  let dummy file-read-line
  while [counter > 0] [
    create-nodes 1 [
      set color green
      set key file-read
      set label file-read
      setxy file-read file-read
      set available-power file-read
      set actual-power file-read
    ]
```

```
    set counter counter - 1
  ]
  set dummy file-read-line
  while [not file-at-end? ] [
    let token file-read
    let next-token file-read
    let first-node one-of nodes with [key = token]
    let second-node one-of nodes with [key = next-token]
    ask first-node [
      create-edge-with second-node [
        set capacity file-read
        set load file-read
      ]
    ]
  ]
  file-close
  draw-structure
end

;;============== Export net-structure in various formats ===

to export
  numerize-nodes
  if format = "NET"
  [
    let network-file check-file-name user-new-file".net"
    if is-string? network-file [
      if file-exists? network-file [ file-delete network-file ]
      write-NET-data-to-file network-file
    ]
  ]
  if format = "VNA"
  [
    let network-file check-file-name user-new-file ".vna"
    if is-string? network-file [
      if file-exists? network-file [ file-delete network-file ]
      write-VNA-data-to-file network-file
    ]
  ]
  if format = "R"
  [
    let node-file check-file-name user-new-file ".nodes.imp"
    let edge-file (word (remove ".nodes.imp" node-file )
".edges.imp")
    if is-string? node-file and is-string? edge-file [
      if file-exists? node-file [ file-delete node-file ]
      if file-exists? edge-file [ file-delete edge-file ]
      write-R-node-data-to-file node-file
      write-R-edge-data-to-file edge-file
    ]
  ]
end
```

```
to write-NET-data-to-file [network-file]
  file-open network-file
  file-type "*Vertices " file-print count nodes
  foreach sort-on [key] nodes  [ [?1] ->
    ask ?1 [
      file-write key
      file-write label
      file-write xcor
      file-write ycor
      file-print " "
    ]
  ]
  file-print "*Arcs"
  ask edges [
    file-write [key] of end1 file-type " "
    file-write [key] of end2 file-type " "
    file-write 1 + load
    file-print " "
  ]
  file-close
end

to write-VNA-data-to-file [network-file]
  file-open network-file
  file-print "*Node data"
  file-print "id available-power actual-power"
  foreach sort-on [key] nodes [ [?1] ->
    ask ?1 [
      if empty? label [ set label (word key)]
      file-write key
      file-write precision available-power 2
      file-write precision actual-power 2
      file-print " "
    ]
  ]
  let size-factor 10
  file-print "*Node properties"
  file-print "id x y color shape size shortlabel"
  let vshape 1
  foreach sort-on [key] nodes [ [?1] ->
    ask ?1 [
      file-write key
      file-write precision (size-factor * (xcor - min-pxcor)) 0
      file-write precision (size-factor * (ycor - min-pycor)) 0
      file-write integer-color
      file-write vshape
      file-write precision (size-factor * size) 0
      file-write label
      file-print " "
    ]
  ]
```

```
  file-print "*Tie data"
  file-print "from to strength load capapcity"
  ask edges [
    file-write [key] of end1
    file-write [key] of end2
    file-write 1
    file-write load
    file-write capacity
    file-print " "
    file-write [key] of end2
    file-write [key] of end1
    file-write 1
    file-write load
    file-write capacity
    file-print " "
  ]
  file-print "*Tie properties"
  file-print "from to color size headcolor headsize active"
  let headsize 0
  let active -1
  ask edges [
    let lcolor integer-color
    file-write [key] of end1
    file-write [key] of end2
    file-write lcolor
    file-write precision (size-factor * thickness) 0
    file-write lcolor
    file-write headsize
    file-write active
    file-print " "
    file-write [key] of end2
    file-write [key] of end1
    file-write lcolor
    file-write precision (size-factor * thickness) 0
    file-write lcolor
    file-write headsize
    file-write active
    file-print " "
  ]
  file-close
end

to write-R-node-data-to-file [network-file]
  file-open network-file
  file-print "key x y available actual"
  ask nodes [
    file-write key
    file-write xcor
    file-write ycor
    file-write available-power
    file-write actual-power
    file-print " "
```

```
  ]
  file-close
end

to write-R-edge-data-to-file [network-file]
  file-open network-file
  file-print "key1 key2 capacity load "
  ask edges [
    file-write [key] of end1
    file-write [key] of end2
    file-write capacity
    file-write load
    file-print " "
  ]
  file-close
end

to-report integer-color
  let value 0
  let color-list extract-rgb color
  let red-value item 0 color-list
  let green-value item 1 color-list
  let blue-value item 2 color-list
  set value red-value + 256 * green-value + 256 * 256 * blue-value
  report value
end

;;============== provide characteristic values for net-structure ==

to-report power-supply-level
  let value 0
  let total power-supply
  if total > 0 [
    set value 100.0 * power-input / total
  ]
  report value
end

to-report power-demand-level
  let value 0
  let total power-demand
  if total > 0 [
    set value 100.0 * power-output / total
  ]
  report value
end

to-report power-supply
  let power 0
  ask nodes with [available-power > 0] [
    set power power + available-power
  ]
```

```
  report power
end

to-report power-demand
  let power 0
  ask nodes with [available-power < 0] [
    set power power + available-power
  ]
  report power * -1
end

to-report power-input
  let power 0
  ask nodes with [available-power > 0] [
    set power power + actual-power
  ]
  report power
end

to-report power-output
  let power 0
  ask nodes with [available-power < 0] [
    set power power + actual-power
  ]
  report power * -1
end

to-report power-variance
  let value 0
  ask nodes [
    let delta available-power - actual-power
    set value value + delta * delta
  ]
  report sqrt value
end

to-report flux-variance
  let value 0
  ask edges [
    let delta capacity - load
    set value value + delta * delta
  ]
  report sqrt value
end

;; ================= Optimize the flux in net-structure ==========

to reset-structure
  ask nodes [
    set actual-power 0
    draw-node
  ]
```

```
  ask edges [
    set load 0
    draw-edge
  ]
end

to optimize-flow
  reset-structure
  let is-isolated? true
  let is-disrupted? false
  let targets nodes with [available-power < 0]
  ask targets [
    let sources nodes with [can-provide?]
    ask min-n-of (count sources) sources [distance myself] [
      if [is-needing?] of myself [
        set is-disrupted? not update-net-structure self myself
        set is-isolated? is-isolated? and is-disrupted?
        set is-grid-disrupted? is-disrupted? or is-grid-disrupted?
      ]
    ]
  ]
  set is-grid-isolated? is-isolated?
  draw-structure
end

to-report is-needing?
  report available-power < 0 and actual-power > available-power
end

to-report can-provide?
  report available-power > 0 and actual-power < available-power
end

to change-power [this-load]
  if available-power > 0 [ set actual-power actual-power + this-load
]
  if available-power < 0 [ set actual-power actual-power - this-load
]
end

to-report calculate-net-flow [start-node target-node]
  let this-flow  0
  ask start-node [
    set this-flow available-power - actual-power
  ]
  ask target-node [
    let that-flow actual-power - available-power
    if that-flow < this-flow [ set this-flow that-flow ]
  ]
  report this-flow
end
```

```
to change-flow-structure [start-node target-node edge-list this-
load]
  if not empty? edge-list [
    ask start-node [
      change-power this-load
      draw-node
    ]
    ask target-node [
      change-power this-load
      draw-node
    ]
    foreach edge-list [ [?1] ->
      ask ?1 [
        set load load + this-load
        draw-edge
      ]
    ]
  ]
end

to-report update-net-structure [start-node target-node]
  let path-found? true
  let edge-list search-go start-node target-node
  let found-path? not empty? edge-list
  ifelse found-path?
  [
    let this-load calculate-net-flow start-node target-node
    if output-level = 1 [ show (word "Power flow: " this-load " with
" (length edge-list)
      " edges between " start-node " and " target-node) ]
    if this-load > 0 [ change-flow-structure start-node target-node
edge-list this-load ]
  ]
  [
    if output-level = 1 [ show (word "No path found between " start-
node " and " target-node) ]
    set path-found? false
  ]
  report path-found?
end

to adjust-capacities
  ask edges [
    if load > capacity [ set capacity load ]
    draw-edge
  ]
end

to remove-unused
  ask edges with [load = 0] [ die ]
  ask nodes with [ count my-edges = 0] [die]
  draw-structure
```

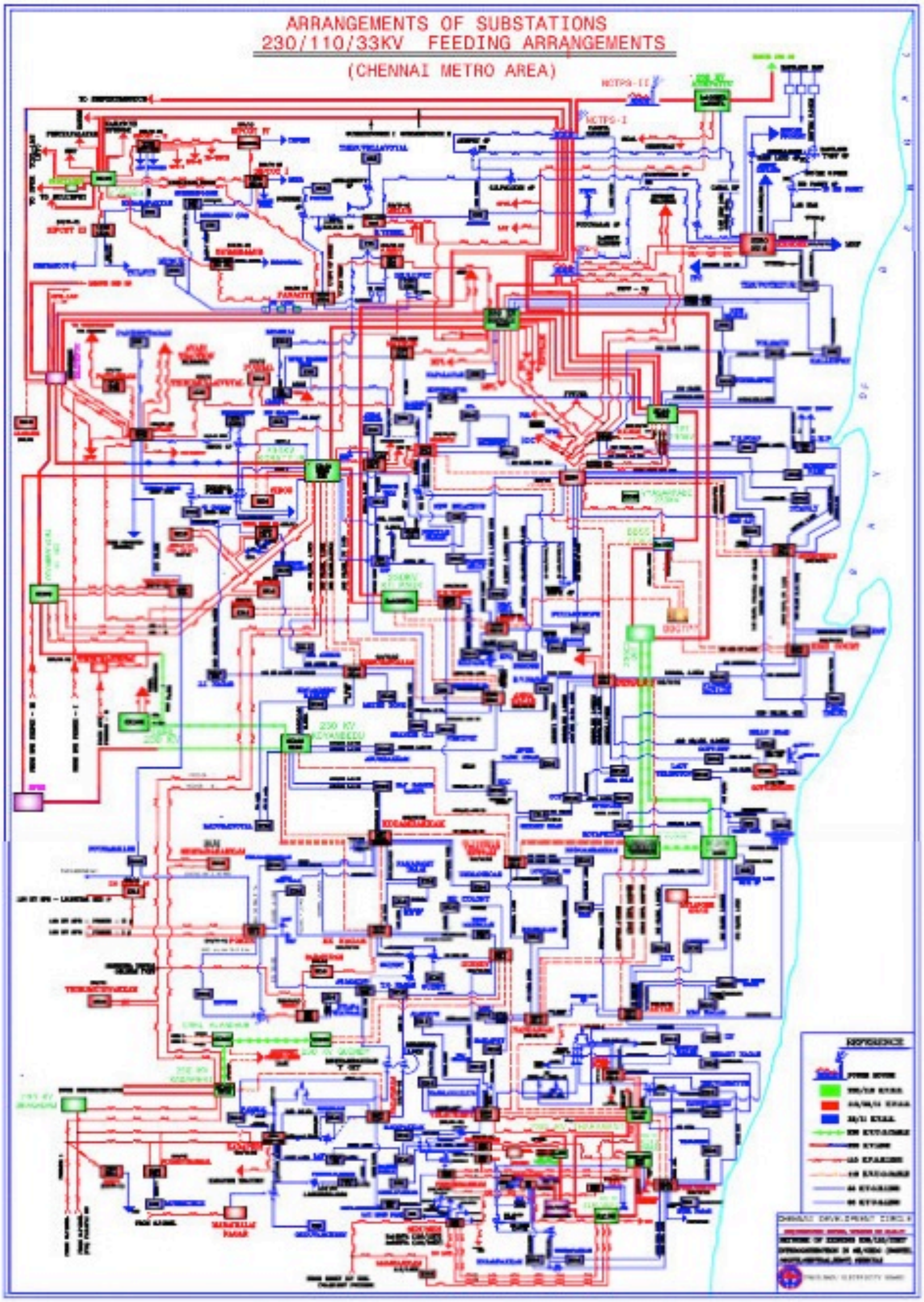
```
end

to optimize-structure
  repeat optimize-steps [
    optimize-flow
    adjust-capacities
  ]
  optimize-flow
end

;; ================ Search shortest path in net-structure =======

to-report search-go [start-node target-node]
  let node-list search-path start-node target-node
  let edge-list search-transfer-node-list-to-edge-list node-list
  report edge-list
end

to-report search-path [start-node target-node]
  if output-level = 2 [ show ( word "Search path between " start-
node " and " target-node ) ]
  let new-path ( list )
  search-init start-node
  if search-do target-node [
    set new-path search-path-back target-node
  ]
  report new-path
end

to search-init [ start-node ]
  if output-level = 2 [ show ( word "Init search from " start-node )
]
  ask nodes [
    set search-parent nobody
    set search-costs-from-start 0
  ]
  set search-open-node-list fput start-node ( list )
  set search-closed-node-list ( list )
end

to-report search-rank
  report search-costs-from-start
end


to-report search-do [target-node]
  if output-level = 2 [ show ( word "Do search to " target-node ) ]
  let current-node nobody
  while [target-node != current-node] [
    if empty? search-open-node-list [
      if output-level = 2 [ show ( word "No path to " target-node )
]
```

```
      report false
    ]
    ; remove lowest rank item from open list of patches and add it
to the closed list
    set search-open-node-list sort-by [ [?1 ?2] -> [ search-rank ]
of ?1 < [ search-rank ] of ?2 ] search-open-node-list
    set current-node first search-open-node-list
    set search-open-node-list but-first search-open-node-list
    set search-closed-node-list fput current-node search-closed-
node-list
    if output-level = 2 [ show ( word "Current node " current-node )
]
    ; check adjacent nodes
    if target-node != current-node [
      ask current-node [ search-handle-neighbors self target-node]
    ]
  ]
  if output-level = 2 [ show ( word "Found target " current-node ) ]
  report true
end

to search-handle-neighbors [parent-node target-node]
  ask my-edges [
    let costs [ search-costs-from-start ] of parent-node + 1
    if load > capacity [ set costs costs + over-capacity-costs ]
    ask other-end [
      if member? self search-open-node-list and costs < search-
costs-from-start [
        set search-open-node-list remove self search-open-node-list
        if output-level = 2 [ show ( word "Neighbor node " self
            " removed from open " search-open-node-list ) ]
      ]
      if member? self search-closed-node-list and costs < search-
costs-from-start [
        set search-closed-node-list remove self search-closed-node-
list
        if output-level = 2 [ show ( word "Neighbor node " self
            " removed from closed " search-closed-node-list ) ]
      ]
      if ( not member? self search-open-node-list )
      and ( not member? self search-closed-node-list ) [
        if output-level = 2 [ show ( word "Neighbor node " self
            " with costs=" costs " to parent " parent-node ) ]
        set search-parent parent-node
        set search-costs-from-start costs
        set search-open-node-list fput self search-open-node-list
      ]
    ]
  ]
end

to-report search-path-back [target-node]
```

```
  let found-path fput target-node ( list )
  let current-node target-node
  if output-level = 2 [ show ( word "Revert search " current-node )
]
  while [ [ search-parent ] of current-node != nobody ] [
    set current-node [ search-parent ] of current-node
    set found-path fput current-node found-path
    if output-level = 2 [ show ( word "Revert search " current-node
) ]
  ]
  report found-path
end

to-report search-edge-for-nodes [that-node this-node]
  report one-of edges with [ (end1 = that-node and end2 = this-node)
    or (end2 = that-node and end1 = this-node) ]
end

to-report search-transfer-node-list-to-edge-list [node-list]
  let edge-list (list)
  let last-node nobody
  foreach node-list [ [?1] ->
    let current-node ?1
    if last-node != nobody [
      let found-edge search-edge-for-nodes current-node last-node
      if output-level = 2 [ show (word "Found " found-edge " of "
current-node " " last-node) ]
      set edge-list fput found-edge edge-list
    ]
    set last-node current-node
  ]
  report edge-list
end

;; ============== plotting ===========================


to plot-histogram-of [that-distribution]
  ifelse length that-distribution > 0 [
    let x-max ( ceiling max that-distribution )
    if x-max <= 0 [ set x-max 1.0 ]
    let y-max length that-distribution
    set-plot-x-range 0 x-max
    set-plot-y-range 0 y-max
    set-histogram-num-bars 20
    histogram that-distribution
  ] [
    clear-plot
  ]
end
```

Appendix 2 – Chennai Grid Map

Note: The full and zoomable grid map is available to view on
https://github.com/NChandrasekharR/MA-Thesis-2017 /


ARRANGEMENTS OF SUBSTATIONS
230/110/33KV FEEDING ARRANGEMENTS
(CHENNAI METRO AREA)
NCTPS-II
NCTPS-I
230 KV
KOYAMBEDU
230 KV
GUINDY