

Robust Optimization for Multi-Hierarchy and Multi-period of Facility Location under Demand Uncertainty

(需要の不確実性を考慮した多階層多期間施設配置問題の
ロバスト最適化)

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Robust Optimization for Multi-Hierarchy and Multi-period of Facility Location under demand uncertainty

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Abstract

Distribution and logistics has been an important feature not only of industrial and economic life but also become a concerning issue in humanitarian logistics. Many aspects of research works are explored in various fields with post disaster such as structural analysis, architecture analysis, social analysis, information system, also logistic analysis and so on. Logistic is the mainly supporter in two ways which are a victim rescuing or evacuation of people and an essential providing to survive them. This study attempts contributes to the previous research by considering the worst-case scenarios of the multi-facility location problems under uncertainty demand. Accordingly, main objective of the study is to tackle the facility locations problem and allocations with demand uncertainty function subsequently improving by vehicle routing. This study would like to design the facility location and also optimize the amount transportation of the relief items. The multi layers of facility location problem with deterministic are studied at the primary. Moreover, also emphasize the uncertainty demand by using robust optimization model. We optimize the multi-echelon of facility location and allocation problem simultaneously with interval demand also known as ellipsoidal uncertainty set which is a rather new approach that has never seen in the location facility fields. To consider the operation constrains, the model is restricted with the maximum storage in each echelon, maximum truck carrying and working hours of drivers. The four layers in network configuration are consisting of suppliers, depots, distribution centers and demand. The location of supplies and demand are known and fixed. However, the interval of demand is fluctuation and not known. The problem is solved by the mixed linear integer programming with robust optimization for deterministic demand and demand uncertainty. Then, given the structure is continued to investigate with cost concerning of opening facility location cost, transportation cost and transshipment cost.

List of Publications

Peer reviewed publications

1. R. Kasemsri, K. Sano and H. Nishiuchi, "Robust Optimization of Relief Distribution under Demand Uncertainty", E-Proceedings of 3rd Conference of Transportation Research Group of India (3rd CTRG).
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Conferences presentations

1. 52nd Japan Society of Civil Engineers (JSCE) Infrastructure and Planning Conference held on 21st-23rd November 2015 at Akita University, Akita, Japan. "A Multi-hierarchy Facility Location with Routing for Relief Distribution Improvement under Demand Uncertainty". R. Kasemsri, K. Sano, H. Nishiuchi and A. Jayasinghe. (Included in the conference proceedings)
2. 3rd Conference of Transportation Research Group of India (CTRG) held on 17th-20th December 2015 at Kolkata, India. "Robust Optimization of Relief Distribution under Demand Uncertainty". R. Kasemsri, K. Sano and H. Nishiuchi. (Published in the E-Proceedings of 3rd Conference of Transportation Research Group of India (CTRG))
3. 22nd International Conference on Urban Transport and the Environment held on 21st - 23rd June 2016 at Crete, Greece. "Robust optimization of facility location models and fundamental resource estimations under demand uncertainty, a case study of relief distribution". R. Kasemsri, K. Sano, H. Nishiuchi and A. Jayasinghe. (Published in the International Journal of Transport Development and Integration)

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The introduction section of this study is compiled into six subsections in order to describe a principle of the facility location problem with deterministic and also handling with uncertainty of demand. The first part is explained an overview of this chapter. Afterwards, background of the study is a next mention. Then, a description of the problem statement and an objective of the study are conducted respectively. Next, scope and limitation are described. Finally, organization of all in this study is presented.

1.2 Background of the study

Logistics and distribution

Distribution and logistics has been an important feature not only of industrial and economic life but also become a concerning issue in humanitarian logistics. There are some associated names and different definitions are applied to distribution and logistics in the industrial and economic terms. Heskett (1973) defines the logistics as “The management of all activities which facilitated movement and the co-ordination of supply and demand in the creation of time and place utility”. While, Cooper (1994) provides the definition that “Logistics is the strategy management of movement, storage and information relating to materials, parts and finished goods in supply chains, through the stages of procurement, work in progress and final destination. Its overall goal is to contribute to maximum current and future profitability through the cost effective fulfilment of customer orders”. Meanwhile, humanitarian logistics have been provided in the similar meaning however more concerns about human effects. Thomas and Mizushima (2005) defined the humanitarian logistics that “It is the process of planning, implementing and controlling the efficient, cost-effective flow of and storage of goods and materials as well as related information, from point of origin to point of consumption for the purpose of meeting the end beneficiary’s requirements.” Van Wassen hove (2006) proposed that “the humanitarian logistics consists of the processes and systems involved in mobilizing people, resources, skills and knowledge to help vulnerable people affected by disaster.”

Disaster

Many aspects of research works are explored in various fields with post disaster such as structural analysis, architecture analysis, social analysis, information system, also logistic analysis and so on. The most widely accepted definition of disaster is the one has been proposed by the world Health Organization. In accordance with this definition, a disaster is any occurrence that brings about damages, destruction, ecological disruption, loss of human life, human suffering, deterioration of health and health service on a scale adequate to warrant an extraordinary response from outside the affected area (Barbarrosoglu and Arda, 2004). There are two types of disasters which are natural disaster and man-made disaster. Moreover, these types of disaster are also separated in two levels which are sudden-onset and slow-onset (L.N. Van Wassenhove, 2006). The classification of disasters is showed in the Figure 1. Nowadays, the natural disaster such as flooding, storm, fire, earthquake and tsunami is often occurs and more deteriorating in the world, for examples the biggest blackout in North America in 2003, The Indonesian tsunami (and earthquake) in 2004, The Hurricane Katrina in 2005, The Heiti earthquake in 2010 and the Chilean one in 2010. There are many enormous effects in humanitarian which are including deaths, injuries, healthy, homeless, malnutrition and etc.

	Natural	Man-made
Sudden-onset	Earthquake Hurricane Tornadoes	Terrorist Attack Coup d'Etat Chemical leak
Slow-onset	Famine Drought Poverty	Political Crisis Refugee Crisis

Figure 1-1 The classification of disaster

Source: L.N. Van Wassenhove, 2006.

On March 11, 2011, the 9.0 Magnitude Earthquakes and more than six meters of tsunami attacked in the northeastern of Japan. Then, it was followed by the 7.4 Magnitude aftershocks and 10 meters of tsunami occurred. This was the most severe seismic disaster in 140 years recording in Japan and was the one of five large scales in the world. There were a big number of people around 16,000 fatalities, 2,700 missing, and 6,200 injured.

Moreover, over than 50 million were homeless people because of effects from disaster such as flooding, building collapse, rock avalanches, mud flows, nuclear incidents which is including radiation releases and etc. There were three main prefectures that were attracted by highest levels of tsunami which was approximately 10 meters. These prefectures were Miyagi, Iwate and Fukushima. Not only these prefectures but also more than 20 cities in Japan were affected by this enormous natural disaster. Aftermath the tsunami was occurrence, the responsibility was a most importance to amelioration. The operations were separated in three levels which are a donor from international level, a prefecture level and a local city level.

Humanitarian logistics

In general, there are three steps in term of logistics which are Pre-disaster humanitarian logistics, During-disaster humanitarian logistics and Post-disaster humanitarian logistics. The Pre-disaster humanitarian logistics are including mitigation and preparedness. Next, the During-disaster humanitarian logistics are concentrated with the response. Other, the Post-disaster humanitarian logistics are consisted of response and recovery. Logistic is the mainly supporter in two ways which are a victim rescuing or evacuation of people and an essential providing to survive them. Evacuation usually proceeds during the initial stage in the Post-disaster humanitarian to extricate the injured and casualties from the area to relief places while logistics activities continue for a longer period of time as they aim to provide the necessary disaster relief commodities to people in the affected areas. Moreover, they transport the injured people to the hospitals or the emergency medical centers within the affected area. An efficient planning of logistical activities during the earthquake response phase can therefore tremendously decrease the loss of human life in the event of an earthquake (Mehdi et al., 2013). This study categorizes sub three problems in logistics activities; location, routing, location-routing which are realized with a cost efficiency, a quick response, a satisfy demand and an environment issue. Moreover, the efficiency of planning and coordinating of logistic activities are necessary to treat them.

Facility location and allocation

The facility location and allocation problem is one of most importance in logistic activity. Suitable transportation network facilities must be available to operate personnel, equipment, raw material, and products to and from the plant or supplier. Highways,

railways, waterways, and airways are common mode which used to transport raw materials and finished goods. The volumes and type of items often determine the most proper mode of transportation. Some research has done about the appropriate location of medical centers that the evacuees can quickly accessibility. Not only the medical centers but also the location of shelters is conducted. These research details are shown in next chapter of literature reviews. This study intends to design that where the depot locations should be located with the cost efficiency and also satisfy with the demand. This study is considered the vital item distributions to relieve the large number of survived victims. A bottle of water is considered to be a requisite item for preliminary succor leading to the single commodity problem. This model is to design principally the distribution network with multi-layer of facility locations by using the multi-source Capacitated Facility Location Problem (CFLP), or sometime is called the Capacitated Concentrator Location Problem (CCLP). The model is designed for single and double layers of depots to make the model more realistic and satisfied with the demand. The number of required facilities and the locations of them are the two main questions in the facility location problem. Then, the assigned link flows of every facility location are designed. The distribution networks consist of a number of suppliers at fixed locations, a number of central depots and depots sites in unknown locations (need to select from a set of potential sites), and finally a number of shelters or demand zones in fixed locations. The model of facility location and transportation design is examined to obtain the minimized total cost in the initial stage demand. There are three costs for distribution. They are travel cost, transshipment cost and opening depot cost. The initial stage is calculated with the determined demand. Then, this model is solved by mixed-integer programming, which offers the appropriate depot locations, total delivery cost and transportation amount. There are five assumptions for facility location model. The first is proposed that the set of potential central depot site is designated for only single hierarchy named as depots. The second and the third are assumed in that the set of potential central depot site is determined for double hierarchies called as central depots, which are located inside the affected areas, and depots. However they are dispatched by distinct truck operation. The fourth and fifth are same structure with second and third one but different location of central depots, which are sited outside of affected areas.

Mixed integer programming is popularly applied to solve the facility location problem. A general concept is determination of two types of variables, one is binary (0, 1) variables

and another is integer variables. Mostly, the selected location variables are defined as binary variables, 0 is assigned that those locations are not selected and 1 is assigned that those locations are selected to open as facility location. Another type of variables is integer variables. These variables are supported to obtain the transportation amount of each link that the facility locations are opened. The first general category is to minimize the total cost of delivery or distance minimization with satisfaction for every constraint. The second common category is oriented for demand objectives which consists demand coverage and demand assignment. The remaining about ten percent of all articles belong in either of last two objective categories. One of these is profit maximization while another one is objectives that address environmental concerns.

Uncertainty parameters

Moreover, this study also stresses the importance of uncertainty of parameters, here is the demand uncertainty. In fact, the post disaster circumstances usually face with the fluctuation of number of evacuees and un-precisely prediction. Therefore, this study aims to handle the facility location problems or mixed integer problems with the uncertainty of demand. The models that illustrate for uncertainty parameters are known as robust optimization model which are opposite with deterministic models. Previously, there are various solution approaches to tackle with the uncertainty of parameters. Here is name list of some techniques which have been used in the previous, sensitivity analysis, stochastic programming, chance constraint programming, fuzzy set modeling, robust optimization, stochastic decision processes based on Markov processes and global optimization. More details are discussed in the literature reviews. This study considers Robust Optimization (RO) which more recently apply to handle under uncertainty parameter models.

In the point of researches, incorporating uncertainty parameters into the planning network design problem and the optimization for robust solutions are become popularity and increasingly important. A robust approach to solving linear optimization problems with uncertain data was proposed in the early 1970s and has recently been extensively studied and extended, a large amount of researches are studied in the theory of robust optimization. Soyster (1970) proposed a linear model to construct solution that is feasible for all data that belong in a convex set. Kouvelis and Yu (1997) discussed the robust discrete optimization and its applications. Ben-Tal and Nemirovski (2000) studied the problem that the robust solution of linear programming problems contaminated with

uncertain data. Bertsimas and Brown (2009) proposed a methodology for constructing uncertainty sets for robust linear optimization based on decision maker risk preferences. Ben-Tal, Bertsimas and Brown (2010) proposed a soft robust model for optimization under ambiguity. Song and Luo (2010) developed a robust portfolio selection model under ellipsoidal uncertainty. Many fields of the academic study had been discussed about uncertainty parameter handling with robust optimization approaches for instance a design and operations of chemical processes, an electrical capacity system, supply chain networks and transportation planning design. The robust model is useful to help the planner identify trade-offs between the inability to recover fully costs for excess link flow, and the need to manage transportation resource such as trucks, drivers and etc. to satisfy with the demand.

Robust optimization

This study considers Robust Optimization (RO) which is provided by AIMMS software and more recently applied to handle under uncertainty of the parameters in the models. Robust optimization is designed to meet some major challenges associated with uncertainty-affected optimization problems as follows; to operate under lack of full information on the nature of uncertainty, to model the problem in a form that can be solved efficiently and to provide guarantees about the performance of the solutions. Robust Optimization is an uncertainty modeling approach suitable for a situation where the uncertainty ranges are known and not necessarily the distribution. Typically some inputs take an uncertain value anywhere between a fixed minimum and a maximum. This demand uncertainty can present how the worst case is when we consider the fluctuation of the demand. The Robust Optimization is very suitable for many problems as only simple inputs are required from the user about the data uncertainty because there are no scenarios or distribution functions need to be defined. In contrast with Stochastic Programming that can result in large models when considering many scenarios. However, these many scenarios should make it important to limit the number of considered scenarios, but therefore also affect that the results are less robust. The advantage of Robust Optimization models is that they grow only slightly when uncertainty is added. As the result, the model can be solved efficiently. Many fields of the academic study had discussed uncertainty parameter handling with robust optimization approaches, for an instance, a design and operations of chemical processes, an electrical capacity system, supply chain networks

and transportation planning design. The robust model is useful to help the planner to identify trade-offs between the inability to recover fully costs for excess link flow, and the need to manage transportation resource such as trucks, drivers and etc. to satisfy with the demand.

Routing

As earlier mentioned, this study introduces some basic concepts for locating facilities and assigning demand to these locations. In addition, this study further focuses to develop the tour or well known as routing. There are several logistic problems with somewhat modified models, this study want to develop a part or a route that connects all demand points that a truck can deliver. The objective is to reduce the minimized transportation cost which relates to reduce the total distance travelling for the tour. Such problem can be known as tour development problem or another classic is the travelling salesman problem which becomes the basic ideas to solve routing problem. The original concept is that a salesperson must visit many customers, each in different cities. They start from their origin city and visit each city to which they are assigned to serve once and only one visiting before returning back home. The distance between all pairs of the cities is fixed and known. The difference between the travelling salesman problem and truck routing problem is, the capacity of vehicle in their travelling or goods carrying is not limited in the travelling salesman problem. As a results, all customers can be visited in one continue tour, starting and finishing at the home city. Similarly to the travelling salesman problem however, the truck routing has some additional considerations affecting the route generating. Referring to the Logistics of Facility Location and Allocation by Dileep R. Sule (2001), some of these practical constraints follow:

- Territory over which the truck is to be operated.
- The load type and the equipment required for such loading or unloading operation as part of the truck. For example, a heavy load may need a truck fitted with lift.
- Truck capacity in weight and volume.
- Maximum number of stops desired on a route.
- Maximum travel time or mileage that should be allowed.
- Any federal, state, or local legal requirement.

The truck routing problem can be formulated as an integer programming problem. It identifies the possible route that a truck can generate and then optimally assigning the trucks to some of these routes which minimize an objective function, such as transportation cost, travelling time and etc. This problem has proved to be NP-hard which means the time required to solve the problem increase almost exponentially whenever the number of customer becomes large, after about 20 customers.

Location-Routing problem (LRP)

Location-Routing problem or LRP is the two integrated optimization problems which becomes intensively concerning topics in recent. This integration is arisen as a new operation management which aims to increase distribution efficiency. The design of distribution systems raises hard combinatorial optimization problems because generally, the facility location problems must be solved at the strategic decision level to determine the transportation facilities such as factories and warehouses, while vehicle routes must be built at the tactical or operational levels to supply customers. The main difference between the location-routing problem (LRP) and the classical location-allocation problem is that, once the facility is located, the former requires a visitation of customers/suppliers through tours, whereas the latter assumes the straight-line or radial trip from the facility to the customer/supplier. Therefore, the classical location-allocation problem ignores tours when locating facilities and subsequently may lead to increased distribution cost (*Salhi and Rand, 1989*).

1.3 Statement of the problems

As well know that there are enormous impacts both a humanitarian crisis and massive economic aftermath of the 2011 Tohoku earthquake and tsunami. Also as mention before, the disaster logistic activities for both commodity dispatch and evacuations become more serious awareness with many issues such as saving life of refugees, maximum evacuee movement, efficiency cost and so on. Their functions are to operate the rescuing and amelioration of huge amount of victims.

The Tohoku's earthquake is the great earthquakes in the east part of Japan. Many cities are damaged along the coast areas of Tohoku region. Moreover, the areas around Fukushima Daiichi Nuclear Power Plant are warned to be evacuation zones because of effecting from the tsunami. Considered the large amount of evacuees, there are

approximately more than 340,000 people had been displaced from their accommodations to shelters. The estimation of economic losses from some analysts is evaluated as amount 10 trillion yen for both immediate problems with industrial production suspended in many factories, and the longer term issue of the cost of rebuilding. However, the Japan government had estimated that this cost is much higher which this cost of just the direct material damage could exceed 25 trillion yen. Moreover, the several costs are generated to recovery the situations during disaster and post disaster period for example reconstruction cost, rescue cost, logistics cost and etc. The logistic cost is approximately 80 percent from overall of operation responding cost. Therefore, the cost efficient should be one of many aspects that must consider. By this reason, this study would like to play on the logistic cost efficiency. An improved supply distribution cost can reduce the expenditure of the whole of operation cost during the amelioration period. Even the total delivery cost minimization is not only one to consider in humanitarian logistics however it is a good criterion to compare the results of distinct network systems.

This study intends to design the two layers of facility locations in order to make the network more realistic and comprehensive. Normally, the network configuration can be consisted at least three layers which are suppliers, facility location and retailer demand. However, the fact is rather more complication. Therefore, the reasons that this study is designed for two layers of depots are to make the model more flexibility and more reasonable. Moreover, not only considering the model by using deterministic demand but this study also applies the uncertainty demand to the facility location model. By the reasons that, during post disaster, it usually meets with the fluctuation of demand in the real circumstances. This demand uncertainty can present the how the worst case is when we consider the fluctuation of demand. In addition, this study would like to illustrate the newish methodology, RO which is simply deal with uncertainty parameters and have never been solve with the facility location problem before.

1.4 Objective of the study

In such background, this study attempts contributes to the previous research by considering the worst-case scenarios of the multi-facility location problems under uncertainty demand. Accordingly, main objective of the study is to tackle the facility locations problem and allocations with demand uncertainty function while integrating vehicle routing. This study would like to design the facility location and also optimize the

amount transportation of the relief items. The multi layers of facility location problem with deterministic are studied at the primary. Moreover, also emphasize the uncertainty demand by using robust optimization model. We optimize the multi-echelon of facility location and allocation problem simultaneously with interval demand also known as ellipsoidal uncertainty set which is a rather new approach that has never seen in the location facility fields.

To consider the operation constrains, the model is restricted with the maximum storage in each echelon, maximum truck carrying and working hours of drivers. The four layers in network configuration are consisting of suppliers, depots, distribution centers and demand. The location of supplies and demand are known and fixed. However, the amount of demand is fluctuation and not known. The problem is solved by the mixed linear integer programming with robust optimization for deterministic demand and demand uncertainty. Then, given the structure is continued to investigate with cost concerning of opening facility location cost, transportation cost and transshipment cost. A bottle of water is considered to be a requisite item for preliminary succor.

This study examines five structures of distribution systems by the number of network configurations and distinct truck capacity to find the most effective network under the demand uncertainty. Moreover, Not only a single deterministic demand model is investigated in each structure but also multi demand scenarios are examined. This method is needed to analyze the sensitivity of three different network structures. The demand is determined for five scenarios which deviate from the historical case in both sides optimistic and pessimistic. These five demand scenarios are separated as less than actual demand by 20 percent (S1) and 10 percent (S2), actual demand (S3), and more than actual demand by 10 percent (S3) and 20 percent (S4) respectively. The objective of the study can be summarized are:

- To manage the facility location problem in the context of both deterministic demand and uncertainty demand, and subsequently compare their robustness according to five demand scenario assumptions.
- To evaluate the total delivery cost efficiency on different networks. Accordingly, we analyze the model on five different networks by the structures and truck sizes.
- To select the best network and improve it by making practical uses of routing.

- To develop the model and expand for multi-period location problem.

The expected results of facility location model with routing are defined as follows:

- To search the appropriate locations of depots to distribution the relief items in Miyagi prefectures.
- To allocate the transportation link flow at each network configurations.
- To minimize the total delivery cost which includes the transportation cost, the opening facility cost and the transshipment cost.
- To search the practical routing to reduce the total delivery cost.

1.5 Scope and limitations

This study is mainly focusing with the most effect areas and most number of evacuees in Tohoku's earthquake which are therein Miyagi prefecture. The exactly candidate of facility locations were not recorded. Thus, the candidate depot locations are determined by demand zone aggregation. The amount of demand can estimate from the number of victims. The available amounts that can be able to serve for each supplier are not known, calculated by the proportional of distance. Therefore, the study can be categorized for four sections which are identify the locations of suppliers and shelters which are known and fixed locations, formulate the formulation to estimate the parameters, formulate the model to estimate the minimize total cost with deterministic demand and formulate the model to estimate the minimize total cost with uncertainty demand followed as the skeleton in figure 1-2.

The limitation of this study is the data analysis and network assumptions. The results and findings are rather effects with this data. The two layers of facility network and the large truck size operation assumptions are probably advantage when they match with the right demand.

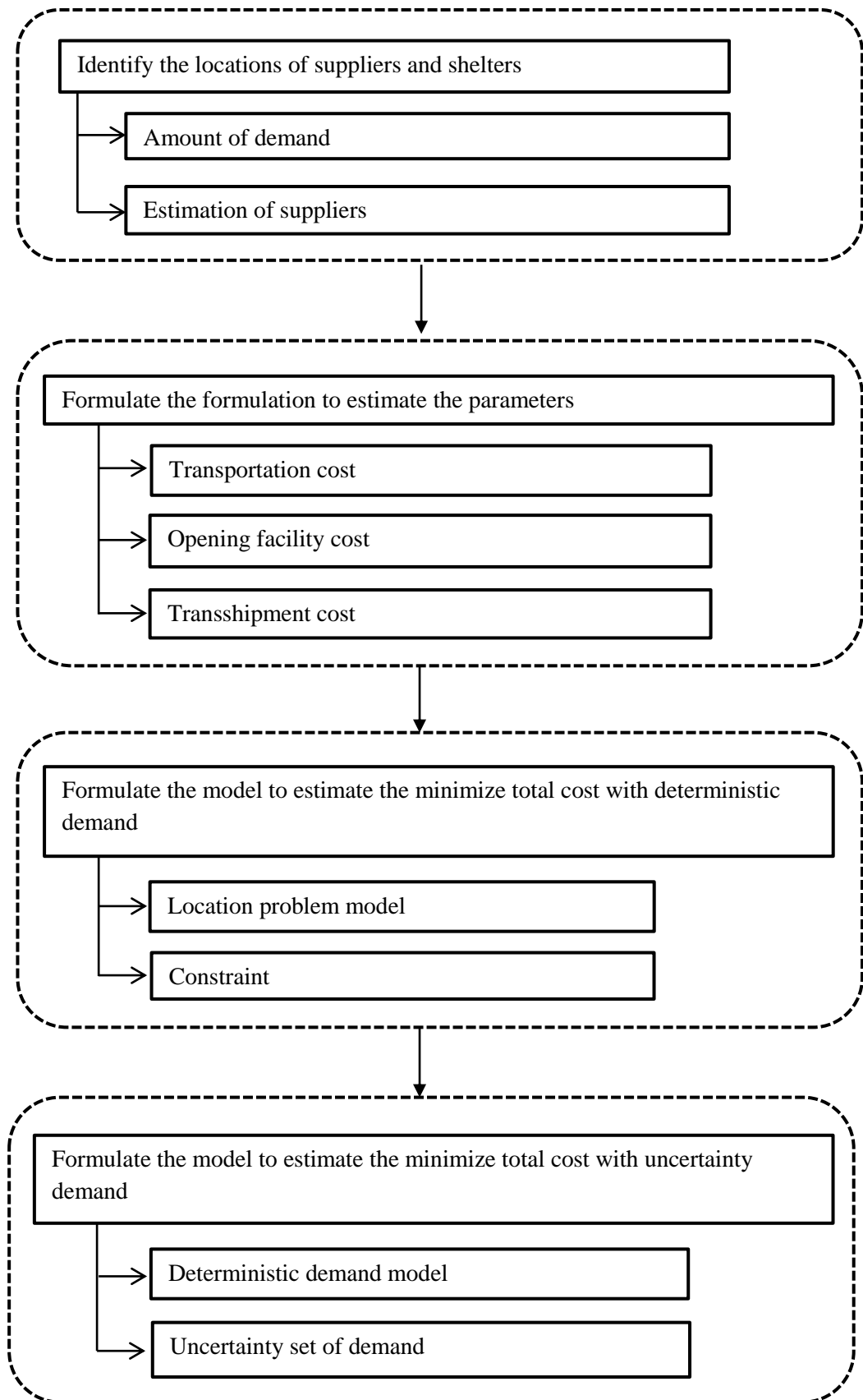


Figure 1-2 shows the conceptual framework of the study

1.6 Dissertation organization

The dissertation is divided into six chapters. Chapter 1 explains the general ideas for this research which are including background, statement of the problems, objectives of the study, and scope and limitations.

Chapter 2 reviews some relative literature in the fields of facility location problem, the methodology to handle with uncertainty parameters, robust optimization approach and finally the relief distribution.

Chapter 3 describes the study areas, scope of the study and data collection. All of needed input parameters are explained in this chapter which is including the amount of demand, locations and cost parameters.

Chapter 4 explains research assumption details and scenario frameworks. The diagram of network assumptions and demand scenarios are explained in this chapter.

Chapter 5 presents the mathematical model and notations of the problems which is multi-source facility location problem of deterministic demand and uncertainty demand. Afterwards, the truck route developing model is performed.

Chapter 6 illustrates for the result analysis of those different model assumptions as mentioned before. The result mainly shows the total delivery cost, the facility sites, number of opened facility, the fundamental resource requirement, the sensitive value comparison and then the result of routing after improvement.

Chapter 7 applied the proposed model to another case study which has different geographical characteristics.

Finally, chapter 8 discussed for the conclusions and recommendations for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There were various aspects that have some dealings with this study. Therefore, this chapter intends to review some relative studies which can be separate for five main aspects as the original Facility Location Problems, the uncertainty parameter problems, Robust Optimization, Location-Routing Problem and the emergency relief distribution.

2.2 Facility location problem

Since before 1990 there were many existence researches of facility location decision problem. Thereby, *John Current et.al (1990)* reviewed such kinds of this problem that play on multi-objective analysis. They introduced that the facility location decision models were attracted from several researchers in many fields since they were pioneered by Alfred Weber (1929). The models were appeared from the academic fields of economics, engineering, geography, mathematics, operation research, planning and regional science. This survey reviewed 45 articles which were published in 20 of different journals. They set three scope of study. First, they have focused on articles which formally structure location problems in a multi-objective framework. Secondly, the articles which propose multi-objective techniques for the generation of alternative facility location schemes were limited in this review. Finally, the articles that publish in major English language journals were limited. Moreover, they categorize the objectives of the study in fours classification which are cost minimization, demand oriented, profit maximization and environmental concern. There are some basic elements of facility location models were found in *Taniguchi et.al (2001)* which are bellowed:

- (a) Space (defining the distribution of demand points and candidate sites of facilities)
- (b) Number of facilities to be located
- (c) Size of individual facilities
- (d) Number of existing facilities
- (e) Objective of decision makers
- (f) Demand (distribution, actual demand, variation)
- (g) Candidate sites for facilities (distribution, number)

- (h) Facility user behavior
- (i) Capacity limits on facilities

Following by above elements, the facility location models can be categorized into three types. Firstly, continuous location models mean that at any point on the plane is available for candidate sites. In the others word the number of candidate sites is infinity which lead to the models can be determined as a non-linear programming problem under the assumption that the facility users move straight along to the available facilities. Secondly, network location models are infinite number of candidate sites. However, those are only nodes or links which allow the facility users can only move within the networks. This model is more realistic because normally, facilities users are unable to move straight on the plan however they are able to move along nodes or links (the road network). Thirdly, discrete location models consider a finite number of candidate sites. The optimal locations are determined by using the location of candidate sites and predetermined cost incurred from demand nodes to the candidate sites.

2.3 Uncertainty parameters

Josef (2004) gave an overview on the state-of-the-art and recent advances in mixed integer optimization to solve planning and design problems in the process in industry. They performed modeling for optimization both deterministic and under uncertainty. Stochastic programming for continuous LP problems is now part of most optimization packages, and there is encouraging progress in the field of stochastic MILP and robust MILP. The list and comments of various solution approaches that have been used in real world projects were illustrated below.

Sensitivity analysis is a difficult problem concept in the context of MIP and mathematical point of view. This is not a serious approach to solve optimization problems under uncertainty. Nevertheless, it is frequently used by engineers or logistic researchers to study the role of certain parameters or scenarios.

Stochastic Programming or in particular multi-stage stochastic models, also called recourse model have been used since long in the previous study. The stochastic programming contains the information on the probability information of the stochastic uncertainty and the distribution does not depend on the decision in most cases. Most of the modeling languages used in mathematical optimization use scenario-based stochastic programming for LP problems. While stochastic MILP (S-MILP) is an active field of research [detailed discussions on various algorithms for stochastic integer optimization.

Chance constrained programming has also a long history. Chance constrained programming deals with probabilistically constrained programming problems, i.e., a constraint holds with a certain probability, and is quite useful to model, for instance, service level features in supply chain optimization problems. There were considered uncertain processing times in batch processes and used chance constraints to model the risk of violating temporal constraints. Some researches proposed a systematic approach to solving approach to solving nonlinear chance constrained optimization problems. As stochastic programming, chance constrained programming also requires probability distributions to be specified. Unfortunately, chance constrained programming is not yet found in commercial software packages.

Fuzzy set modeling supporting uncertainties which fall into the class of vague information and which are expressible as linguistic expressions [fuzzy set theory in the context of LP problems has been used. This methodology is much younger than SP and is used when, from the SP point of view, the information is incomplete.

Robust optimization is a quite relatively new methodology to handle with optimization under uncertainty in case that the uncertainty does not have a stochastic background and/or that information on the underlying distribution is not or hardly available which is, unfortunately, often the case in real world optimization problems. The approach replaces linear models by nonlinear ones. Direct extensions of Ben-Tal's approach for MILP problems have been developed for batch scheduling under uncertainty by *Lin et al. (2004)*. A different approach to robust optimization has been developed by *Bertsimas (2003)*. This approach claims to have the advantage that the type and the complexity of the problem do not change, and it is applicable to MILP problems. While in stochastic programming the number of variables increases drastically, in this robust optimization approach the number of variables approximately only doubles.

Stochastic decision processes based on Markov processes and/or the control of time discrete stochastic processes allow for decision-dependent probability distributions but typically require stronger assumptions on the stochasticity. The paper by *Cheng et al. (2003)* gives an excellent illustration of such techniques applied to design and planning under uncertainty.

Global optimization and the techniques, such as interval arithmetic may not appear as a particular tool to deal with uncertainties. Indeed, it has nothing to do with uncertainties as such (although uncertainties can be part of the deterministic equivalent model). However, global optimization, in particular when based on interval analysis, can

provide safe results, for instance, in safety analysis. The author was once involved in a project modeling a chemical reactor, in which, under no circumstances, the pressure was allowed to increase a certain value. Thus, the problem was to establish, for a range of temperatures and other physical parameters subject to deviations from the nominal value, that the maximum pressure could never exceed the critical value.

Shabbir and Nikolaos (1998) applied many approach in the design and operations of chemical processes to overcome the difficulty problem of two-stage stochastic optimization models, which is a frequently taken approach. These approaches are studied: two-stage stochastic programming, robust optimization and restricted recourse. They referred that the resulting two-stage stochastic optimization models minimize the sum of the costs of the first stage and the expected cost of the second stage. However, this approach is that it does not report for the variability of the second stage costs and might lead to solutions where the actual second-stage costs are unacceptable. Therefore, they introduced a robustness measure that penalizes second-stage costs or the expected costs.

Tjendera et al. (2005) proposed a stochastic programming model and solution algorithm for solving supply chain network design problems of a realistic scale. They had developed a practical approach for large-scale supply chain network problem under uncertainty. The method was integrated an accelerated decomposition scheme along with the recently developed SAA, the sample average approximation method. The objective function is to minimize the total investment and operational costs. The case study is the supply chain network of a US company that supplies cardboard packages to breweries and soft-drink manufacturers. It was tested for both domestic and global. There were some criteria to measure the efficiency or performance such as CPU time, variability of total cost range, variability of worst cost range with different size of samples. Moreover, many acceleration schemes were compared for example logistics constraints (LC); trust region (TR); cut disaggregation (CD); Knapsack inequalities (KI); upper-bounding heuristic (UH); and cut strengthening (CS). This proposed methodology provided an efficient framework for identifying and statistically testing a variety of candidate design solutions. Their results presented the computational efficacy of the proposed method. Furthermore, it demonstrated that the candidate solutions identified by the proposed method are not only superior to traditional mean value problem solutions in an expectation sense, but also result in significantly smaller cost/cash flow variability, and this reduction is more pronounce in case of higher variability in the uncertain environment.

Tsiakis et al. (2001) designed the multi-echelon and multiproduct supply chain networks under uncertainty in product demand. The networks include a number of manufacturing sites, a number of warehouses, a number of distribution centers and finally a number of customer zones, where the manufacturing sites and customer zones are known and fixed, and where the warehouse and distribution centers are unknown and need to be selected from a set of potential locations. They performed a mixed-integer linear programming optimization to determine the number, location and capacity of warehouse and distribution centers to be opened. Moreover, the transportation links, flows and production rates of materials are established in the network. The minimized total annualized cost taking into account both infrastructure and operating costs is the objective. They classified the two primary approaches to handle with uncertainty as the probabilistic approach and the scenario planning approach. The probabilistic models diagnose the uncertainty issues of the supply chain by handling one or more parameters as random variables with known probability distributions. This approach was studied in many researches of *Cohen and Lee (1988)*, *Svoronos and Zipkin (1991)*, *Lee and Billington (1993)*, *Pyke and Cohen (1993)*, and *Lee et al. (1997)*. On the other hand, *Mulvey et al. (1997)* predicated that the scenario planning attempts to catch uncertainty by generating it in terms of a moderate number of discrete realizations of the stochastic quantities or constituting distinct scenarios. The objective is to find robust solutions which perform well under all scenarios. These are several common approaches to robust optimization seeking, for example, to optimize the expected performance over all scenarios, to optimize the worst-case scenario, or to minimize the expected or worst-case “regret” across all scenarios.

Jin et al. (2013) studied the continuous transportation network design problem with demand and cost uncertainties while the generated trip between each origin-destination pair is deterministic. They proposed a bi-level uncertain model with robust optimizations, here is separated as upper-level and lower-level problem. The costs are expanded as uncertainty in the upper-level problem by adding random variables to the cost function coefficients, these random variables belongs to $[0,1]$. Then, the demand between each origin-destination pair is performed in the lower-level problem as uncertainty and belongs to a bounded interval and an ellipsoid. Finally, the problem was solved by a genetic algorithm combined with the Frank-Wolfe algorithm. There are the advantage of

operability and stability from the robust model over than the deterministic model in the numerical examples.

Dimitris et al. (2007) surveyed both theoretical and applied in the field of Robust Optimization (RO). The overall aim of this paper is to outline the development and main aspects of Robust Optimization, with an emphasis on its power, flexibility, and structure. There are four main focuses in this surveying. First of all, they focus on the computational attractiveness of RO approaches and also the modeling power and broad applicability of the methodology. Moreover, the most prominent theoretical results of RO over the past decade were reviewed. they also presented some recent results linking RO to adaptable models for multi-stage decision-making problems. Finally, they highlight successful applications of RO across a wide spectrum of domains, including, but not limited to, finance, statistics, learning, and engineering. They said that Stochastic Optimization starts by assuming the uncertainty has a probabilistic description. However, this study considers Robust Optimization (RO) which is a more recent approach to optimization under uncertainty. The uncertainty in Robust Optimization model is not stochastic, but rather deterministic and set-based. Instead of seeking to immunize the solution in some probabilistic sense to stochastic uncertainty, here the decision-maker constructs a solution that is optimal for any realization of the uncertainty in a given set. The motivation for this approach is twofold. First, the model of set-based uncertainty is interesting in its own right, and in many applications is the most appropriate notion of parameter uncertainty. Next, computational tractability is also a primary motivation and goal. It is this latter objective that has largely influenced the theoretical trajectory of Robust Optimization, and, more recently, has been responsible for its burgeoning success in a broad variety of application areas. Central issues they seek to address in this paper include: 1. Tractability of Robust Optimization models: In particular, given a class of nominal problems (e.g. LP, SOCP, SDP, etc.) and a structured uncertainty set (polyhedral, ellipsoidal, etc.), what is the complexity class of the corresponding robust problem? 2. Conservativeness and probability guarantees: How much flexibility does the designer have in selecting the uncertainty sets? What guidance does he have for this selection? And what do these uncertainty sets tell us about probabilistic feasibility guarantees under various distributions for the uncertain parameters? 3. Flexibility, applicability, and modeling power: What uncertainty sets are appropriate for a given application? How fragile are the tractability results? For what applications is this general

methodology suitable? Afterwards, they give (abridged) answers to the three issues raised above.

1. Tractability: In general, the robust version of a tractable optimization problem may not itself be tractable. They outline tractability results, which depend on the structure of the nominal problem as well as the class of uncertainty set. Many well-known classes of optimization problems, including LP, QCQP, SOCP, SDP, and some discrete problems as well, have a RO formulation that is tractable.

2. Conservativeness and probability guarantees: RO constructs solutions that are deterministically immune to realizations of the uncertain parameters in certain sets. This approach may be the only reasonable alternative when the parameter uncertainty is not stochastic, or if no distributional information is available. But even if there is an underlying distribution, the tractability benefits of the Robust Optimization paradigm may make it more attractive than alternative approaches from Stochastic Optimization. In this case, we might ask for probabilistic guarantees for the robust solution that can be computed a priori, as a function of the structure and size of the uncertainty set. In the sequel, we show that there are several convenient, efficient, and well-motivated parameterizations of different classes of uncertainty sets that provide a notion of a budget of uncertainty. This allows the designer a level of flexibility in choosing the tradeoff between robustness and performance, and also allows the ability to choose the corresponding level of probabilistic protection.

3. Flexibility and modeling power: In Section 2, we survey a wide array of optimization classes, and also uncertainties sets and consider the properties of the robust versions. In the final section of this paper, we illustrate the broad modeling power of Robust Optimization by presenting a broad variety of applications.

Snyder (2006) reviewed the literature on stochastic and robust facility location models. Their intent is to illustrate both the rich variety of approaches for optimization under uncertainty that have appeared in the literature and their application to facility location problems. In a few instances for which examples in facility location are not available, they provided examples from the more general logistics literature. The literature on facility location under uncertainty has been growing steadily. Roughly half of the papers cited in this article were published in the past 10 years and roughly a third were published in the past five years. The growing interest in these problems is due to the increased recognition of the uncertainties faced by most firms, as well as to improvements in both

optimization technology and raw computing power. When we think of facility location under uncertainty, many of us think only of the two most common objectives:

1. Minimizing expected cost (for stochastic problems) and
2. Minimizing maximum regret (for robust problems)

Yet a wide variety of other approaches has been proposed; this paper discusses at least a dozen such measures. Many of these approaches have modeling, analytical, and computational advantages over the traditional objectives. They have explored these alternative measures with the intention of providing a foundation for researchers doing work in this and related fields. In their opinion, the lack of successful applications can be explained, at least in part, by the cumbersome data requirements of many stochastic models, which often require estimates of many parameters over a range of hypothetical scenarios. Robust optimization reduces the data burden by hedging against a set of scenarios whose probabilities, or even whose composition, need not be known explicitly. On the other hand, robust location problems have proven difficult to solve for realistic instances. Reducing the data and computational burden will be critical for this active body of research to become practical. To that end, they have identified four research avenues that they believe are within the grasp of today's operations research technology:

1. Exact algorithms for minimax problems
2. Multi-echelon models
3. SP technology
4. Meta-heuristics for general problems

Most of the information received at the disaster management center – such as the number of injured people, the amount of demands, network situation, available commodities and hospital's capacities – is imprecise and uncertain. To take this uncertainty into account, *Barbarosoglu and Arda (2004)*, *Ma et al. (2010)*, *Jotshi et al. (2009)* and *Zhan and Liu (2011)* use stochastic modeling techniques. *Zhan and Liu (2011)* consider the uncertainty of demand, supply and the availability of paths in a location-allocation problem, and use chance constraints, scenario planning and goal programming to handle these uncertainties. Moreover, *Jotshi et al. (2009)* use scenario planning to consider the uncertainty of damages and available network. *Ma et al. (2010)* present a min-max robust multi-point, multi-vehicle transportation model to minimize the maximum rescue time for moving injured people. In the model, it is assumed that the distances between affected area and medical centers are uncertain. Scenario planning is used represent the data

uncertainty. *Barbarosoglu and Arda (2004)* develop a two-stage stochastic programming framework for minimizing the expected transportation cost in the disaster response phase. They also use scenario planning-but in two stages-to model data uncertainty. In the first stage, a limited number of Earthquake Scenarios (ES) are considered to determine the magnitude of earthquake. Along the same lines, few impact scenarios (IS) specific possible impacts of the earthquake in each ES.

2.4 Robust optimization

Beyer and Sendhoff (2007) review the state of the art in robust design optimization. Concepts of robustness and robust design optimization have been developed independently in different scientific disciplines, mainly in the fields of operations research (OR) and engineering design. While the methods of stochastic (linear) programming may be regarded as a first approach to deal with uncertainties treating robustness as a side effect only, the notion of robust optimization gained focus in OR after the publication of *Mulvey et al. (1995)*. This survey is concluded as follows. First, they provided a short introduction into the “Taguchi method” of robust design. The seminal work of Taguchi marks the beginning of systematic design methods taking robustness into account. Then, they briefly reviewed the different sources and kinds of uncertainties that can be encountered when facing design problems. Next, in order to incorporate uncertainties in design optimization, robust counterparts to the original design objectives were defined – the robustness measures. After that, they gave an overview over how the robustness measures can be optimized using different approaches from mathematical programming, nonlinear optimization, and direct (randomized) search methods including evolutionary algorithms. Most often robust design optimization will rely on simulation programs evaluating the different designs. Moreover, the outcome of such simulations is often noisy. In such cases direct search methods might be the means of choice. However, it is not clear which of the various direct search algorithms are the most efficient ones. To this end, it would be helpful to have a collection of scalable test function in order to compare the different algorithms. They made a first attempt to propose such a test bed. Being based on the results of this review, the conclusion in final section aims to identify promising future research areas.

Ben-Tal and Nemirovski (2002) said that Robust Optimization (RO) is a modeling methodology, combined with computational tools, to process optimization problems in

which the data are uncertain and is only known to belong to some uncertainty set. They surveyed the main results of RO as applied to uncertain linear, conic quadratic and semi-definite programming. For these cases, computationally tractable robust counterparts of uncertain problems are explicitly obtained, or good approximations of these counterparts are proposed, making RO a useful tool for real-world applications. They introduced that for real-world optimization problems, the “decision environment” is often characterized by the following facts: 1. The data are uncertain/inexact; 2. The optimal solution, even if computed very accurately, may be difficult to implement accurately; 3. The constraints must remain feasible for all meaningful realizations of the data; 4. Problems are large-scale (n or/and m are large); and 5. “Bad” optimal solutions (those which become severely infeasible in the face of even relatively small changes in the nominal data) are not uncommon. They discussed some of these applications, specifically: antenna design, truss topology design and stability analysis/synthesis in uncertain dynamic systems. They also described a case study of 90 LPs from the NETLIB collection. The study reveals that the feasibility properties of the usual solutions of real world LPs can be severely affected by small perturbations of the data and that the RO methodology can be successfully used to overcome this phenomenon.

Yao et al. (2009) developed a robust optimization approach with uncertainty demand of evacuation transportation planning. They had shown the importance of robustness by focusing on infeasibility cost. They found that a robust solution improves both feasibility and quality comparing to a nominal solution.

Mudchanatongsuk et al. (2005) performed the network design problem with faces significant uncertainty in transportation costs and demand. Then, they describe the robust optimization methodology as it pertains to the problem, and introduce the general form of the robust network design problem (RNDP). They presented a robust optimization based formulation for the network design problem under uncertainty of transportation cost and demand. They illustrated that solving an approximation to this robust formulation of the network design problem can be done efficiently for a network with single origin and destination per commodity and general uncertainty in transportation costs and demand that are independent of each other. Then, they proposed an efficient column generation procedure to solve the linear programming relaxation for a network with path constraints. In the Path Constrained Network Design section they introduced a column generation method suitable for the LP relaxation of RNDP with path constraints under polyhedral

uncertainty. Moreover, they also report computational results that present that the approximate robust solution found provides significant savings in the worst case while incurring only minor sub-optimality for specific instances of the uncertainty. Most of earlier work on network design under uncertainty addresses the uncertainty through scenario based stochastic programming. These scenario based methods face the following difficulties: 1) they assume a known discrete description of the uncertainty, which can be a crude approximation of reality; 2) the large number of scenarios used in accurately representing the uncertainty can lead to large, computationally challenging problems; and 3) the solution obtained can be sensitive to possible uncertainty outcomes, a difficulty already addressed by (Mulvey *et al.* 1995). These drawbacks of scenario based approaches are addressed via the Robust Optimization methodology, which aims for a solution that is robust or insensitive to the uncertainty considered and thus is an efficient solution in practice. In addition, this robust optimization approach can obtain robust solutions by solving a problem that is no harder than the deterministic problem. Although initially developed for continuous convex optimization, there are extensions of robust optimization to integer programming and in particular to the network design problem. Alternative robust optimization methods for integer programming problems, such as (Averbakh and Berman 2000; Kouvelis and Yu 1997; Yaman *et al.* 2001), typically rely on combinatorial arguments making them difficult to generalize, in addition they can lead to problems that are significantly more difficult to solve than the deterministic version of each problem. The results show that the approximated robust solution, even its LP relaxation has modest sub-optimality on any specific deterministic scenario while significantly reducing the worst case cost, in particular as the uncertainty increases. In addition the simulation studies show that the approximate robust solution reduces the mean and standard deviation of the total cost, in particular for large problems.

Scott and Stavros (1994) applied the robust optimization model with power system capacity expansion which is faced with uncertainty of power demand. This study had developed the robust optimization model to generate both solutions and model robust. Therefore, the optimal solution from the model is ‘almost’ optimal for any realization of the demand scenarios such as solution robustness. Moreover, the solutions from the model had reduced excess capacity for any realization of the scenarios. There were experiences of the model effectiveness in controlling the sensitivity of its solution to the uncertain input data. Also appearance illustrates the differences of robust optimization

from the original stochastic programming formulation. They referred the general robust optimization modeling framework from *Mulvey et al. (1991)* at first. Then, they were dealing with two distinct components. First is a structural component that is fixed and free of any noise in its input data. Second is a control component that is subjected to noisy input data. The results were compared the robust optimization with the stochastic programming. The objective function of the robust model was composed of three sections. The first section is the expected cost of the model that is covered over all possible scenarios. The second section is the variance of the cost that is weighted by λ . The last section is a function that penalize deviations from feasibility that is weighted by ω . The concept to obtain a measure solution and model robustness is varied the penalty parameters λ and ω . Then, observing the changes in expected value and expected infeasibility are investigated.

Mehdi et al. (2013) considered a multi-objective for logistics planning model with robust optimization in the earthquake response phase. They proposed a multi-objective, multi-mode, multi-commodity, and multi-period stochastic model to operate both commodities and injured people for earthquake response. Moreover, they also developed a robust approach and used for make sure that the distribution plan supports well under the several circumstance during the post disaster. After that, a solution methodology was proposed and used to illustrate the customized robust modeling approach. The proposed linear model includes three objective functions to operate humanitarian and cost issues in both disaster relief commodities and injured people during the initial period of earthquake response. The model is also considered for the emergency relief conditions under capacity and demand uncertainty. Finally, this model is ability for routing and designing solutions for different capacitated transportation modes which included the transport combination.

2.5 Location-Routing Problem

Location-Routing Problems (LRP) is defined in the study of *Drexl and Schneider (2015)* as a mathematical optimization problem where at least the following two types of decisions must be made interdependently. First is that facilities out of a finite or infinite set of potential ones should be used (for a certain purpose)? Second is that vehicle routes should be built, i.e., which customer clusters should be formed and in which sequence should the customers in each cluster be visited by a vehicle from a given fleet (to perform a certain service)? Then they further define a standard LRP as a deterministic, static,

discrete, single-echelon, single-objective problem where each customer (vertex) must be visited exactly once for the delivery of a good from a facility, and where no inventory decisions are relevant. This paper discusses variants and extensions of the standard LRP, which include problems with stochastic and fuzzy data, multi-period planning horizons, continuous location in the plane, multiple objectives, more complex requests or route structures, such as pickup-and-delivery requests or routes with load transfers, and inventory decisions. They categorize the literature papers by important criteria problem type as main characteristics defining new problem variants and sub-characteristics not defining new variants.

1. Main characteristics defining new problem variants.

Deterministic vs. stochastic vs. fuzzy data: In a deterministic planning situation, all problem data are known in advance. Stochastic data means that some information (in most cases, customer demands or travel times) is given in the form of probability distributions. Fuzzy data means that some problem parameters are available in the form of fuzzy numbers. Most papers in this review assume deterministic data. They mentioned four papers dealing with stochastic and five concerned with fuzzy data. The four papers with stochastic are studied by (1) *Ahmadi-Javid and Seddighi (2013)*, (2) *Hassan-Pour, Mosadegh-Khah, and Tavakkoli-Moghaddam (2009)*, (3) *Zhang, Ma, and Jiang (2008)* and (4) *Ahmadi-Javid and Azad (2010)*. The five papers with fuzzy data dealing are (1) *Liu (2004)*, (2) *Zarandi, Hemmati, Davari, and Turksen (2013)*, (3) *Zare Mehrjerdi and Nadizadeh (2013)*, (4) *Sahraeian and Nadizadeh (2009)*, (5) *Nadizadeh and Hosseini Nasab (2014)* and (6) *Golozari, Jafari, and Amiri (2013)*.

Static vs. dynamic vs. periodic problems: Static problems consider one single planning period. The term dynamic refers to problems with multiple planning periods where some information (usually customer demands) is initially unknown and becomes available over time. Periodic LRPs (PLRPs) comprise multiple planning periods and assume complete information on all relevant data. The aim of periodic problems is to determine visiting patterns for customers, i.e., to decide on the periods in which to visit each customer. They have reviewed several papers on PLRPs and one paper on a multi-period LRP, however they have not found any work on a dynamic LRP.

Discrete vs. continuous vs. network locations: In discrete problems, the potential locations for opening facilities are given as a (sub) set of vertices of a graph. In continuous or planar problems, the choice of facility locations is not restricted to a discrete set, but facilities may be located freely in the plane. In network location

problems, a facility may be opened at any vertex of a graph/network or anywhere on a link (edge, arc). The large majority of papers considers discrete problems. The planar problem was first studied by *Schwardt and Dethloff (2005)* for locating a single facility. To the best of their knowledge, the only work dealing with the case of multiple facilities is (*Salhi & Nagy, 2009*), which is already included in the review of *Nagy and Salhi (2007)*. Other than that, they found only two papers on planar location, which are *Schwardt & Fischer (2009)*, *Manzour-al-Ajdad, Torabi, & Salhi (2012)*. They found no paper considering network location.

Single vs. multiple echelons: The basic idea of Multi- or N-Echelon Vehicle Routing Problems and LRPs (NE-VRPs/LRPs) is that customers are not served directly from a central depot but via N legs in an N-stage distribution network. An N-stage distribution network contains $N + 1$ levels of locations. Echelon $n \in \{1, \dots, N\}$ considers transports from location level $n - 1$ to n , see Fig. 1. For each echelon n , there are dedicated vehicles that can only visit the facilities defining echelon n . Load transfers are required between vehicles of different echelons. Many papers on multi-echelon LRPs have appeared in the last few years.

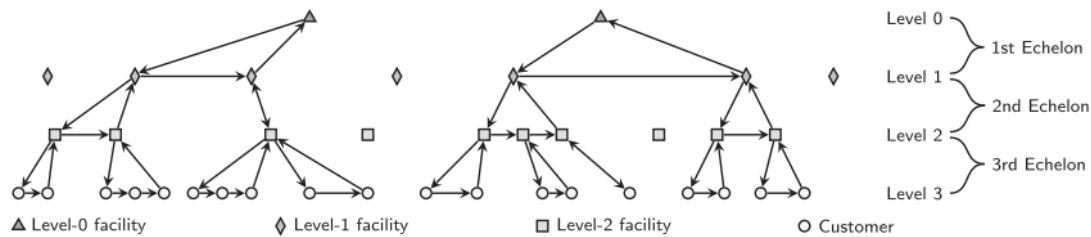


Figure 2-1 Example of a three-echelon routing problem

Source: *Prodhon, C., and Prins, C. (2014)*

Single vs. multiple objectives: Most papers consider a single objective such as minimization of the sum of fixed facility location costs and fixed and variable vehicle routing costs. Some works, though, deal with several objective functions simultaneously. Mostly, qualitative measures such as service levels are considered along with monetary objectives.

Vertex routing vs. arc routing: While in vertex-routing problems service is performed at vertices, Location Arc-Routing Problems (LARPs) consider service requirements along the links of a network. *Ghiani and Laporte (2001)* present a survey on the topic. They have found only two papers that have appeared since then, *Hashemi Doulabi and Seifi (2013)* and *Gouveia, Mourão, and Pinto (2010)*.

Generalized LRPs (GLRPs): Similar to the well-known generalized traveling salesman problem (TSP) (Fischetti, Salazar-González, & Toth, 2002), in GLRPs, the customers are clustered into disjoint groups. The requirement in the GLRP is to find routes, starting and ending at a facility, so that exactly one customer from each group is visited exactly once. Obviously, the LRP variants discussed above can be regarded as GLRPs of the type where each group contains exactly one customer. They found only two papers on GLRPs, Glicksman & Penn, (2008) and Harks, König, & Matuschke, (2013).

Prize-Collecting LRPs (PCLRPs): PCLRPs allow that some customers are not visited by any tour. For these customers, a per-customer penalty (e.g., an outsourcing cost) is incurred. The sum of fixed facility opening, variable tour and outsourcing costs is to be minimized. Here, they mentioned only two papers, and these are Ahn, de Weck, Geng, & Klabjan, (2012) and Glicksman & Penn, (2008).

Split delivery LRPs (SDLRPs): The option of split delivery allows that a customer can be visited more than once and by more than one vehicle in order to fulfill his demand. There is quite a number of papers on VRPs with split delivery (see the survey by Archetti & Speranza, 2008, whereas they found only one paper considering split delivery LRPs (Glicksman & Penn, (2008)).

Pickup-and-delivery LRPs: The tasks to be performed in LRPs may consist in delivering goods to customers from one of several potential facilities, in picking up goods at customers and delivering these goods to one of several potential facilities, or both. In this last case, it is possible that goods must be picked up at one customer and delivered to another. Such problems are called pickup-and-delivery LRPs. It is also possible that a single customer requires both a pickup and a delivery of goods, and that pickup and delivery at a customer have to be done during the same visit. This is called simultaneous pickup and delivery (LRPSPD). Many-to-many LRPs are pickup-and-delivery problems where the planning goal is to locate a network of intermediate facilities or hubs for the transshipment of goods. Pickups and deliveries are performed on local, multi-stop routes starting and ending at a hub; inter-hub transports are usually direct. Such problems arise, e.g., in postal or parcel delivery applications. Papers on pickup-and-delivery and many-to-many LRPs are studied in several papers.

Inventory LRPs (ILRPs): ILRPs integrate inventory management decisions at the facilities, i.e., how much of a good to keep in stock and when and how much to order from the manufacturer. Several papers have integrated such a component into an LRP.

2. Sub-characteristics not defining new variants

Besides the above characteristics, LRPs may differ with respect to the following by these aspects:

- (i) (Un) directed network.
- (ii) (Un) capacitated facilities.
- (iii) (No) fixed costs for opening a facility.
- (iv) (Un) limited/(un) capacitated fleet.
- (v) Homo-/heterogeneous fleet.

They discussed that these aspects do not change the nature of a problem so much as to constitute a new LRP variant. The majority of the reviewed papers consider capacitated facilities with fixed costs for opening and with capacitated vehicles. Therefore, they only indicate exceptions from this ‘rule’.

2.6 Relief distribution

Oh and Haghani (1996, 1997) analyze the transportation of different disaster relief commodities such as food, clothing, medicine, medical supplies, machinery and personnel to minimize the loss of life and maximize the efficiency of the rescue operations. The authors formulate a multi-commodity, multi-modal network flow models for generic disaster-relief operations. Other commodity logistics planning models are provided by *Barbarosoglu et al. (2002)*, *Ozdamar et al. (2004)*, *Tzeng et al. (2007)*, *Sheu (2007, 2010)*, *Nolz et al. (2011)*, *Lin et al. (2011)*, *Zhan and Liu (2011)*, *Afshar and Haghani (2012)*, and *Zhang et al. (2012)*. *Barbarosoglu et al. (2002)* focus on the use of helicopters for aid delivery and rescue missions during natural disasters. The authors use existing research on the helicopter routing to address crew assignment, routing and transportation issues during the initial response phase of disaster management. *Ozdamar et al. (2004)* present a network-based multi-period model to plan the commodity logistics in the natural disaster response. The model first determines the amount of commodities to be transported between two adjacent nodes in the network. Then, another algorithm uses these amounts to determine the origin and destination of commodities transporting in the networks. *Tzeng et al. (2007)* develop a multiobjective relief-distribution model for designing real-life relief delivery systems. The model features three objectives, including minimization of the total cost, minimization of the total travel time, and maximization of the minimal satisfaction during the planning period. *Sheu (2007)* presents a hybrid fuzzy clustering-optimization approach to coordinate the relief logistics flows in a three-layer relief supply network during the crucial rescue period. The proposed approach involves

two recursive mechanisms (disaster-affected area grouping and relief co-distribution) in a network with relief suppliers, urgent relief distribution centers, and relief demanding areas. *Sheu (2010)* also presents a dynamic relief-demand management model for emergency logistics operations under imperfect information conditions in large-scale natural disasters. This model consists of three main steps: data fusion to forecast relief demand in multiple areas, fuzzy clustering to classify affected area into groups, and multi-criteria decision making to rank the order of priority of groups. *Nolz et al. (2011)* develop a multi-objective model for relief aid distribution for a post-natural-disaster situation. This model encompasses three objective functions, including minimizing the risk, maximizing the coverage provided by the logistics system and minimizing the total travel time. Moreover, *Lin et al. (2011)* propose a multi-item, multi-vehicle, multi-period and multi-objective model for delivery of prioritized items in disaster-relief operations. This model includes two objective functions, which minimize the total unsatisfied demands and the total travel time for all tours and all vehicles. *Zhan and Liu (2011)* present a multi-objective stochastic programming model to handle the uncertainty of demand, supply and the availability of transportation paths in an emergency logistics network. The model focuses on minimizing the expected travel time and the proportion of unmet demands by using chance constraints and scenario planning. *Afshar and Haghani (2012)* propose a mathematical model to control the flow of several relief commodities in the response network. This model considers the optimal locations for several layers of temporary facilities, routing and pick up or delivery schedules. Finally, *Zhang et al. (2012)* propose an integer mathematical model to allocate the available resources to demand points subject to constraints on multiple resources and possible secondary disasters. This model minimizes the cost of the total time of dispatching emergency resources.

Another stream of research mainly focused on transport of injured people, such as *Fiedrich et al. (2000)* and *Jotshi et al. (2009)*. *Fiedrich et al. (2000)* present a model for allocating resources in an earthquake response phase to handle the logistics of injured persons. Moreover, *Jotshi et al. (2009)* develop a robust methodology for the dispatching and routing of emergency vehicles in a post-disaster environment.

Although most of the previous papers examine a single type of logistical activity, some have addressed both disaster relief commodity and injured people logistics during the earthquake response phase. *Yi and Ozdamar (2007)* present a dynamic logistics

coordination model for evacuation during the disaster response phase. This model investigates flows of both commodities and wounded people, and minimizes the sum of unserved injured persons and unsatisfied commodity demand. Also, *Yi and Kumar (2007)* present a model to schedule the dispatching of commodities to distribution centers in the affected areas and for transporting the injured persons from the affected areas to the medical centers. *Ozdamar (2011)* propose a mathematical model to transport injured people and medical items such as medicine and vaccines to the affected locations by helicopter. This model aims to minimize the total mission time required to complete the transportation tasks. Finally, *Ozdamar and Demir (2012)* present a hierarchical cluster and route procedure for coordinating vehicle routing in large-scale post-disaster distribution and evacuation activities.

Wisetjindawat et al. (2012) studied on the vehicle routing model for distribution of emergency goods to victims. The time for responding was considered to develop the relief supply operation model in Aichi prefecture's plans for the locations of hubs. This model was applied for prediction Tokai, Tonankai and the coupled earthquake for Aichi prefecture. This study is solved by vehicle routing problem which was restricted by the maximum load of truck and working time of drivers.

Nagurney et al. (2012) presented that "disaster relief and associated cost are approximately 80 percent logistics. Therefore, more transparent, efficient, and effective logistics operations and supply chain management in disaster cannot save only lives but also enables better preparedness for natural as well as man-made disaster." These support that the logistics operation improvements are interested in the present.

During the post-earthquake, the delivery relief items are given priority. A major criteria for evaluating the efficiency of transportation is time and cost. These criteria relate with the operating such as the appropriate locations of depots.

Lin et al. (2012) focused on logistics efficiency improvement. They said that the prioritized items for delivery and an extensive time period are importance of humanitarian logistics. They would like to present the location of temporary depots around the disaster-affected area between the long travel distances of demand points and the central depots. The two-phase heuristic approach was presented. The best solution from Phase I, which was located the temporary depots and allocate covered demand area was assigned in Phase II to achieve the best logistics performance.

CHAPTER 3

STUDY AREA AND DATA COLLECTION

3.1 Introduction

Here, the study is applied to evaluate the model in Miyagi prefecture. As know well that there was an enormous earthquake and tsunami in Japan in 2011. Miyagi prefecture is most attracted and affected by this disaster. Therefore, this study is focused with this area. This chapter is described into nine sections. The first section is the introduction of some facts that gives general information of situations and study area. The second section is the research and data assumptions which these data collection is conducted to estimate the demand during disaster time. The third section is the number of victims. The peak number of evacuees which indicates a one week aftermath is surveyed for initial data. These data can use for demand estimation in the section fifth. The fourth section is the location of the suppliers and the demands, where deliver the items and require the amelioration respectively are defined under the assumption. Also, the specification of the candidate of facility locations is appeared. The fifth section is continuously relative with the previous data. The demand estimation, here is a single commodity of the supplements to deliver to the victims. This is a bottle of water. Then, the amount of demand items is provided by using the number of victims both volume and weight. The sixth section is a calculation of the available relief goods that can serve from each supplier. This data is not exactly and clearly available in the report so, it is approximated by the proportional distance. Finally, the three costs are calculated. These three costs are including the transportation cost, the transshipment cost and the opening facility cost as mentioned in last three sections. The expected results are the total delivery cost and the link flow or the amount of relief item to deliver from origin to destination nodes.

3.1.1 General information of disaster

First of all, this section is introduced some general information that how the severe of disaster and study area are related. As well known in the several name are the 2011 earthquake off the Pacific coast of Tohoku, the Great East Japan Earthquake and also the 2011 Tohoku earthquake, this earthquake occurred undersea with mega thrust earthquake off the coast of Japan on Friday 11 March 2011. There was the epicenter approximately 70 kilometers from east of the Oshika Peninsula of Tohoku and the hypocenter at an

underwater depth of approximately 30 km. The earthquake was initially reported as 7.9 magnitudes by the USGS, and it was quickly upgraded to 8.8 magnitudes, then increase to 8.9 magnitudes and finally up to 9.0 magnitudes. The effect of this most powerful, which was 9 magnitudes is trigger of powerful tsunami waves that reached heights of up to 40.5 meters in Sendai area, travelled up to 10 km inland. Sendai was the nearest major city to the earthquake which far 130 km from the epicenter.



Figure 3-1 Diagram of the 2011 Tohoku earthquake on March 11, 2011

Source: http://commons.wikimedia.org/wiki/File:JAPAN_EARTHQUAKE_20110311.png

3.1.2 Geography and general information of the study area

This section is presented some facts which relate the study area. These facts are generally used to specify where should be the candidate facility location in case of lacking with the full data. The demand areas are located cover all in Miyagi prefecture. Miyagi Prefecture is located in the central part of Tohoku and connected the Pacific Ocean. There are four boundaries which are Iwate, Akita, Yamagata and Fukushima that connect at north, northwest, west and south respectively as shown in the figure 3.2. Moreover, Miyagi contains Tohoku's largest city as known as Sendai city which is also the capital city. There are high mountains on the west and along the northeast coast however the central plain around Sendai is fairly large. The prefecture is separated for 13 cities, 10 districts and 22 towns and villages belong in the districts. The demand site is located for every cities, towns and villages which the number of site depends on the amount of evacuees.



Figure 3-2 Map of Miyagi prefecture shows all the cities and prefecture boundaries

Source: <http://www.mapsofworld.com/japan/prefectures/miyagi.html>

3.2 Data assumptions

This section is explanation for the assumptions of the data that necessary to apply in the model. The explanation is stated from the largest scope of the distribution network design which is the structure of the model. Then, the assumptions of each network configuration such as supply locations, facility depot locations, demand locations, amount of demand and circumstance are mentioned.

Generally, the network configuration consists of suppliers, manufacturing centers, warehouses, distribution centers and retailers or demand. The intention of this study is to design the distribution network for a commodity to relieve the victims after natural disaster. A single commodity is assumed, here is a bottle of water. The facility location is determined to investigate the total cost for delivery per a day. Thus, to design the network planning need to specify that the supplier and demand locations or defined as shelter locations are assumed to be fixed and known. However, these data may not completely available in the report. Also, the candidate of the facility locations need to specify and unknown. Therefore, some assumptions are assigned to solve the lacking of information.

First of all, this distribution network is determined that there are four layer of network configuration which is suppliers, central depots, depots and shelters (demand). The first and forth layers are fixed and known, and the second and third layers need to search by

minimum of total delivery cost. These all locations are defined by using the coordination of longitude and latitude.

Second, actuality, there are not exactly known for the locations of suppliers that provide the relief goods. Thus, these locations are primary defined as followed by the Miyagi Prefectural Government Report. The reports has summarized presented where the relief goods are delivered from. Afterwards, the suppliers that no significant in term of distance are combined in order to save calculation time, these locations are shown in the next sections.

Third, the locations of shelters are assigned followed by the reports of Miyagi prefecture. This report has shown the location of shelters take place and also the number of evacuees in each shelter. So, the assumption is that each city is assigned single demand point, exempt there are several demand points in Sendai because of large serving demand.

Fourth, the amount of demand is estimated based on the number of victims in each shelter as illustrated in the section 3.3. As mentioned before that a single commodity, a bottle of water is served to the victims. Then, the attribute of a bottle of water is estimated under the assumption that the size of goods is 500 ml. The amount of bottle of water can sufficiently serve for every meal, a one bottle per meal and three meals per a day.

Fifth, the first layer of depots is assumed for two study cases. The first case is located in the demand area or in the Miyagi prefecture. The assumption of these locations is grouping by considering the amount of demand and serving area size. This assumption is shown in the section 3.4. The second case is located outside the demand area. These locations are assigned in the prefectures where are along the edge of demand area, one prefecture per one candidate of depots as illustrate in section 3.3. After that, the second layer of depots is belonged in the serving area for both study cases.

Sixth, the 10-ton and 4-ton truck size are assumed to carry the distribution goods in this study. Their limitations are two issues as capacity of volume and weight. The assumption is that the truck can carry amount of goods until reach to the one among two of their limitations. Not only the limitations of truck are determined but also the limitation of working driver time is considered. The working driver time is restricted at eight hours per day especially for driving. In case of the travel time is over than time limitation then, the number of driver is assigned for two or more.

Seventh, the transportation cost is performed as the function that varies by the distance and energy consumption rate. Moreover, the expense that needs for transportation is set; here is driver cost, purchase truck cost and also vehicle insurance cost. Then, the assumption for transshipment cost is referred from the previous study, the unit cost per unit loading and unloading. This transshipment cost is equally set both first layer and second layer. Next, the cost for facility opening is assumed by the value of land in each area. However, the opening cost in the second layer is equally assumed for every candidate facility.

Finally, this assumption is under uncertainty of demand. After the deterministic of two cases are calculated in the previous assumptions, then the robust optimization is applied to solve the problem with demand uncertainty for all networks that describe in chapter 4. There are several ways to work with uncertainty as mentioned before in chapter 2. The methodology for handling under uncertain here is robust optimization by using ellipsoidal robust counterpart.

3.3 The number of evacuees

The number of evacuees in Miyagi prefecture is collected to use in this study. This amount is available in the Miyagi Prefectural Government Report. They have published the evacuation situation and circumstances of the Great East Japan Earthquake. The number of evacuees is used for estimation the amount of relief items. The locations and the number of shelters are also illustrated. Moreover, the information about the prefectures that who are a supporter of them are provided in the records. These data can locate the location shelter nodes. The data is shown that the evacuees are rather huge in the flat area and a capital city. There is the biggest demand in Sendai which is approximately 70,000 as shown in figure 3.3. Thus, under the assumption that Sendai is divided for five of demand sites which show in figure 3.4. By the way, even the amount of victims in Ishinomaki is also high. However, the demand site in Ishinomaki is not divided by the reason that the flat area is quite small so there is no significance in term of distance. On the other hand, there are fairly less amount of evacuees on the top site and below site where locate near Sendai city. The lowest evacuees are in Marumori town where connected under Sendai, which are presented at 5 victims. Exempt these mentions before the amount of evacuees are quite small when comparing with Sendai and Ishinomaki. These amounts are some hundreds of people for each shelter.

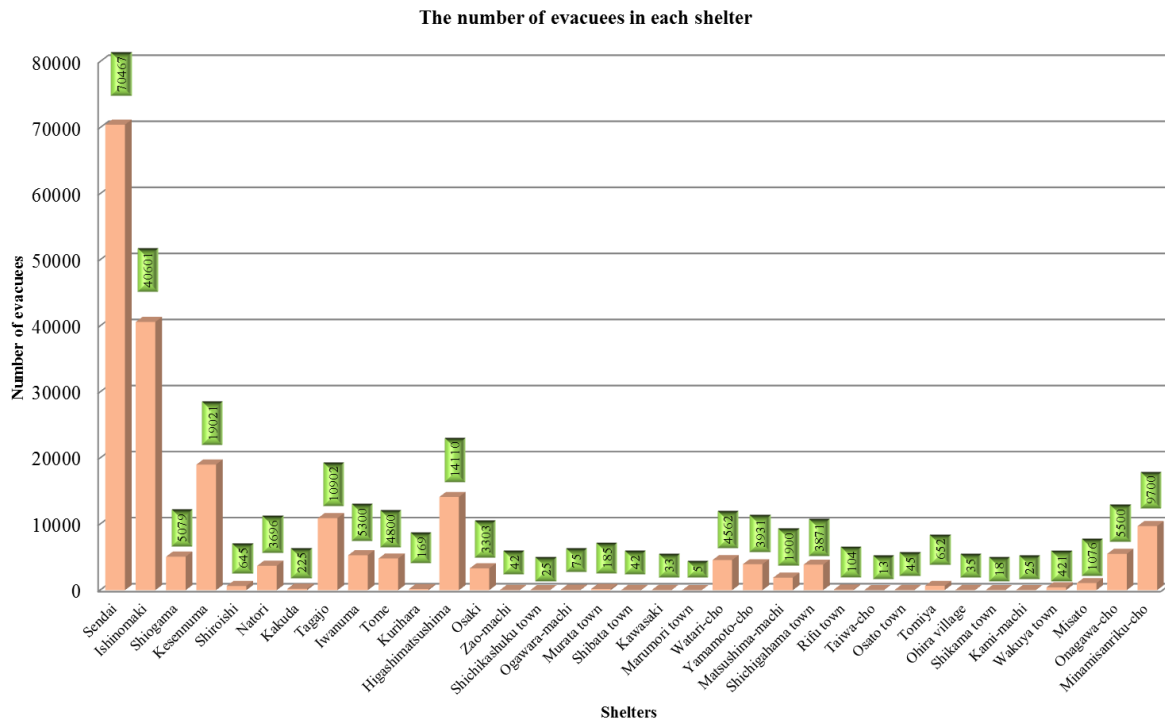


Figure 3-3 The number of evacuees in each area of Miyagi prefecture

3.4 Identify the locations of suppliers and shelters

This section would like to specify the facility locations of network configurations for relief distribution. These locations are represented in latitude and longitude coordinates. There are assumptions that locations are easily accessibility by the expressway or main road. These locations are also group for some site where is no significant in term of distance.

First of all, the locations of suppliers are determined. The Miyagi Prefectural Government Report presents that there are 29 sites cover all in Japan where are available for serving goods to the affected area during post disaster. However, these 29 sites are grouped into nine sites of suppliers by using the adjacent zone ideal. The coordinates of supplier locations are illustrated in the table 3.1 below.

Table 3.1 The coordinates of supplier locations

No.	Supplier	Latitude (decimal degree)	Longitude (decimal degree)	Latitude (radians)	Longitude (radians)
1	Hokkaido	43.34247	142.38322	0.756468807	2.485055989
2	Tochigi	36.38149	139.73034	0.634976787	2.438754498
3	Tokyo	35.68972	139.69171	0.622903123	2.438080277
4	Toyama (Namerikawa)	36.7654	137.3413	0.641677281	2.397057884
5	Aichi	35.1809	136.9067	0.614022539	2.389472683
6	KINKI (Kansai) region	35.011692	135.768026	0.611069302	2.369599073
7	CHUGOKU region	34.38566	132.45527	0.600142982	2.311780573
8	SHIKOKU region	33.5619	133.5312	0.585765658	2.330559094
9	KYUSHU-OKINAWA region	32.8065	130.7079	0.572581441	2.281283213

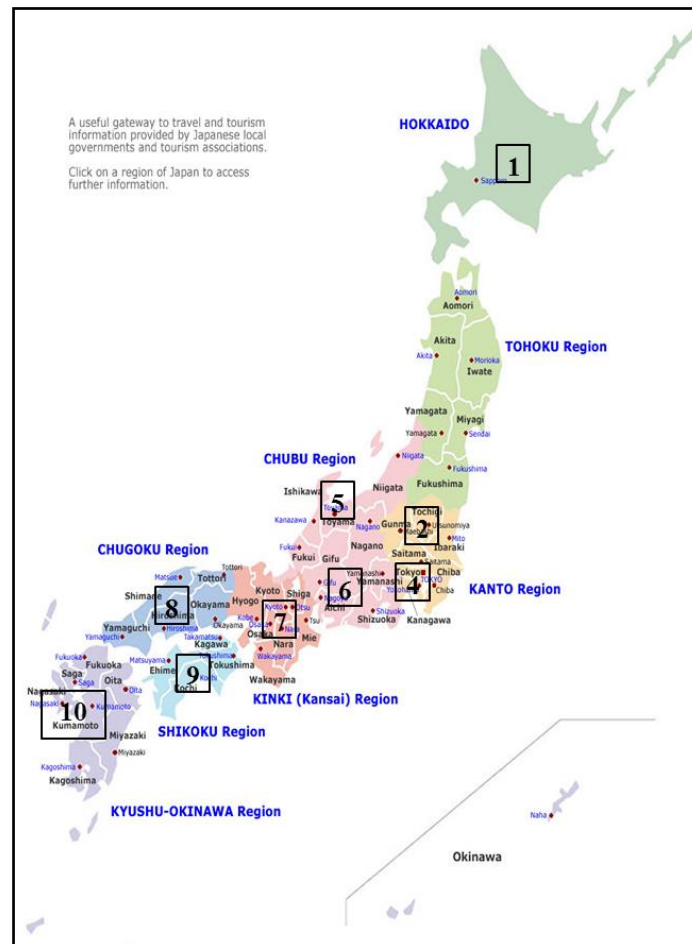
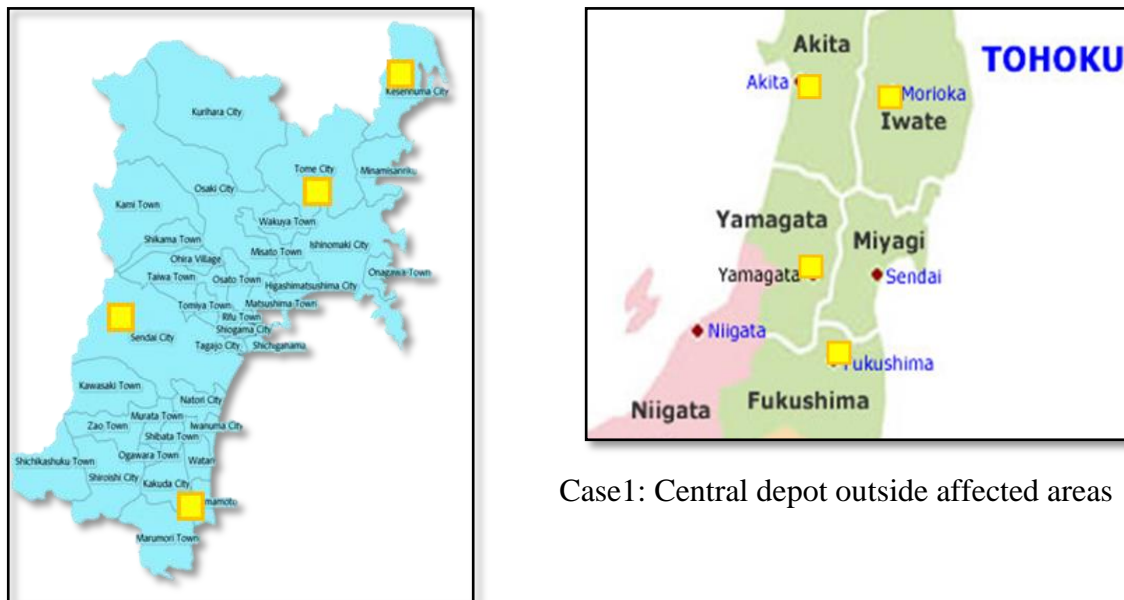


Figure 3-4 The map of supplier locations

Then, the locations of candidate central depots are defined. Two assumption cases that this layer is located at inside and outside of demand areas are supposed. The first assumption is that the central depots belong inside the demand areas. These are assigned by covering to response the areas of the next layer or depots. This means that these central depots should response to the next layer by considering the zoning characteristics. The coordinates of candidate central depots for the second case study are illustrated in the table 3-2. Another assumption is to define the central depot belong outside and along the edges of demand areas as presented in the table 3-3. In this case there are four boundaries where are connected with the demand area or Miyagi prefecture. Thus, these prefectures which are Fukushima, Yamagata, Akita and Iwate are defined to represent the candidate central depots.



Case1: Central depot outside affected areas

Case2: Central depot inside affected areas

Figure 3-5 The map of central depot locations

Table 3-2 The coordinates of central depot locations of second assumption

No.	Candidate Depots	Latitude (decimal degree)	Longitude (decimal degree)	Latitude (radians)	Longitude (radians)
1	Kesennuma	38.91096	141.4996	0.679124	2.469634
2	Tome	38.6111	141.179	0.673891	2.464039
3	Sendai(Kumagane)	38.29955	140.6819	0.668453	2.455363
4	Yamamoto	37.92089	140.9041	0.661844	2.459241

Table 3-3 The coordinates of central depot locations of first assumption

No.	Candidate central depots	Latitude (decimal degree)	Longitude (decimal degree)	Latitude (radians)	Longitude (radians)
1	Fukushima	37.7643	140.4749	0.659111375	2.451749521
2	Yamagata	38.25579	140.33963	0.667689493	2.449388615
3	Akita	39.7262	140.104	0.693352989	2.445276095
4	Iwate	39.9742	141.2125	0.697681406	2.46462307

Next, the location of depots are specified by clustering zoning areas and demand size. At first, the totally of five zoning are separated to response for their area, these five zones are illustrated by difference of color in the figure 3-6. The blue color is represented to response in the central of the prefecture which includes Sendai. Then, the green color cover five demand sites in the upper zone of Sendai. Thereupon, the brown color serve with the demand that belongs in the north area of Miyagi prefecture. Next, the red color is shown to definde the area scope below zone of Sendai. Finally, the yellow color is defined for present the area coverage in the south part of Miyagi prefecture. After that, each zone are again equalized by considering the amount of demand as presented in the figure 3-7. Subsequently, the candidate depot locations are indicated in total 11 places. Five sites among all of them belong in the blue zone then, the three sites are located in green zone. Next, a one site is responded per each zone for these zones which are brown zone, yellow zone and red zone respectively.

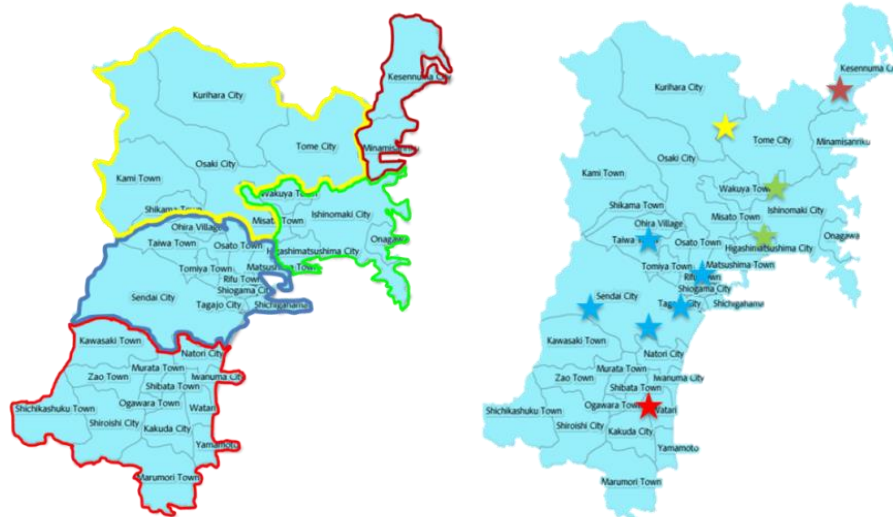


Figure 3-6 The map of demand clustering zone

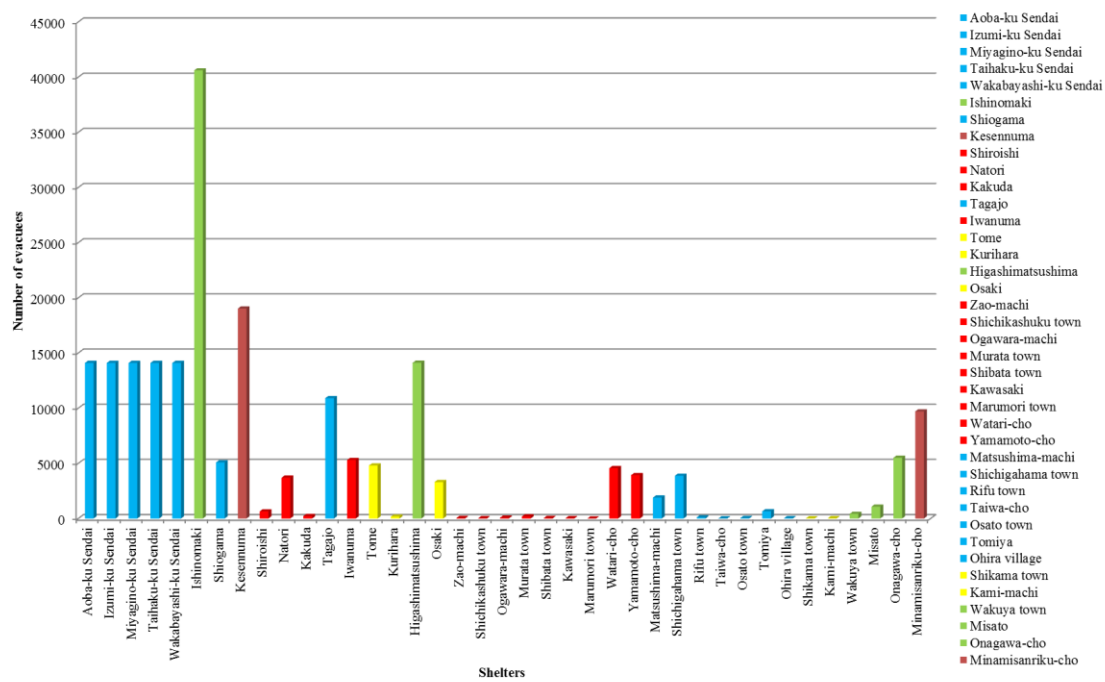


Figure 3-7 The graph of demand clustering zone

Table 3-4 The coordinates of depot locations

No.	Candidate depots	Latitude (decimal degree)	Longitude (decimal degree)	Latitude (radians)	Longitude (radians)
1	Tome-Kurihara	38.743	141.1195	0.676192912	2.462999914
2	Kesennuma	38.79368	141.50229	0.677077445	2.46968086
3	North Ishinomaki	38.5868	141.2737	0.673466708	2.465691211
4	South Ishinomaki	38.4266	141.2616	0.67067069	2.465480027
5	East South Ishinomaki	38.428	141.3756	0.670695125	2.467469702
6	Taiwa Town	38.4035	140.8812	0.670267519	2.458840794
7	North West Sendai	38.2556	140.6802	0.667686177	2.455332682
8	North East Sendai	38.219	140.889	0.667047387	2.45897693
9	Central Sendai	38.2367	140.8967	0.66735631	2.45911132
10	South East Sendai	38.2525	140.9043	0.667632072	2.459243965
11	South Sendai	38.0328	140.8174	0.663797584	2.457727274

Finally, the list of demand sites is referred from Miyagi Prefectural Government Report as shown in the table 3-5. This report not directly presents the location of demand but they summarize the number of victims who temporarily live in the shelters of each city. Therefore, this study is assumed that every city in Miyagi is determined one demand site per each city. However Sendai is divided for five demand site because they need to serve

a large amount of demand. Furthermore, these locations are probably represented to serve all demand at the centroid in each area.

Table 3-5 The coordinates of shelter demand

No.	Demand site	Latitude (decimal degree)	Longitude (decimal degree)	Latitude (radians)	Longitude (radians)
1	Aoba-ku Sendai	38.26912	140.8704	0.667922	2.458652
2	Izumi-ku Sendai	38.3273	140.8814	0.668938	2.458844
3	Miyagino-ku Sendai	38.26619	140.9098	0.667871	2.459341
4	Taihaku-ku Sendai	38.2314	140.874	0.667264	2.458715
5	Wakabayashi-ku Sendai	38.2459	140.9007	0.667517	2.459181
6	Ishinomaki	38.43497	141.3028	0.670817	2.466199
7	Shiogama	38.31448	141.022	0.668714	2.461299
8	Kesennuma	38.90833	141.57	0.679078	2.470862
9	Shiroishi	38.0041	140.6198	0.663297	2.454279
10	Natori	38.1723	140.8919	0.666232	2.459028
11	Kakuda	37.97731	140.782	0.662829	2.457109
12	Tagajo	38.29402	141.0042	0.668357	2.460988
13	Iwanuma	38.1053	140.87	0.665063	2.458645
14	Tome	38.6989	141.188	0.675423	2.464195
15	Kurihara	38.7361	141.02	0.676072	2.461263
16	Higashimatsushima	38.4278	141.2098	0.670692	2.464576
17	Osaki	38.5847	140.955	0.67343	2.460129
18	Zao-machi	38.1015	140.6583	0.664997	2.45495
19	Shichikashuku town	38.007	140.442	0.663347	2.451175
20	Ogawara-machi	38.0534	140.7304	0.664157	2.456209
21	Murata town	38.1203	140.7225	0.665325	2.456071
22	Shibata town	38.0603	140.7654	0.664278	2.45682
23	Kawasaki	38.1837	140.643	0.666431	2.454683
24	Marumori town	37.9177	140.765	0.661789	2.456813
25	Watari-cho	38.0385	140.8526	0.663897	2.458342
26	Yamamoto-cho	37.96178	140.8778	0.662558	2.458782
27	Matsushima-machi	38.38143	141.069	0.669882	2.462118
28	Shichigahama town	38.3054	141.0592	0.668555	2.461947
29	Rifu town	38.332	140.9753	0.66902	2.460483
30	Taiwa-cho	38.445	140.886	0.670992	2.458925
31	Osato town	38.4318	141.004	0.670761	2.460984
32	Tomiya	38.4052	140.896	0.670297	2.459099

No.	Demand site	Latitude (decimal degree)	Longitude (decimal degree)	Latitude (radians)	Longitude (radians)
33	Ohira village	38.4688	140.8798	0.671407	2.458816
34	Shikama town	38.5488	140.8492	0.672803	2.458282
35	Kami-machi	38.586	140.852	0.673453	2.458331
36	Wakuya town	38.5406	141.1281	0.67266	2.46315
37	Misato	38.5462	141.0565	0.672758	2.4619
38	Onagawa-cho	38.4504	141.4431	0.671086	2.468648
39	Minamisanriku-cho	38.6836	141.4598	0.675156	2.468939

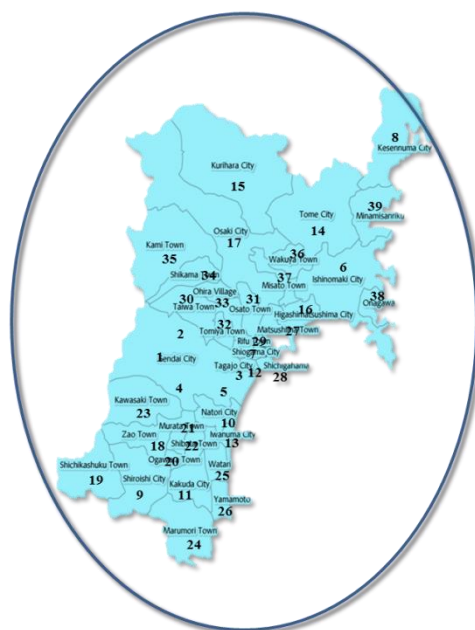


Figure 3-8 The map of shelter locations

3.5 The demands of relief item estimation

The relief item demand estimations are under assumptions of the vital items and the number of victims. The necessary items for daily life are served, which are consisting of a bottle of water, 500 ml. The bottle of water is served one for a meal and three meals per a day or three bottles of water per day. The 4-ton trucks are carried eight pallets per a trip of relief items. At first the dimension of pallet is defined as 1*1.2 square meters. The assumption is that a one pallet can carry 960 bottles or 40 packs of water. The weight of one pallet water carrying is 480 kilograms. The 10-ton trucks can serve twice and half volume. The amount of demand is reported by Miyagi Government report which is shown in table 3-6.

Table 3-6 The amount of demand requirement at shelter demand

No.	Demand sites	Amount of demand	No.	Demand sites	Amount of demand
1	Aoba-ku Sendai	42282	21	Murata town	555
2	Izumi-ku Sendai	42282	22	Shibata town	126
3	Miyagino-ku Sendai	42282	23	Kawasaki	99
4	Taihaku-ku Sendai	42282	24	Marumori town	15
5	Wakabayashi-ku Sendai	42282	25	Watari-cho	13686
6	Ishinomaki	121803	26	Yamamoto-cho	11793
7	Shiogama	15237	27	Matsushima-machi	5700
8	Kesennuma	57063	28	Shichigahama town	11613
9	Shiroishi	1935	29	Rifu town	312
10	Natori	11088	30	Taiwa-cho	39
11	Kakuda	675	31	Osato town	135
12	Tagajo	32706	32	Tomiya	1956
13	Iwanuma	15900	33	Ohira village	105
14	Tome	14400	34	Shikama town	54
15	Kurihara	507	35	Kami-machi	75
16	Higashimatsushima	42330	36	Wakuya town	1263
17	Osaki	9909	37	Misato	3228
18	Zao-machi	126	38	Onagawa-cho	16500
19	Shichikashuku town	75	39	Minamisanriku-cho	29100
20	Ogawara-machi	225			

3.6 The amount of supply estimation

Actually, the amount of available items at each supplier is exactly known and given. However, in some cases, there are insufficient of data collection. For example, this data is collected during the emergency time which has some constraints of surveyors, communications, time constraints and etc. The lacking of this data collection is that only the types of commodities are recorded without the amount of them. Hence, this section is clarified how to estimate the amount of obtainable goods in each supplier. Generally, there are some factors such as population rate, production rate, proportional distance and etc. to consider the equilibrium between demand and supply based on individual researchers. First of all, this study is assumed that the total amount of supply must be satisfied with total demand, at least equal to or more than the total demand. Then, the distance factor is applied to estimate supply in this study. After that, the supplier where locates farthest is provided at least one and must be minimum. Herein, Kyushu region is

the longest distance which is approximately 1,500 kilometers from the demand area so the supply is set as the minimum. This briefly understands that the amount at demand sites will be served by considering from the more close sites first. The relationship of them, serving amount at suppliers and distance is opposite direction.

Table 3-7 The amount of supply serving at suppliers

No.	Supplier sites	Amount of supply
1	Hokkaido	87436
2	Tochigi	131710
3	Tokyo	121174
4	Toyama (Namerikawa)	110847
5	Aichi	91208
6	KINKI (Kansai) region	81026
7	CHUGOKU region	59088
8	SHIKOKU region	55557
9	KYUSHU-OKINAWA region	20963

3.7 The total delivery cost

The total delivery costs are under the assumptions that they are separated in three sections of travel cost, opening facility cost and transshipment cost. Firstly, the travel cost is estimated by the fuel consumption of a small truck, the size is 4-ton which rate at 7.69 yen per kilometer. This travel cost varies with the distance between origins or suppliers and destinations or shelters. Moreover, the travel cost is also concluded a driver salary under the working time limitation, purchase truck cost that divided per day and vehicle insurance cost that also divided per day. Secondly, the opening facility cost is determined for both assumption deterministic models inside and outside effect areas. This cost is estimated from the average price of rental building based on the business firms and it is differences depending on each area. Finally, the transshipment cost is set at 5,000 yen per ton per day for loading and unloading of goods. This cost is included salary, bonus, social insurance and pension saving. This value is referred from the firm's Logistic Behavior Survey (PWRI) (Hosoya et al. 2003).

$$\begin{aligned}
 & \text{Total delivery cost} = \\
 & (\text{Travel cost})(\text{amount of link flow}) + (\text{opening facility cost}) + \\
 & (\text{Transshipment cost})(\text{amount of loading and unloading at facility sites}) \quad 3.1
 \end{aligned}$$

3.7.1 The travel Cost

Basically, the travel cost is changed by the distance and energy consumption rate. At the beginning, the energy consumption rate for 4-ton trucks is set at 7.69 yen while 10-ton truck is 11.69 yen for a kilometer driving. Then, the travel distance matrix is calculated from the coordinates of all network configurations. There are four distance matrixes starting from the suppliers to central depots, two study cases of central depots to depots and depots to shelters. These distances are calculated by using coordinates based on the radian units followed by formulation 3.1. Afterwards, the travel cost is performed below which includes travel cost from length, driver salary, purchase truck cost and insurance cost. The driver cost is defined per hour of driving but must be not over than eight hours per day. In case of the travel time is over than eight hours then the number of drivers is assigned for two or more for a trip so the driver cost is double from normal. The purchase truck cost and vehicle insurance cost is divided in one day unit.

$$\text{Radians} = \text{Decimal degree} * \frac{\pi}{180} \quad 3.2$$

$$\text{Distance} = \text{ACOS}(\text{SIN}(\text{Lat1}) * \text{SIN}(\text{Lat2}) + \text{COS}(\text{Lat1}) * \text{COS}(\text{Lat2}) * \text{COS}(\text{Lon2} - \text{Lon1})) * 6371 \quad 3.3$$

$$\text{Travel cost} = (\text{energy consumption rate} * \text{distance}) + (\text{driver salary} * \text{working time}) + \text{purchase truck cost} + \text{vehicle insurance cost} \quad 3.4$$

$$\text{*salary driver} = 1250 \text{ yen per hour or } 10,000 \text{ yen per day}$$

$$\text{*purchase truck cost} = 1375 \text{ yen per day}$$

$$\text{*vehicle insurance cost} = 688 \text{ yen per day}$$

3.7.2 Opening facility cost

Secondly, the opening facility cost or fixed cost includes construction cost, electricity cost and water supply cost as known in the other as a rental building cost. This value is estimated by average prices of rental storage building in each area of candidate central depots. This cost is generated by the linear relationship between the size of storage and rental prices, it means that the price of building rental is the function with the storage size as shown in the table 3-8 and 3-9 below. However, by the reasons that during post disaster, the effect area has a severe destroys then this is very difficult to obtain the suitable place where can be the candidate of depots for the second's assumption of

deterministic model. Therefore, the opening cost for the facility location where locates in effect areas are determined higher than the original with some factors.

Table 3-8 The inside central depot opening facility cost estimation

Central Depot	Average opening cost/m ²	Opening facility cost of 400 m ² capacity
Kesennuma	14.12	5,646.87
Tome	439.56	175,824.18
Sendai	2247.55	899,019.81
Yamamoto	468.59	187,434.40

Table 3-9 The outside central depot opening facility cost estimation

Central depot	Average opening cost/m ²	Opening facility cost of 400 m ² capacity
Fukushima	1082.67	433,068.29
Yamagata	1389.25	555,699.00
Akita	1280.18	512,072.56
Iwate	855.45	342,181.32

Table 3-10 The depot opening facility cost estimation

Depot	Average opening cost/m ²	Opening facility cost of 280 m ² capacity
Tome and Kurihara	439.56	123,076.92
Kesennuma	14.12	3,952.81
North Ishinomaki	439.56	123,076.92
South Ishinomaki	439.56	123,076.92
South East Ishinomaki	439.56	123,076.92
Taiwa Town	1396.36	390,981.80
North West Sendai	2247.55	629,313.87
North East Sendai	2247.55	629,313.87
Central Sendai	2247.55	629,313.87
South East Sendai	2247.55	629,313.87
South Sendai	2247.55	629,313.87

Moreover, during this time is also lack of necessary resources which are including the human resources, the electricity supplies, the water supplies, the fuel energy and especially the land areas. Therefore, the opening cost for the facility location where plans to locate in effect areas are determined higher than the original with some factors.

3.7.3 Transshipment cost

Finally, the transshipment cost is at 5,000 yen per ton for loading or unloading of goods at the facility sites. This cost will generate when the set of facility sites is selected to operate. This cost is included salary, bonus, social insurance and pension saving of human resources. This value obtains from the firm's Logistic Behavior Survey (PWRI) (*Hosoya et al. 2003*).

Transshipment cost = 5,000 (weight of items)

* loading and unloading = 5,000 yen per ton

CHAPTER 4

RESEARCH FRAMEWORK

4.1 Introduction

This study assigns some possible circumstances to cover the realistic distribution plan. This section explains a research framework which is including network assumptions, a demand scenario framework analysis, uncertainty demand analysis, implemented routing problem, time series and Location-Routing problem. The research framework appraises the entire concepts (see figure 4-1) which initiate from ordinary facility location then examine with some network assumptions under deterministic demand. Then, this study extends the problem to play on the demand oriented which is uncertainty demand which is relatively new method to apply on facility location problem. Next, the routing is built to develop the distribution network in the layer that demand is suitable. Later, the distribution network goes on to consider the time series. Finally, the combined problem of Location-Routing is studied.

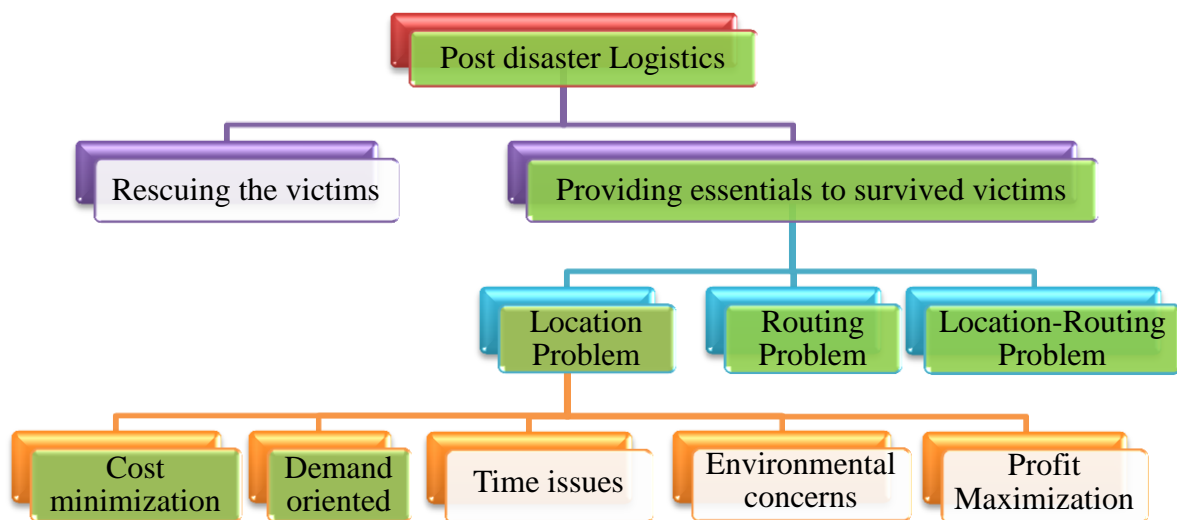


Figure 4-1 The research framework

4.2 Network assumptions

The initial study begins from the basic location problem which means using the deterministic demand. Afterward, the network assumptions are expanded by their structure, location of candidate facility and truck size. These assumptions are summary shown in Table 4-1 and itemize the detail in the section 4.2.1. We categorized these five

networks based on the network configurations, their candidate locations and the dispatched truck sizes. Two types of the network configurations are single layer and double layers of facility site candidates, defined as central depots and depots. Then, the problem is imposed that there are three network elements with two hierarchies and four network elements with three hierarchies. The first network element is the locations where the serviceable supports known as suppliers. The second network element is the central relief depot in case of double hierarchies. The third element is the relief depots for double hierarchies and the relief depot in case of a single hierarchy. These second and third network locations are unknown and need to be defined with the most efficiency. Finally, a possible area that was attacked by the natural disaster is called an affected area which can be defined known locations as shelter demands. The transportation truck sizes are 10-ton trucks and 4-ton trucks. The specification of the networks is described below.

Table 4-1 Network assumption compositions

Network	Structure (number of facility layer)	Candidate facility location		Truck size		
		CD	D	E1	E2	E3
Network 1	1 (3 network configurations)	-	Inside	-	10	4
Network 2	2 (4 network configurations)	Inside	Inside	10	10	4
Network 3	2 (4 network configurations)	Inside	Inside	10	4	4
Network 4	2 (4 network configurations)	Outside	Inside	10	10	4
Network 5	2 (4 network configurations)	Outside	Inside	10	4	4

*CD = Central depots, D = Depots, E = Echelon

4.2.1 Structure of network facility alternatives

There are two structures determined by the structures of networks or network configurations. Figure 4-2 is the simple network structures which consist of three network configurations, the suppliers, the depots and finally shelters. The simply network structure is probably suitable with idealistic model. According to the theory, the model tend to less distribution cost when it is not consider the constraint of operational such as driver working time. Also, it is the idea of the small network distance when the length between suppliers to depots is short then the central depots is not requisite. However, in the real incidents the distance is not known whether how far it is. Therefore, to prevent this

weakness the further model is proposed by adding one more layer called as central depots.

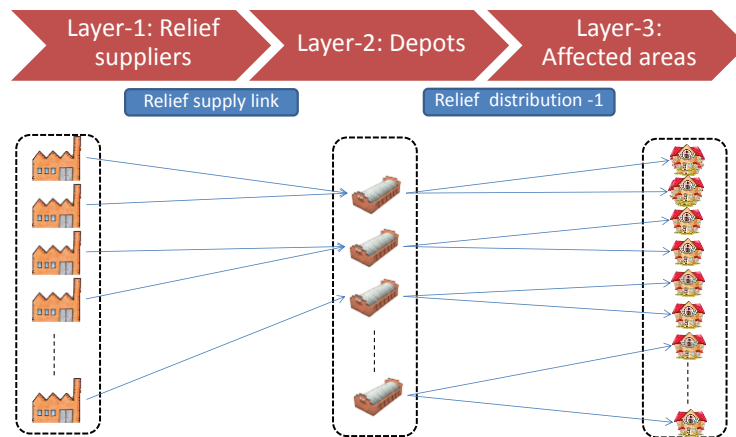


Figure 4-2 The single-hierarchy distribution network framework

The figure 4-3 below is illustrated the structure of distribution network framework. There are four network configurations which start from the suppliers, central depots, depots and finally shelters. Each network configuration is represented for their locations. The layer-2 and layer-3 will be selected simultaneously under the objective function and constraint satisfactions. Moreover, the picture is also shown the blue line links between each network configuration. These are represented for the amount of transportation or link flow after the model is optimized.

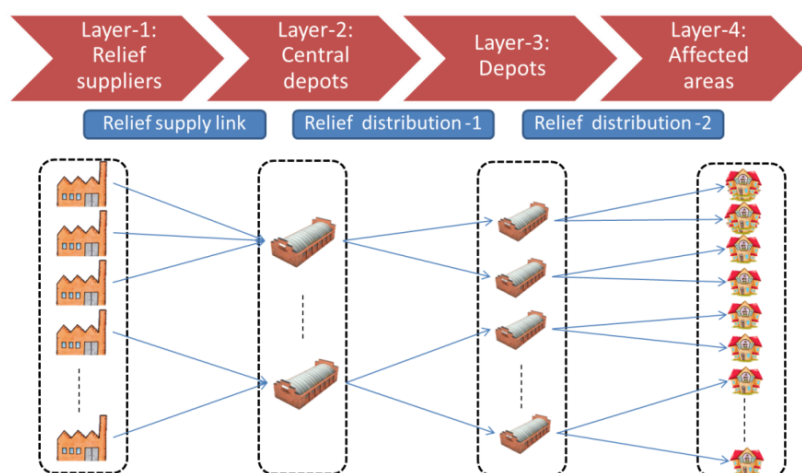


Figure 4-3 The multi-hierarchy distribution network framework

4.2.2 Location of candidate facility alternatives

As mention before in chapter 3, there are two assumptions for candidate facility location in the model. The first is proposed that the set of potential central depot sites is designated outside study area or Miyagi prefecture. These candidate sites are located along the boundary of Miyagi prefecture, one central depot is represented for one boundary. The second is assumed in the different hand that the set of potential central depot sites is determined inside of effect demand area. However, there are some obstacles to operate the facility sites in effect areas. This causes to the opening facility cost become higher than the ordinary circumstance.

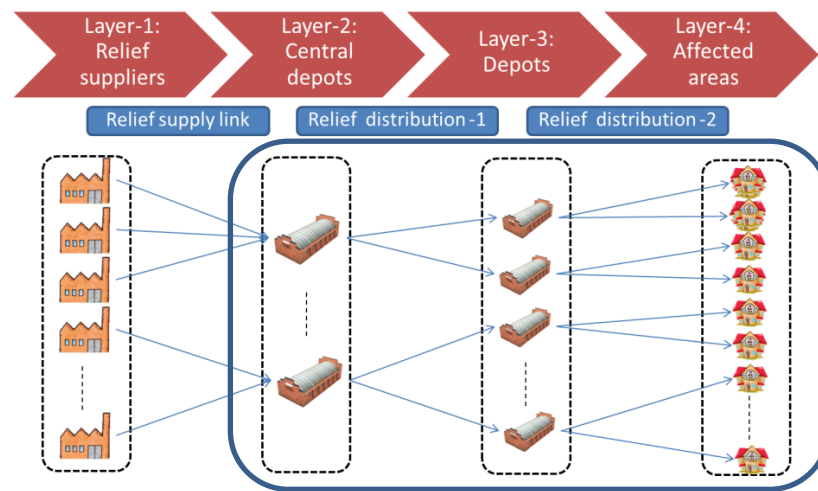


Figure 4-4 The distribution network of central depot inside

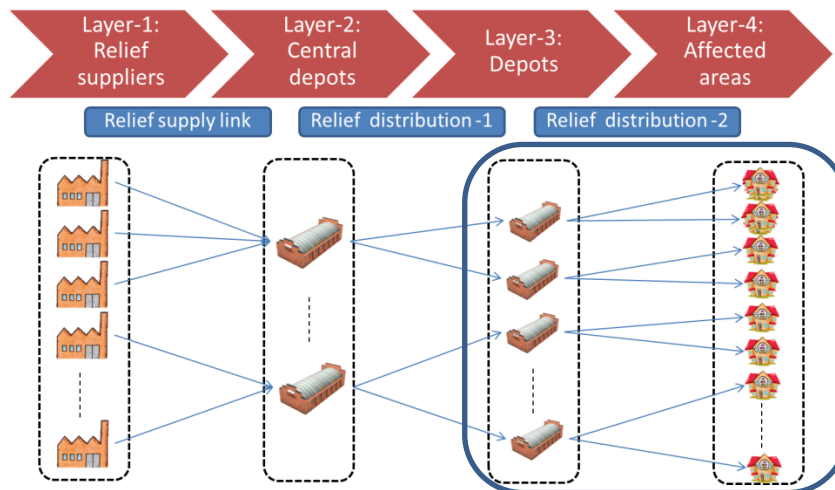


Figure 4-5 The distribution network of central depot outside

4.2.3 Truck size alternatives

The truck size operation evidently depends on the amount of demand and allocation between each link flow. Generally, the large trucks are efficiency in case of there is fulfilled with maximum capacity. Therefore, the large trucks always use to deliver from supplies to the next layers in this study.

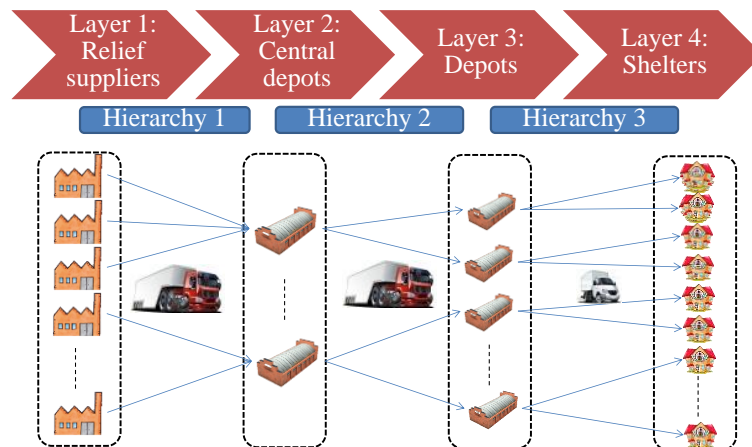


Figure 4-6 The two-hierarchy network framework and 10-10-4-ton truck delivery

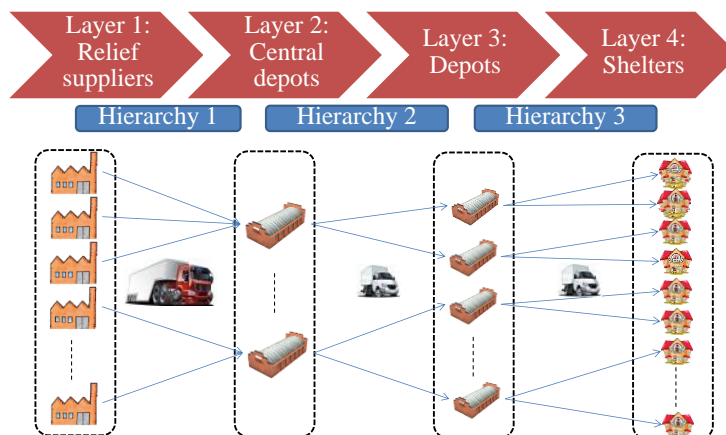
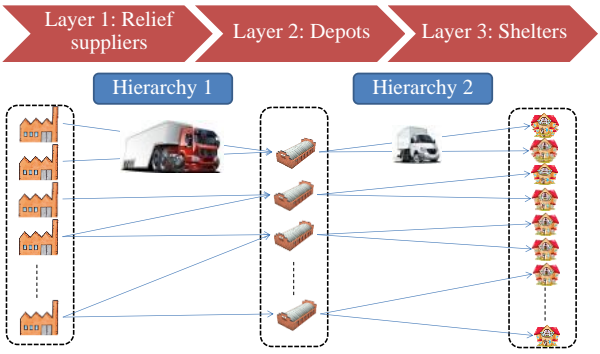
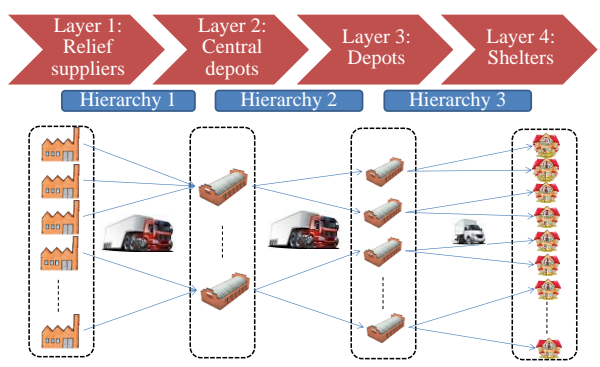


Figure 4-7 The two hierarchies network framework and 10-4-4-ton truck delivery

Following by those mentioned above, the problem is designed for five different networks. The brief explanation and network layouts are below.

<p>Network 1</p>  <p>Figure 4-8 Network 1</p>	<p>This network is determined by the three network elements which include suppliers, relief depots and shelter demands. The relief depot candidate sites are located inside the affected areas. The relief items are dispatched from suppliers to relief depots by using 10-ton trucks. Then, the 4-ton trucks are used for portage the relief items from relief depots to shelter demands.</p>
<p>Network 2</p>  <p>Figure 4-9 Network 2</p>	<p>This network is determined by the four network elements which include suppliers, central relief depots, relief depots and shelter demands. The central relief depot candidates are supposed to locate inside the affected areas. The 10-ton trucks are proposed to transport the relief items from supplies to central relief depots and central relief depots to relief depots. Then, the relief items are carried from relief depots to shelter demands by using 4-ton trucks.</p>

Network 3

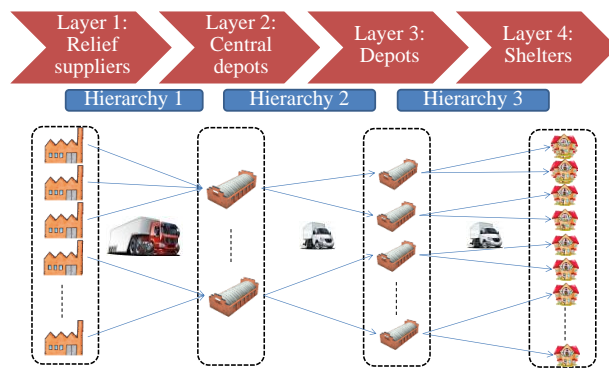


Figure 4-10 Network 3

This network is a duplicate structure with the Network 2. However, there is the difference in term of the truck size. The 10-ton trucks are assumed to deliver the relief items from supplies to central relief depots. Then, 4-ton trucks are assigned to deliver from central relief depots to relief depots and from relief depots to shelter demands respectively.

Network 4

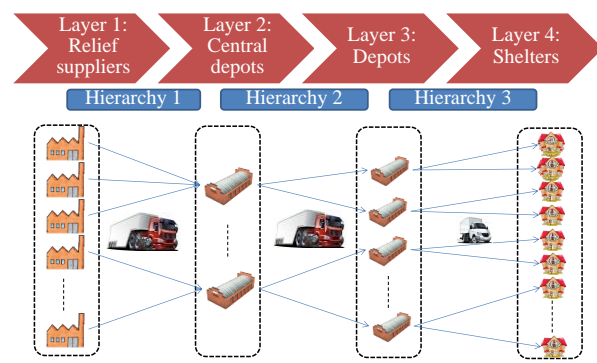


Figure 4-11 Network 4

The central relief depot candidates are supposed to locate outside the affected areas. The 10-ton trucks are proposed to transport the relief items from supplies to central relief depots and central relief depots to relief depots. Then, the relief items are carried from relief depots to shelter demands by using 4-ton trucks.

Network 5

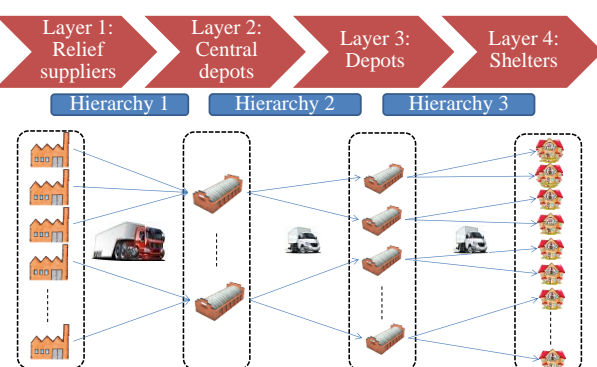


Figure 4-12 Network 5

This network is a duplicate structure with the Network 4. However, there is the difference in term of the truck size. The 10-ton trucks are assumed to deliver the relief items from supplies to central relief depots. Then, 4-ton trucks are assigned to deliver from central relief depots to relief depots and from relief depots to shelter demands respectively.

4.3 Demand scenario framework analysis

The study not only examines a single demand model but also multi-demand scenarios are examined. These demand scenarios are used in order to analyze the sensitivity of three different network structures. The demand is determined for five scenarios which deviate from the historical case in both sides optimistic and pessimistic. These five demand scenarios are separated as less than historical demand by 20 percent (S1) and 10 percent (S2), historical demand (S3), and more than actual demand by 10 percent (S3) and 20 percent (S4) respectively. Each demand scenario is also examined for uncertainty demand as shown in the figure 4-13.

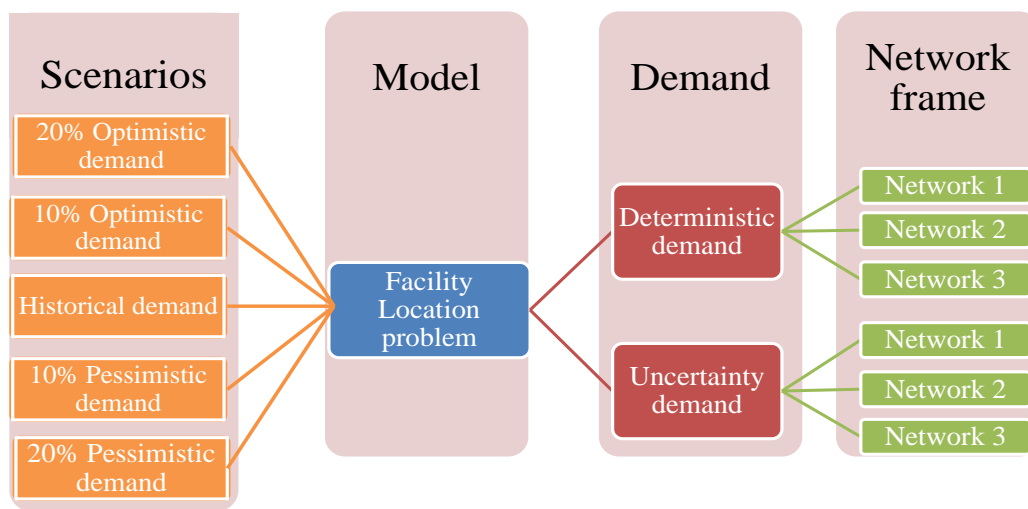


Figure 4-13 Demand scenario frameworks

4.4 Uncertainty demand analysis

Normally, the mathematical models such as linear programming, mixed-integer programming, nonlinear programming and etc. have a common assumption that all of the input data in the model is exactly known beforehand with certainty. This is the decision making under certainty of data which are called deterministic model. On the other hand, a specific class of models that account for uncertainty in the input data by using uncertainty ranges for the input data is called robust optimization models which are briefly discussed in section 5.3.

This model is to design the distribution network with multi-layer of facility locations by using the multi-source Capacitated Facility Location Problem (CFLP), or sometime is called the Capacitated Concentrator Location Problem (CCLP). The number of required facilities and the locations of them are the two main questions in facility location

problem. Then, the assigned link flows of every facility location are designed. The model would like to minimize the total delivery cost under three costs which are transportation cost, opening facility cost and transshipment cost which need to indicate the multi-layer facility location. The distribution networks consist of a number of suppliers at fixed location, a number of central depots and depots sites at unknown locations (need to select from a set of potential sites), and finally a number of shelters or demand zones at fixed locations. The model is performed mathematically as a mixed-integer linear programming optimization problem. The decision variables to be determined include the location of unknown locations as binary variables, 0 or 1, and the number of facility location of both central depots and depots. Another variable is integer variables which are used for the transportation link flow optimization.

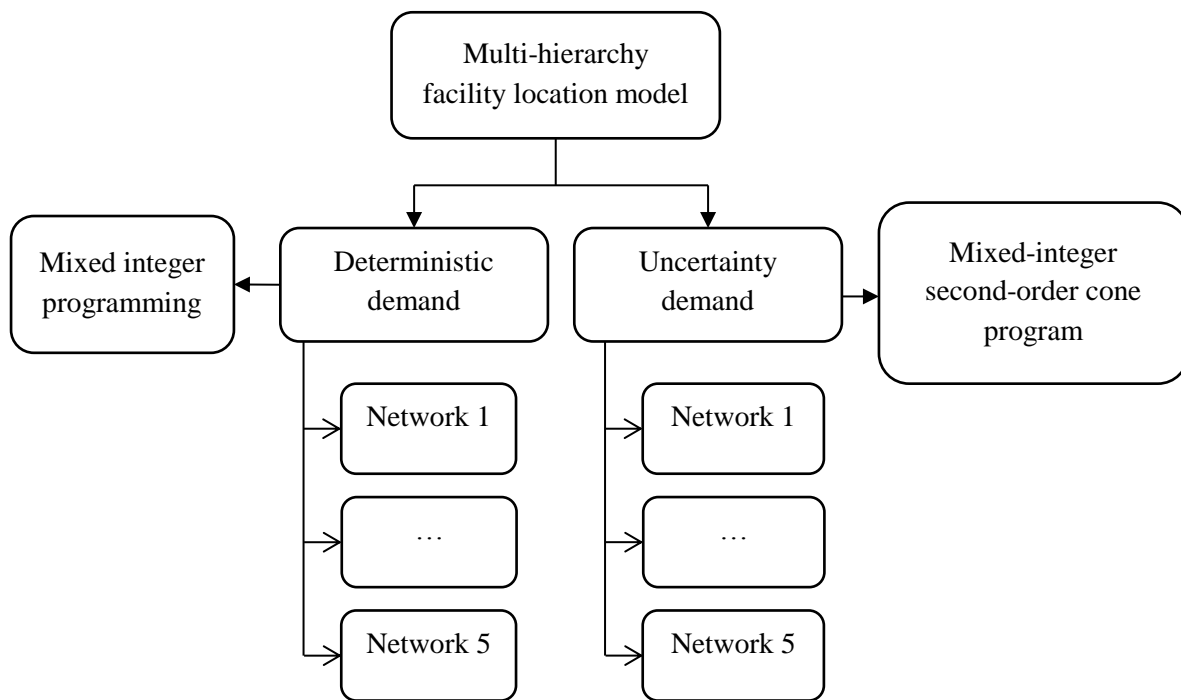


Figure 4-14 Deterministic and uncertainty demand frameworks

4.5 Implemented routing problem

Routing problem is one of the most significant models have been studied so far in distribution network. Obviously, routing problem operates in practical level which designs behind strategy level. Therefore, this study intends to design the whole procedures from strategy level to practical level that can be improved.

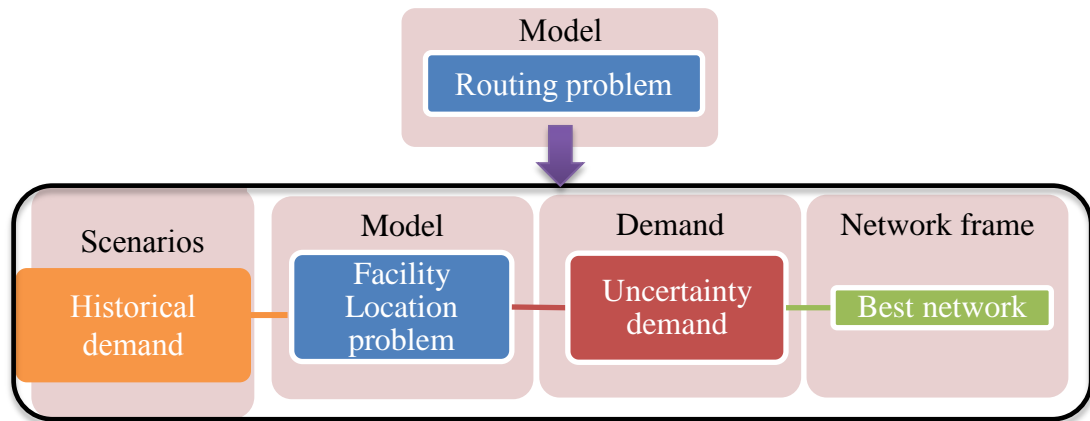


Figure 4-15 Implemented routing frameworks

4.6 Time series

Time-dependent data is the one of important role in several real-life modeling application known as time-based modeling. Typically, literatures of time-based modeling are found in the planning models, scheduling models, and control models. Each model type usually expresses in different time scale. The seconds and minutes of time scale usually determines in the control model, while hours and days typically use for scheduling models. The time units of week, months or even years can be applied in planning models. According to this study, the problem is distribution network planning and evidently, the data is possibly huge changes by weeks. Therefore, this study applies the week scale to become time-based.

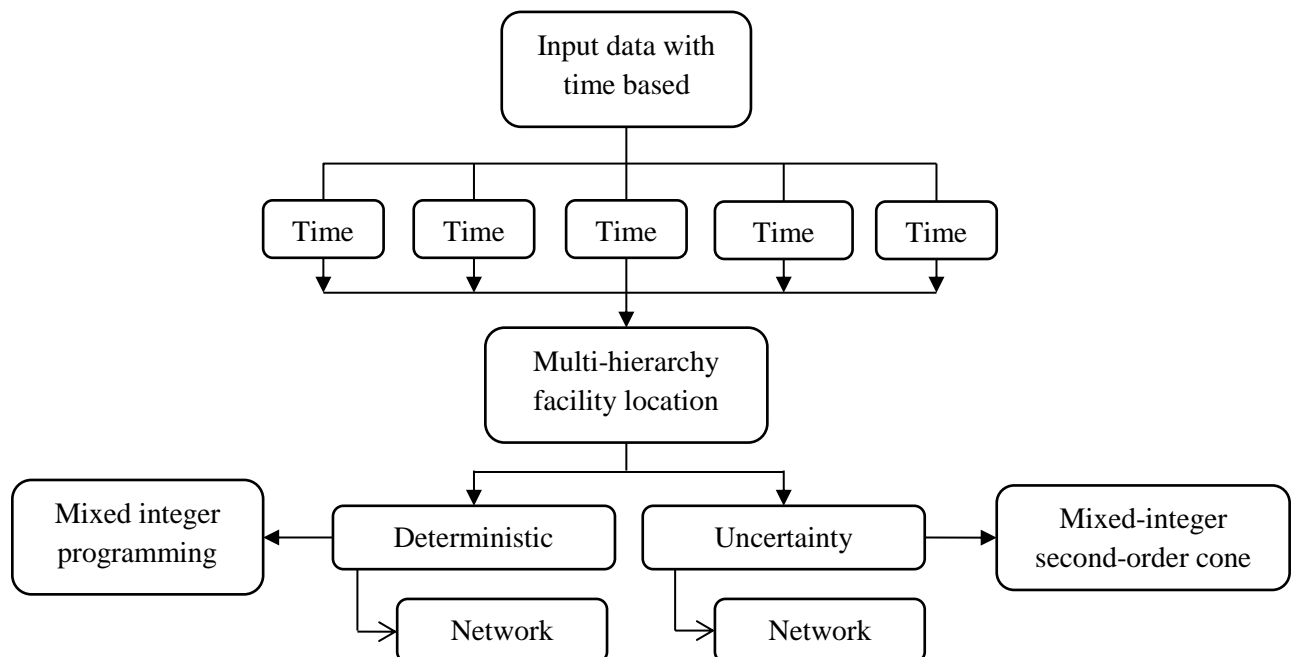


Figure 4-16 Time-series frameworks

CHAPTER 5

MATHEMETICAL MODEL

5.1 Introduction

This chapter is discussed for the mathematical model both objective functions and constraint functions. The location facility model is based on the mixed-integer linear programming that the facility needs to be selected by given the best solution of objective value. This chapter is separated for two main aspects. Firstly, the ordinary location facility model is performed with deterministic of demand parameters both single-hierarchy and multi-hierarchy. In this section, the basic concepts and general ideas of facility location problem are regarded. Afterwards, the facility location model with demand uncertainty is generated by using robust optimization approach. Some methodology frameworks and some notions of robust optimization are explained in this section.

5.2 Location facility problem with deterministic demand

5.2.1 Overview of location facility problem

A logistics network consists of suppliers, manufacturing centers, distribution centers, warehouse and retailers, as well as raw material, work-in-process inventory and product flows between network configurations. The goal is to success following these aspects: the process of planning, implementing, and controlling the efficient, effective flow and storage of goods, services, and related information from point of origin to point of consumption for the purpose of conforming to customer requirements. These strategies and decision planning are a serious determinant of material flow whether can efficiently flow through the distribution system. Not only efficiency is to be considered but also cost effective across the whole system by minimization of system wide costs from transportation and distribution. Indeed, a decision making is typically classified in three level following *Hax and Candea's (1984)*. These are a strategic level, a tactical level and an operational level. First is that the strategic level deals with the decisions that have long-lasting effect on the firm. The decisions regard to the number, location and capacities of facility location, and also the flow of material through the logistics network. Second is the tactical level which generally includes the decisions that are updated anywhere between once every quarter and once every year. These usually include

purchasing and production decisions, inventory policies and transportation strategies. Finally, the operational level refers to the day-to-day decisions such as scheduling, routing and loading trucks.

Where to locate the facilities such as manufactures, distribution centers, warehouses or retailers are the one of most important issues of logistics planning. The location problems extensively encompass a range of problems such as the location of emergency services (fire houses or ambulances), the location of hazardous materials, problems in telecommunications network design and etc. The several location problems have been proposed in *Bramel and Simchi-Levi (1997)* as followed the p-Median Problem, the single-source Capacitated Facility Location Problem and a distribution system design problem. The differences of two first methods are that, for p-Median Problem, there is no fixed cost for locating at a particular site and there is no capacity restriction at facility site whereas there is a fixed cost and capacity limitation when the single-source CFLP is modeled. The p-Median Problem is to choose the facility sites where will be located the way that the transportation cost is minimized or the facility is located closet each other with retailer demand. The single-source CFLP is required that each retailer have only one facility that can provide. However, when this single-source is relaxed, is simply called multi-source Capacitated Facility Problem. In that meaning, a retailer's demand can be divided between any numbers of facilities. The problem is to locate the facility location in the distribution network. If the facility locations are selected to be opened then a fixed cost is incurred and there is a capacity limitation on the amount of demand that can satisfy. A typical assumption for cost of locating at a particular site is fixed cost such as building cost, rental costs and etc. and a variable cost for transportation. This variable cost includes the cost of moving the products to the retailers as well as the cost of transportation the materials from manufacturers to warehouses. Therefore, a retailer will not always be assigned to its nearest facilities by the located fixed costs and capacity constraint. The general objective function is to locate a set of facilities by cost minimization which subject to a variety of constraints for example below:

- ❖ Each facility location has a limitation of a capacity that area can supply.
- ❖ Each retailer or customer zone receives a shipment from one and only one facility locations.
- ❖ Each retailer must be within a fixed distance of the facility location that serves them. This means that a reasonable delivery lead time is ensured.

The single-source Capacitated Facility Location Problem is basically conducted as the following integer linear programming. Note that the notations of the basic model here and study model which can see in section 4.2.2 are differences.

$$\min \sum_{i=1}^n \sum_{j=1}^m c_{ij} X_{ij} + \sum_{j=1}^m f_j Y_j \quad 5.1$$

Subject to

$$\sum_{j=1}^m X_{ij} = 1 \quad 5.2$$

This constraint ensures that each retailer is exactly assigned to one facility.

$$\sum_{i=1}^n w_i X_{ij} \leq q_j Y_j \quad 5.3$$

This constraint guarantees that the facility's capacity is not exceeded the limitation. Also that if the facility is not located at site j so the retailer cannot be assigned to that site.

$$X_{ij}, Y_j \in \{0,1\} \quad 5.4$$

The decision variables Y_j and X_{ij} is assigned to be integer variables. The Y_j and X_{ij} is equal to 1, if the facility is located and retailer is served by selected facility, 0 is otherwise.

5.2.2 Single-hierarchy facility

Notation of facility location mathematic formulation

Indices

- I : Set of the supplier nodes (i) (i=1,2,3...I)
- K : Set of the candidate depots (k) (k=1,2,3...K)
- L : Set of the demand nodes or shelters (l) (l=1,2,3...L)
- TS : Set of the truck size (s)

Notations

- x_{ik}^1, x_{kl}^2 : The flow of items from i and j, k and l
- C_k^1 : The capacity at the candidate depots (k) (k=1,2,3...K)

Sets of parameters

S_i	: The amount of items at the supply i
D_l	: The demand at the affected area l
c_{ik}^1, c_{kl}^2	: The travel cost between i and k and k and l
f_k^1	: The opening depot cost at k
tc_k^1	: The transshipment cost at k
v_{ik}^1, v_{kl}^2	: The capacity of truck between i and k and k and l
w_{ik}^1, w_{kl}^2	: The maximum working time of drivers between i and k and k and l
d_{ij}^1, d_{kl}^3	: The distance between i and k and k and l
t_{ik}^1, t_{kl}^2	: The travel time between i and k and k and l
E_s	: The energy consumption rate of truck size s
DS_s	: The driver salary of truck size s
T_s	: The truck cost of truck size s

Objective function

$$\min \left\{ \sum_{k=1}^K \sum_{i=1}^I c_{ik}^1 x_{ik}^1 Z_k + \sum_{l=1}^L \sum_{k=1}^K c_{kl}^2 x_{kl}^2 Z_k + \sum_{k=1}^K f_k^1 Z_k + \sum_{k=1}^K tc_k^1 Z_k \right\} \quad 5.5$$

When

$$c_{ik}^1 = (E_s d_{ik}^1) + (DS_s t_{ik}^1) + T_s \quad 5.6$$

$$c_{kl}^2 = (E_s d_{kl}^2) + (DS_s t_{kl}^2) + T_s \quad 5.7$$

The objective formulation 5.5 is determined to minimize the total delivery cost for single-hierarchy of facility of location problem. The first two parts of the objective function are generated for the transportation cost which depends on the amount of transportation. The latter two parts are performed to calculate the opening facility cost of layer-2 or as known as depots. The last two parts are calculated for loading/unloading cost at each facility location.

Decision variables

$$Z_k = \begin{cases} 1, & \text{if depots is located at } k \\ 0, & \text{otherwise} \end{cases} \quad \text{for } k \in K$$

Z_k is the decision variable which is specified as binary variables, to select the depot locations from the set of potential site $k \in L$.

Subject to

$$\sum_{k=1}^K x_{ik}^1 \leq S_i \quad 5.8$$

Constraint 5.8 guarantees that the total amount flow from supplier locations i to depots k is not over than the amount of serving goods at suppliers i .

$$\sum_{i=1}^I x_{ik}^1 \geq \sum_{l=1}^L x_{kl}^2 Z_k \quad 5.9$$

Constraint 5.9 restricts for the summation of link flow from i to k not exceed than the capacity of opening depots k .

$$\sum_{i=1}^I x_{ik}^1 \leq C_k^1 Z_k \quad 5.10$$

Constraint 5.10 ensures that the total amount from suppliers i to depots k is not over than the capacity C at depots k .

$$\sum_{k=1}^K x_{kl}^2 \geq D_l \quad 5.11$$

Constraint 5.11 confirms that the total amount from depots k is satisfied with the demand l .

$$\sum_{k=1}^K x_{ik}^1 \leq v_{ik}^1 \quad 5.12$$

$$\sum_{l=1}^L x_{kl}^2 \leq v_{kl}^2 \quad 5.13$$

Constraint 5.12 and 5.13 determine to prohibit that the amount of a commodity cannot exceed the maximum truck volume restriction.

$$\sum_{k=1}^K t_{ik}^1 \leq w_{ik}^1 \quad 5.14$$

$$\sum_{l=1}^L t_{kl}^2 \leq w_{kl}^2 \quad 5.15$$

Constraint 5.14 and 5.15 restrict for the total driving hours of driver which are not over than the maximum working time.

$$x_{ik}^1, x_{kl}^2 \geq 0 \quad 5.16$$

Constraint 5.16 confirms that each link flow from site i to j , j to k and k to l need to define with some amount of goods.

$$Z_k \in \{0,1\} \text{ for all } k \quad 5.17$$

Constraint 5.17 generates to specify that variables Z_k is binary variable 0 and 1, 1 is represented, if the facility is located at k and 0 is otherwise.

5.2.3 Multi-hierarchy facility

Notation of facility location mathematic formulation

Indices

- I : Set of the supplier nodes (i) ($i=1,2,3 \dots I$)
- J : Set of the candidate central depots (j) ($j=1,2,3 \dots J$)
- K : Set of the candidate depots (k) ($k=1,2,3 \dots K$)
- L : Set of the demand nodes or shelters (l) ($l=1,2,3 \dots L$)
- TS : Set of the truck size (s)

Notations

- $x_{ij}^1, x_{jk}^2, x_{kl}^3$: The flow of items from i and j , j and k , k and l
- C_j^1 : The capacity at the candidate central depots j ($j=1,2,3 \dots J$)
- C_k^2 : The capacity at the candidate depots k ($k=1,2,3 \dots K$)

Sets of parameters

- S_i : The amount of items at the supply i
- D_l : The demand at the affected area l
- $c_{ij}^1, c_{jk}^2, c_{kl}^3$: The travel cost between i and j , j and k , k and l
- f_j^1, f_k^2 : The opening depot cost at j and k
- tc_j^1, tc_k^2 : The transshipment cost at j and k
- $v_{ij}^1, v_{jk}^2, v_{kl}^3$: The capacity of truck between i and j , j and k , k and l
- $w_{ij}^1, w_{jk}^2, w_{kl}^3$: The maximum working time of drivers between i and j , j and k , k and l

- $d_{ij}^1, d_{jk}^2, d_{kl}^3$: The distance between i and j, j and k, k and l
 $t_{ij}^1, t_{jk}^2, t_{kl}^3$: The travel time between i and j, j and k, k and l
 E_s : The energy consumption rate of truck size s
 DS_s : The driver salary of truck size s
 T_s : The truck cost of truck size s

Objective function

$$\begin{aligned}
 \min \left\{ \sum_{j=1}^J \sum_{i=1}^I c_{ij}^1 x_{ij}^1 Y_j + \sum_{k=1}^K \sum_{j=1}^J c_{jk}^2 x_{jk}^2 Y_j Z_k \right. \\
 \left. + \sum_{l=1}^L \sum_{k=1}^K c_{kl}^3 x_{kl}^3 Z_k + \sum_{j=1}^J f_j^1 Y_j + \sum_{k=1}^K f_k^2 Z_k + \sum_{j=1}^J t c_j^1 Y_j + \sum_{k=1}^K t c_k^2 Z_k \right\}
 \end{aligned} \tag{5.18}$$

The objective formulation 5.18 determines to minimize the total delivery cost. The first three parts of objective function are generated for the transportation cost which depends on the amount of transportation. The latter two parts are performed to calculate the opening facility cost of layer-2 and layer-3 or as known as central depots and depots. The last two parts are calculated for loading/unloading cost at each facility location.

When

$$c_{ij}^1 = (E_s d_{ij}^1) + (DS_s t_{ij}^1) + T_s \tag{5.19}$$

$$c_{jk}^2 = (E_s d_{jk}^2) + (DS_s t_{jk}^2) + T_s \tag{5.20}$$

$$c_{kl}^3 = (E_s d_{kl}^3) + (DS_s t_{kl}^3) + T_s \tag{5.21}$$

Formulation 5.19, 5.20 and 5.21 represent travel cost parameter functions including travel cost and operation cost.

Decision variables

$$Y_j = \begin{cases} 1, & \text{if central depots is located at } j \\ 0, & \text{otherwise} \end{cases} \quad \text{for } j \in J$$

$$Z_k = \begin{cases} 1, & \text{if depots is located at } k \\ 0, & \text{otherwise} \end{cases} \quad \text{for } k \in K$$

These two decision variables are specified as binary variables. Y_j is the decision variable whether to select the central depot location from the location set $j \in J$ or not. Z_k is the variable to select the depot locations from the set of potential site $k \in K$.

Subject to

$$\sum_{j=1}^J x_{ij}^1 \leq S_i \quad 5.22$$

Constraint 5.22 guarantees that the total amount flow from supplier locations i to central depots j is not over than the amount of serving goods at suppliers i .

$$\sum_{i=1}^I x_{ij}^1 \geq \sum_{k=1}^K x_{jk}^2 Y_j \quad 5.23$$

Constraint 5.23 ensures that the sum of link flows from i to j does not exceed the total availability of goods at opening central depots j .

$$\sum_{i=1}^I x_{ij}^1 \leq C_j^1 Y_j \quad 5.24$$

Constraint 5.24 limits the total amount of link flows from j to k to the capacity of opening central depots j .

$$\sum_{j=1}^J x_{jk}^2 \geq \sum_{l=1}^L x_{kl}^3 Z_k \quad 5.25$$

Constraint 5.25 limits the sum of link flows from j to k to the availability of goods at depots k .

$$\sum_{j=1}^J x_{jk}^2 \leq C_k^2 Z_k \quad 5.26$$

Constraint 5.26 ensures that the total amount of link flows from depots k to demand l must not be higher than the capacity of next network configuration or depots k .

$$\sum_{k=1}^K x_{kl}^3 \geq D_l \quad 5.27$$

Constraint 5.27 confirms that the total amount of goods from depots k satisfies demand l .

$$\sum_{j=1}^J x_{ij}^1 \leq v_{ij}^1 \quad 5.28$$

$$\sum_{k=1}^K x_{jk}^2 \leq v_{jk}^2 \quad 5.29$$

$$\sum_{l=1}^L x_{kl}^3 \leq v_{kl}^3 \quad 5.30$$

Constraints 5.28, 5.29, and 5.30 prohibit that the amount of a commodity exceeds the maximum truck volume.

$$\sum_{j=1}^J t_{ij}^1 \leq w_{ij}^1 \quad 5.31$$

$$\sum_{k=1}^K t_{jk}^2 \leq w_{jk}^2 \quad 5.32$$

$$\sum_{l=1}^L t_{kl}^3 \leq w_{kl}^3 \quad 5.33$$

Constraints 5.31, 5.32 and 5.33 limit the total amount of driving hours to the maximum working time.

$$x_{ij}^1, x_{jk}^2, x_{kl}^3 \geq 0 \quad 5.34$$

Constraint 5.34 confirms that each link flow from site i to j , j to k , and k to l needs to define some amount of goods.

$$Y_j, Z_k \in \{0,1\} \text{ for all } j \text{ and } k \quad 5.35$$

Finally, constraint 5.35 specifies that both decision variables Y_j and Z_k are binary variables, taking value 1 if the facility is located at sites j and k , and 0 otherwise.

5.3 Location facility model under demand uncertainty

5.3.1 Robust optimization Methodology

Robust optimization is an approach which is rather new considered for decision making under uncertainty parameters which depend on the decision makers such as price, temperature, demand and etc. This is suitable for a situation where the range of the uncertainty is known and not necessarily the distribution. Commonly some inputs hold an

uncertain value anywhere between a fixed minimum and a maximum. Solutions will be feasible for all the constraints when the inputs drift within the uncertainty ranges. This is widely known as robust counterpart. However, if this constraint is too strict, there is another one method as known as chance constraint. This can provide a probability for which the solution is required to satisfy specific constraints for example the chance that the demand for electricity will be met is at least 95%. The robustness of your decisions is measured in terms of the best performance against all possible realizations of the parameters values. The definition of robustness decisions is indicated in terms of the best performance in the worst case possible (min-max optimization).

The robust optimization approach was introduced in (*Ben-Tal and Nemirovski 1998*) for convex optimization and in (*El-Ghaoui et al. 1998*) for semidefinite programming. The robust solution for an optimization problem under uncertainty is defined as the solution that has the best objective value in its worst case uncertainty scenario. Attractive features of a robust solution are that while it is only close to optimal for any specific scenario, it behaves well over all likely uncertainty outcomes. In addition, in many set tings finding the robust solution is no harder than solving the deterministic problem. Robust Optimization has provided interesting answers to applications on structural de sign (*Ben-Tal and Nemirovski 1997*), least-square optimization (*El-Ghaoui and Lebret 1997*), portfolio optimization problems (*Goldfarb and Iyengar 2003; El-Ghaoui et al. 2003*), supply chain management problems (*Bertsimas and Thiele 2003; Ben Tal et al. 2003*), and integer programming and network flows (*Atamtürk and Zhang 2004; Bertsi mas and Sim 2003*). The network design problem has a natural separation between “here and now” decisions and “wait and see” decisions: investment decisions must be made before we observe the results of the demand and transportation cost uncertainty, while the routing decisions made by the planner have to route whatever demand occurred and under the transportation conditions that are set forth by the realized transportation costs.

The Robust Optimization is very suitable for many problems as only simple inputs are required from the user about the data uncertainty because there are no scenarios or distribution functions need to be defined. In contrast with Stochastic Programming that can result in large models when considering many scenarios. However, these many scenarios should make it important to limit the number of considered scenarios, but therefore also affect that the results are less robust. The advantage of Robust Optimization

models is that they grow only slightly when uncertainty is added. As the result, the model can be solved efficiently.

In robust optimization, the model with uncertain data is transformed into the robust counterpart. For example is the following robust linear programming optimization problem below.

$$\min\{c^T x : A^T x \leq b\} \quad 5.36$$

where $c \in R^m$, $b \in R^n$, and $A \in R^{m \times n}$. Assume that the actual matrix A is in fact uncertain and it only knows a bound uncertainty set $U_A \in R^{m \times n}$. Also the right hand side b belongs to an uncertainty set $U_b \in R^n$. Finally, the objective coefficients c are into an uncertainty set $U_c \in R^m$. The robust counterpart (RC) for the nominal problem (P) is defined as follow.

$$\min\{c^T x : A^T x \leq b, \forall A \in U_A, c \in U_c, b \in U_b\} \quad 5.37$$

The sets U_A , U_c and U_b indicate all possible realizations of the uncertain data and are collectively called the uncertainty set. However, the main incredulities with uncertainty set are:

- ❖ When and how can the robust counterpart of an uncertain problem be reformulated as a computationally tractable optimization problem?
- ❖ How to specify a reasonable uncertainty set such for example meaningful for a particular application and yielding a tractable robust counterpart?

5.3.2 Uncertainty sets

Here briefly discusses the types of sets considered in this work to represent the uncertainty in transportation cost and demand. The uncertainty sets in this work are defined as deviations from an estimated or nominal value of the uncertain parameter. For example, for the uncertain parameter $A \in U_A$, this considers sets around the estimated value $\bar{A} \in U_A$ and using a scalar value ρ to control the confidence on the estimate, of the following form:

$$\text{Polyhedral} \quad : \quad U = \{A + \rho A \in R^{m \times n} : LA \leq h, A \geq 0\} \quad 5.38$$

$$\text{Box} \quad : \quad U = \{A \in R^{m \times n} : |A - \bar{A}| \leq \rho G_{m \times n}, m, n = 1, \dots, N\} \quad 5.39$$

$$\text{Ellipsoidal} \quad : \quad U = \{A \in R^n : \left[\frac{(A - \bar{A})}{r * (A - \bar{A})} \right]^2 \leq \rho^2} \quad 5.40$$

In particular, the polyhedral and ellipsoidal sets are quite general and can represent arbitrary correlation structures in the uncertain parameter A . This work presents results where the uncertainties in demand U_A are defined in one among two of these forms as ellipsoidal uncertainty set.

Ellipsoidal uncertainty set

Let U be “ellipsoidal,” i.e., $U = U(\Pi, Q) = \{\Pi(u) \mid kQuk \leq \rho\}$, where $u \rightarrow \Pi(u)$ is an affine embedding of R^L into $R^{m \times n}$ and $Q \in R^{M \times L}$. Then Problem (2.3) is equivalent to a second-order cone program (SOCP). Explicitly, if we have the uncertain optimization

$$\min\{c^T x\} \quad 5.41$$

$$\text{subject to } A^T x \leq 0, \quad \forall A \in U_A \quad 5.42$$

where the uncertainty set is given as:

$$U = \{(A_1, \dots, A_m) : A_i = A^0 + \Delta u_i, i = 1, \dots, m, \|u\|_2 \leq \rho\} \quad 5.43$$

(A^0 denotes the nominal value) then the robust counterpart is:

$$\min\{c^T x\} \quad 5.44$$

$$\text{subject to } a_i x \leq b_i - \rho \|\Delta i x\|_2, \forall i = 1, \dots, m. \quad 5.45$$

The intuition is as follows: for ellipsoidal uncertainty, the subproblem (2.4) is an optimization over a quadratic constraint. The dual, therefore, involves quadratic functions, which leads to the resulting SOCP.

5.3.3 The procedure to solve robust optimization in AIMMS

These approaches are available to solve in AIMMS software by using following these solvers CPLEX, Gurobi and Mosek. AIMMS provides aiding for generating a robust optimization model from any given deterministic LP/MIP model without the need to reformulate any of the constraint definitions, only additional attributes for selected parameters, variables and constraints is needed. AIMMS can generate both a deterministic model and a robust model from the same formulation. A deterministic model, a stochastic model and a robust optimization model can again co-exist within the same

master model and their respective solutions can be compared. The major challenges associated with the effects from uncertainty are handled by robust optimization. These challenges from uncertainty effects are listed below. There are descriptions for creating and solving robust optimization models in AIMMS which is able to automatically create without reformulation of any constraint definitions for existing deterministic linear program (LP) or mixed-integer program (MIP). The steps necessary to create a robust optimization model are shown in the figure 5-1.

- ❖ To operate the model under lack of full information on the nature of uncertainty
- ❖ To solve the efficient problem
- ❖ To provide guarantees about the performance of the solutions

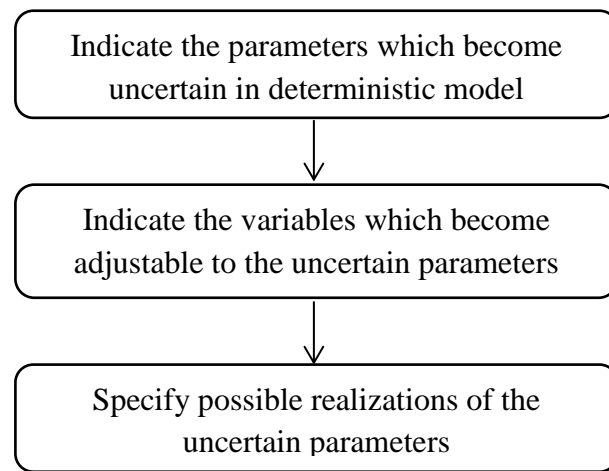


Figure 5.1 The procedure to construct the model in AIMMS

After the uncertainty parameters are modeled in AIMMS, the two new attributes “REGION” and “UNCERTAINTY” are created to offer the easy way to specify the uncertainty set without additional uncertain parameters. Here regions are supported which can set for three types of uncertainty set as Box, Ellipsoid and ConvexHull. This study frame to apply the ellipsoid uncertainty set of demand. However, these following show the examples for all types of the uncertainty set specification. Here, the examples want to specify that parameter A is uncertain parameters and constrained as follows by types of uncertainty set.

- ❖ Box(l, u)

$$l(i, j) \leq A(i, j) \leq u(i, j) \quad 5.46$$

❖ Ellipsoid(c, r)

$$\sum_{i,j} \left(\frac{A(i,j) - A.level(i,j)}{r(i,j)} \right)^2 \leq 1 \quad 5.47$$

❖ ConvexHull($s, v(s)$)

$$A(i,j) = \sum_s \lambda_s A_s(s, i, j) \quad 5.48$$

$$1 = \sum_s \lambda_s, \quad \lambda_s \geq 0 \quad 5.49$$

5.3.4 Mathematical with robust formulation by using robust counterpart

This study focuses on the multi-source and multi-layer of facility location problem with uncertainty demand by considering the ellipsoidal uncertainty set in robust optimization approach. There are some researchers, Ben-Tal and Nemirovski and El Ghaoui et al. who consider ellipsoidal uncertainty set. Whenever the uncertainty set of a mixed-integer robust problem is an ellipsoidal, and then the robust counterpart can be reformulated as a mixed-integer second-order cone program (SOCP).

$$\text{Ellipsoidal: } U = \left(\frac{(D - \bar{D})}{\delta \times (D - \bar{D})} \right)^2 \leq \rho^2 \quad 5.50$$

$$\begin{aligned} \min \left\{ \sum_{j=1}^J \sum_{i=1}^I c_{ij}^1 \bar{x}_{ij}^1 \bar{Y}_j + \sum_{k=1}^K \sum_{j=1}^J c_{jk}^2 \bar{x}_{jk}^2 \bar{Y}_j \bar{Z}_k \right. \\ \left. + \sum_{l=1}^L \sum_{k=1}^K c_{kl}^3 \bar{x}_{kl}^3 \bar{Z}_k + \sum_{j=1}^J f_j^1 \bar{Y}_j + \sum_{k=1}^K f_k^2 \bar{Z}_k + \sum_{j=1}^J tc_j^1 \bar{Y}_j + \sum_{k=1}^K tc_k^2 \bar{Z}_k \right\} \end{aligned} \quad 5.51$$

$$\sum_{k=1}^K \bar{x}_{kl}^3 \geq \bar{D}_l \quad 5.52$$

5.4 Routing establishing

Classical location problem

$$\begin{aligned} \min \left\{ \sum_{j=1}^J \sum_{i=1}^I c_{ij}^1 x_{ij}^1 Y_j + \sum_{k=1}^K \sum_{j=1}^J c_{jk}^2 x_{jk}^2 Y_j Z_k \right. \\ \left. + \sum_{l=1}^L \sum_{k=1}^K c_{kl}^3 x_{kl}^3 Z_k + \sum_{j=1}^J f_j^1 Y_j + \sum_{k=1}^K f_k^2 Z_k + \sum_{j=1}^J t c_j^1 Y_j + \sum_{k=1}^K t c_k^2 Z_k \right\} \end{aligned} \quad 5.18$$

Decision variables

$$Y_j = \begin{cases} 1, & \text{if central depots is located at } j \text{ for } j \in J \\ 0, & \text{otherwise} \end{cases}$$

$$Z_k = \begin{cases} 1, & \text{if depots is located at } k \text{ for } k \in K \\ 0, & \text{otherwise} \end{cases}$$

Decision variables

$$R_{kl} = \begin{cases} 1, & \text{if shelter } l \text{ is delivered} \\ & \text{from depots } k \text{ by truck } s \text{ for } k \in L, l \in P \\ 0, & \text{otherwise} \end{cases}$$

Location problem with routing

$$\begin{aligned} \min \left\{ \sum_{j=1}^J \sum_{i=1}^I c_{ij}^1 x_{ij}^1 Y_j + \sum_{k=1}^K \sum_{j=1}^J c_{jk}^2 x_{jk}^2 Y_j Z_k \right. \\ \left. + \sum_{l=1}^L \sum_{k=1}^K c_{kl}^3 x_{kl}^3 Z_k R_{kl} + \sum_{j=1}^J f_j^1 Y_j + \sum_{k=1}^K f_k^2 Z_k + \sum_{j=1}^J t c_j^1 Y_j + \sum_{k=1}^K t c_k^2 Z_k \right\} \end{aligned} \quad 5.53$$

Additional subject to

$$\sum_{l=1}^L R_{kl} \geq 1 \quad 5.54$$

$$\sum_{k=1}^K x_{kl}^2 Z_k \sum_{l=1}^L R_{kl} \leq v_{kl}^3 \quad 5.55$$

$$\sum_{l=1}^K R_{kl} - \sum_{l=1}^L R_{kl} = 0 \quad 5.56$$

This section infers to the second stage of this study, it is in the part of improving by routing. The variables in location problem which are the locations and allocation were determined in the primary stage. In other words, the decision Y_j, Z_k and variables $x_{ij}^1, x_{jk}^2, x_{kl}^3$ in 5.53 were optimized from 5.18 under the demand uncertainty 5.50, 5.51, 5.52. Then, the decision Y_j, Z_k and variables $x_{ij}^1, x_{jk}^2, x_{kl}^3$ in 5.51 become parameters to substitute in 5.53. Subsequently, the variable R_{kl} is added to make the tours at the third hierarchy. The objective formulation 5.53 is determined to minimize the total delivery cost of location with routing problem. Constraint 5.54 ensures that the delivery route will be linked to the opening depots. Constraint 5.55 is to ensure the capacity of trucks at depots. Constraint 5.56 requires that the trucks ought to leave every point that they visited.

CHAPTER 6

ANALYSIS RESULTS

6.1 Introduction

This study is principally analyzed the multi-facility location problem under both issues deterministic demand and uncertainty demand. The five network models are constructed to handle both demand known and unknown circumstances. The first model is to identify the single set of potential location where is opened for facilities and solve by the popular approaches, multi-source facility location problem by using mixed-integer linear programming. The second model is the assumption of central depot additional, which these depots are the candidates at inside an effected area, then the third model is different by truck size dispatching. These potential sites of central depots are available at the Kesenuma, Tome, Sendai (Kumagane), Yamamoto. The fourth model is also added the central depot layers however these depots are the candidate at outside an effected area, then final network is different by truck size. The assumption is that the set of potential sites of central depots is available at the boundary of Miyagi prefecture as followed Fukushima, Yamagata, Akita and Iwate. The demand is set for five scenarios which deviate from the realistic case in both sides optimistic and pessimistic. These five demand scenarios are separated as less than realistic demand at 20 percent and 10 percent, realistic demand, and more than realistic demand at 10 percent and 20 percent respectively.

Therefore, this chapter is separated for eight sections following by an introduction, results of facility location and inventory, total delivery cost, inventory and allocation, sensitivity, truck requirements, working time estimation, routing implementation and time series model. The introduction is briefly explained the all components which are including in this chapter. Those mentioned sections will be described in both deterministic demand and uncertainty demand.

6.2 Facility location and inventory

The deterministic model investigates the ordinary multi-source capacitated facility location with two decision variables or two layers of facility, a set of central depot and a set of depot. This model derives from the single-source capacitated facility location problem by relaxing the single-source constraint which means that a shelter's demand can

be divided between any numbers of depot facilities. The model is determined as mixed-integer linear programming.

The table 6-1 below is illustrated the deterministic results of the decision variables central depots and depots of the all network assumptions, here is set as the binary variables 0 and 1. The value 1 is represented for the facility locations where are selected to open. These central depots and depots are selected by the reasons that they provide the best solution or minimum of total delivery cost. There are five networks and each network has five scenarios. The outputs of central depots in network 1 are all blank because we assign only one hierarchy in this network. Network 2 and 3, there are two facility sites which are located Kesennuma and Tome for central depots of all scenarios. Likewise, there are two central depots in network 4 and 5, Fukushima and Iwate. The depot locations all network and scenarios result in the same locations. The four sites of depots are determined in scenario 1 and 2, and one depot is added in scenarios 3, 4 and 5. However, some depot locations are changed when the uncertainty demand is applied in table 6-2.

Table 6-1 Location facility of deterministic demand

Deterministic	Network														
Central depot	Network 1					Network 2					Network 3				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Kesennuma						1	1	1	1	1	1	1	1	1	1
Tome						1	1	1	1	1	1	1	1	1	1
Sendai(Kumagane)															
Yamamoto															
Depot	Network 1					Network 2					Network 3				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara			1	1	1			1	1	1			1	1	1
Kesennuma	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
North Ishinomaki	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
South Ishinomaki	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
South East Ishinomaki	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Taiwa Town															
North West Sendai															
North East Sendai															
Central Sendai															
South East Sendai															
South Sendai															

Deterministic	Network														
Central depot	Network 4					Network 5									
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5					
Fukushima	1	1	1	1	1	1	1	1	1	1					
Yamagata															
Akita															
Iwate	1	1	1	1	1	1	1	1	1	1					
Depot	Network 4					Network 5									
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5					
Tome and Kurihara			1	1	1						1	1	1		
Kesennuma	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
North Ishinomaki	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
South Ishinomaki	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
South East Ishinomaki	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Taiwa Town															
North West Sendai															
North East Sendai															
Central Sendai															
South East Sendai															
South Sendai															

Table 6-2 Location facility of uncertainty demand

Uncertainty															
	Network														
	Network 1					Network 2					Network 3				
Central depot	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Kesennuma						1	1	1	1	1	1	1	1	1	1
Tome						1	1	1	1	1	1	1	1	1	1
Sendai(Kumagane)															
Yamamoto															
Depot	Network 1					Network 2					Network 3				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara				1	1	1	1		1	1	1	1		1	1
Kesennuma		1	1	1	1	1	1	1	1	1	1	1	1	1	1
North Ishinomaki		1	1	1	1	1		1	1	1	1		1	1	1
South Ishinomaki		1	1	1	1	1	1	1	1	1	1	1	1	1	1
South East Ishinomaki		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Taiwa Town															
North West Sendai															
North East Sendai															
Central Sendai															
South East Sendai															
South Sendai															

Uncertainty															
	Network														
	Network 4					Network 5					Network 5				
Central depot	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Fukushima		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Yamagata															
Akita															
Iwate		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Depot	Network 4					Network 5					Network 5				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Kesennuma		1	1	1	1	1	1	1	1	1	1	1	1	1	1
North Ishinomaki			1	1	1	1					1	1	1	1	1
South Ishinomaki		1		1	1	1	1	1	1	1	1	1	1	1	1
South East Ishinomaki		1	1	1	1	1	1	1	1	1			1	1	1
Taiwa Town															
North West Sendai															
North East Sendai															
Central Sendai															
South East Sendai															
South Sendai															

As shown in the table before, there are two central depots which are selected. Thus, the number in the table 6-3 presents for the summation of transportation amount from suppliers to central depots. The table 6-3 shows the facility sites that are selected and their inventory of deterministic demand. The blank means that those facility sites are not chosen. The outputs of central depots in network 1 are all blank because we assign only one hierarchy in this network. There are two central depots which are located in Kesennuma and Tome for every demand scenarios and both network 2 and network 3. The main relief items are dispatched to the central depots at Tome until they are full capacity. Then, there are four depot locations at Kesennuma, North Ishinomaki, South Ishinomaki and South East Ishinomaki in case of demand scenario 1 and scenario 2 of all networks. However, it needs one additional depot at Tome and Kurihara to satisfy with the demand scenario 3, scenario 4 and scenario 5. These central depots and depots are selected by the reasons that they provide the best solution or minimum of total delivery cost. Likewise the dominant relief items are dispatched to the central depots at Fukushima until they are full capacity in network 4 and network 5, leftover items dispatch through Iwate.

Table 6-3 Transportation amount through opening facility of deterministic demand

Central depot	Network									
	Network 1					Network 2				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Kesennuma						105,406	168,585	231,743	294,934	358,104
Tome						400,000	400,000	400,000	400,000	400,000
Sendai(Kumagane)										
Yamamoto										
Depot	Network 1					Network 2				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara			84,780	146,698	153,600			84,780	139,354	153,600
Kesennuma	80,857	107,785	86,163	87,436	143,704	80,857	107,785	86,163	94,780	143,704
North Ishinomaki	117,349	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600
South Ishinomaki	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600
South East Ishinomaki	153,600	153,600	153,600	153,600	153,600	117,349	153,600	153,600	153,600	153,600
Taiwa Town										
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

Central depot	Network									
	Network 4					Network 5				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Fukushima	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000
Yamagata										
Akita										
Iwate	105,406	168,585	231,743	294,934	358,104	105,406	168,585	231,743	294,934	358,104
Depot	Network 3					Network 3				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara			145,580	153,600	153,600			145,580	153,600	153,600
Kesennuma	68,931	107,785	86,163	94,780	143,704	80,857	107,785	86,163	94,780	143,704
North Ishinomaki	129,275	153,600	92,800	139,354	153,600	117,349	153,600	92,800	139,354	153,600
South Ishinomaki	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600
South East Ishinomaki	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600	153,600
Taiwa Town										
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

Similarly as deterministic demand, the Table 6.4 shows the facility sites and their storage of uncertainty demand. The uncertainty demand model is solved by robust optimization and using ellipsoid uncertainty set. The two representative central depots as follows Kesennuma and Tome are selected to open for all demand scenarios of network 2 and network 3. However, the main relief items are shuffled delivery and depend on demand scenarios. The central depot at Kesennuma supports the major quantity of relief items in case of optimistic demand and actual demand scenarios, scenario 1, scenario 2 and scenario 3. Contrariwise, the relief items in pessimistic demand, scenario 4 and scenario 5 are mostly collected at Tome until it reaches to capacity limits.

Comparing the deterministic demand and uncertainty demand, some opening depot locations in demand scenario 1 and scenario 2 are changes. In case network 1- scenario 2, the central depot at Tome and Kurihara of uncertainty demand is selected instead of South East Ishinomaki of deterministic demand. Likewise, scenario 1 of both network 2 and network 3, Tome and Kurihara of uncertainty demand are also selected instead of North Ishinomaki deterministic demand. As same as deterministic, the central depots at Fukushima and Iwate are selected in network 4 and network 5. The main central depot to serve is Iwate which is opposite with deterministic cases. Moreover, the depot locations at Tome-Kurihara of scenario 1 and scenario 2 in network 4 and network 5 are selected instead of North Ishinomaki and South East Ishinomaki.

Table 6-4 Transportation amount through opening facility of uncertainty demand

Central depot	Network									
	Network 1					Network 2				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Kesennuma						368,883	400,000	400,000	319,457	358,143
Tome						136,562	168,624	231,782	375,516	400,000
Sendai(Kumagane)										
Yamamoto										
Depot	Network 1					Network 2				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara		107,824	153,600	137,509	153,600	136,562		78,182	153,600	143,743
Kesennuma	81,026	153,600	22,367	136,583	153,600	61,683	121,181	137,705	152,940	153,600
North Ishinomaki	153,600	153,600	153,600	152,673	146,765		140,243	153,600	153,600	153,600
South Ishinomaki	152,593	153,600	153,600	153,600	153,600	153,600	153,600	108,695	153,600	153,600
South East Ishinomaki	131,710		148,615	152,541	150,578	153,600	153,600	153,600	81,233	153,600
Taiwa Town										
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

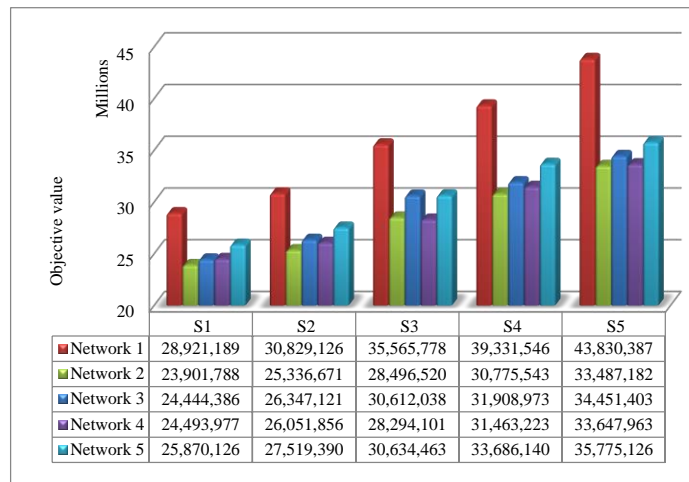
Central depot	Network									
	Network 4					Network 5				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Fukushima	154,489	168,624	231,782	314,750	400,000	154,489	168,624	270,499	314,750	400,000
Yamagata										
Akita										
Iwate	350,956	400,000	400,000	380,223	358,143	350,956	400,000	361,283	380,223	310,454
Depot	Network 3					Network 3				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Tome and Kurihara	140,590	153,600	153,600	153,600	153,600	140,590	153,600	153,600	153,600	153,600
Kesennuma	57,655	109,624	60,941	153,600	153,600	57,655	109,624	27,498	153,600	153,600
North Ishinomaki		153,600	130,423	80,573	153,600		153,600	153,600	80,573	153,600
South Ishinomaki	153,600	151,800	153,600	153,600	147,646	153,600	151,800	153,600	153,600	147,646
South East Ishinomaki	153,600		133,218	153,600	149,697	153,600		143,484	153,600	149,697
Taiwa Town										
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

6.3 Total delivery cost

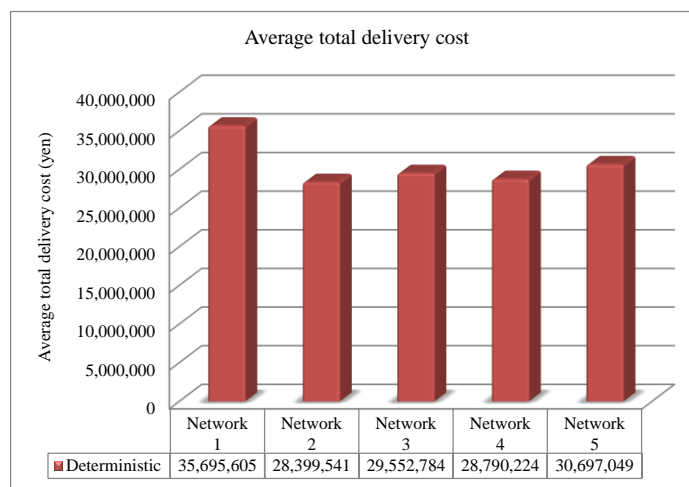
The results here are evaluated for the minimized total delivery cost by considering the two decision variables as a set of potential facility location selection and transportation link flow optimization. We demonstrate the calculation results and the objective function value comparison of five different networks for all demand scenarios. From the results, we found that the network configurations and their systems are affected with the total delivery cost both deterministic demand and uncertainty demand as shown in figure 6-1 and figure 6-3 respectively. It can be seen that the network 2 to network 5 as defined for two hierarchies of facility are obviously preferable cost performance when comparing with the network 1 which is single hierarchy. The average total delivery cost of network 2 to network 5 are lessened from network 1 by 22.77 percent, 18.83 percent, 21.42 percent and 15.06 percent respectively.

When comparing Network 2 and Network 3, all demand scenarios in Network 2 can be reduced by 2.24 percent, 3.91 percent, 7.16 percent, 3.62 percent and 2.84 percent respectively. Likewise, Network 4 and network 5, all demand scenarios in Network 4 less than Network 5 at 5.46 percent, 5.48 percent, 7.94 percent, 6.82 percent, 6.13 percent. These results demonstrated that not only network configurations but together with the truck size operations were significant with the total delivery cost function. By using 10-ton trucks to deliver from the suppliers to the central depots and from the central depots to the depots can have a benefit of cost reduction. To apply model, we suggest to establish the central depots and use large truck to deliver both inbound and outbound with similar amount of demand.

However, there is not much difference when we compare the average total delivery cost of Network 2 with Network 4 and also Network 3 with Network 5 (figure 6-1). These network pairs are the comparison to see whether the how significance of central depot locations potential set affects to the model. The average total delivery cost of Network 2 is 28,399,541 yen while Network 4 is 28,790,224 yen. As well, Network 3 has the average total cost at 29,522,784 yen while Network 5 is 30,697,049 yen. Therefore, it does not matter for a whole network delivery cost whether the central depot locations potential set will be located inside or outside disaster areas.



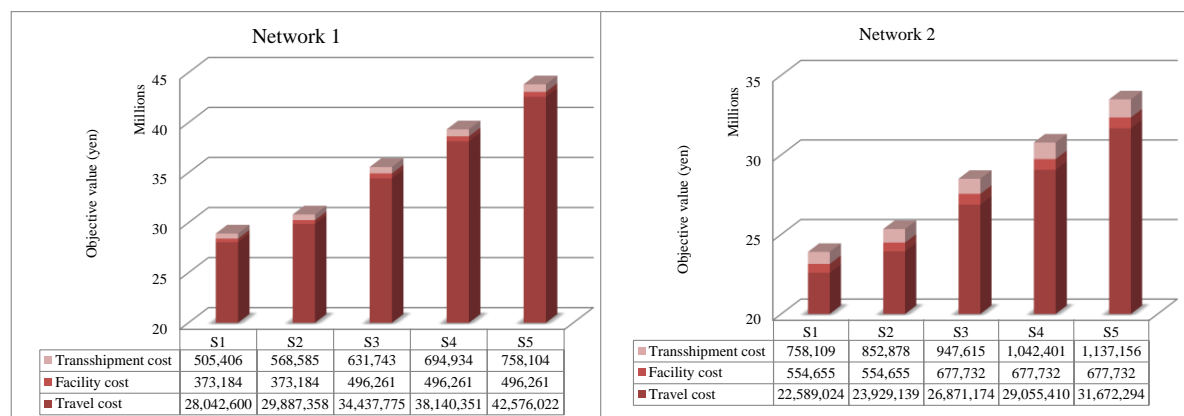
(a) Total delivery cost comparison



(b) Average total delivery cost

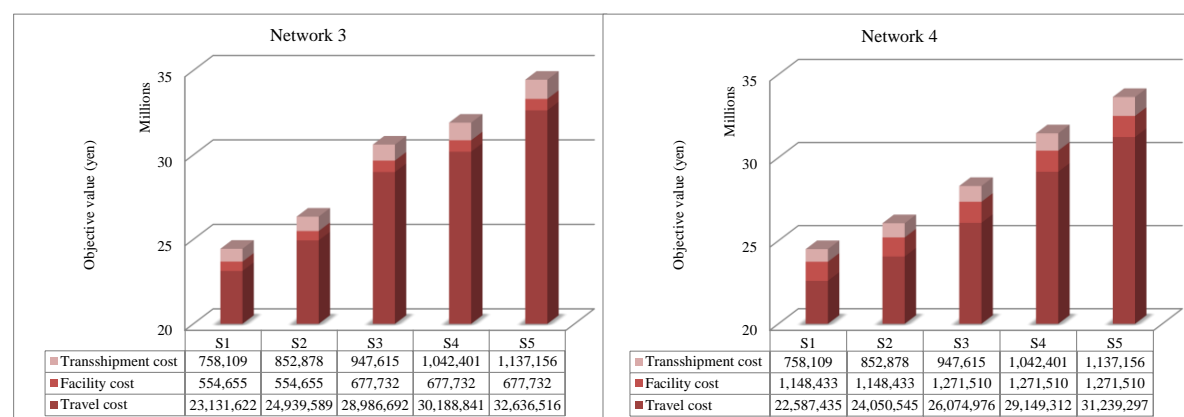
Figure 6-1 Total delivery cost of deterministic

Figure 6-2 shows the total delivery cost for five scenarios. The total delivery cost is mostly generated by travel which is more than about 90 percent and its rapid increase depends on the amount of transportation. The comparison shows that even the opening facility cost of network 1 is less than all networks however the total delivery cost of network 1 is higher than all networks. This can prove that the facility location model considers not only the cost for opening but also the transportation cost simultaneously. Then, this result shows that the travel cost is reduced when compare with another case. Therefore, the total delivery cost of network 2 is lower than the others by the reasons that they have more significance in travel cost even though the opening facility cost is higher. The average travel cost of network 2 is 28,715,418 yen less than all networks especially network 1, 35,695,605 yen.



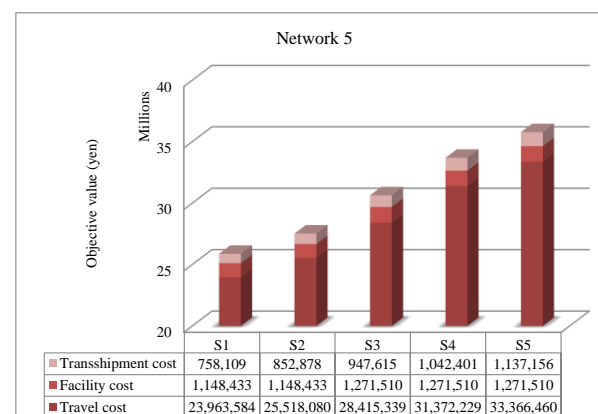
(a) Network 1

(b) Network 2



(c) Network 3

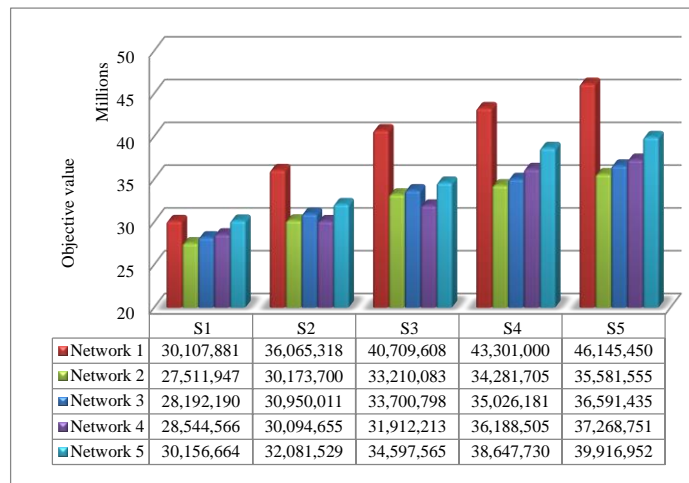
(d) Network 4



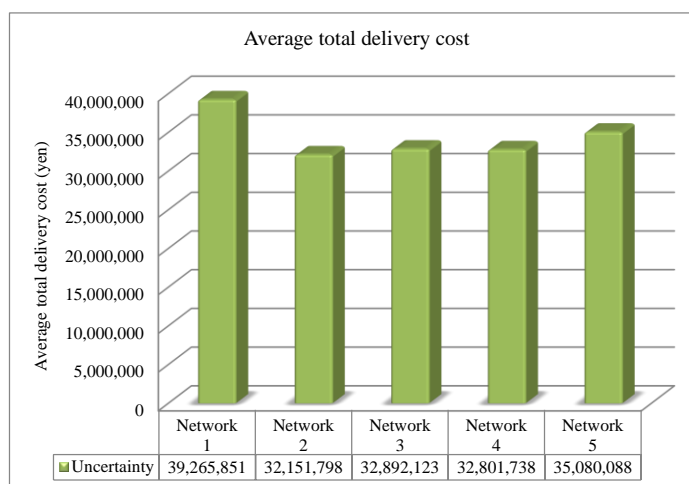
(e) Network 5

Figure 6-2 Total delivery cost for each network scenario of deterministic demand

Figure 6-3 shows the objective function value comparison and the calculation results of five different networks for each uncertainty demand scenario. We determine the uncertainty demand as ellipsoid uncertainty set then the model is solved by robust optimization. As same as deterministic demand scenarios, the network 2 presents the best alternative among five networks. The average total delivery cost of network 2 is 32,151,798 yen while network 1 is 39,265,851 yen. However, similarly with deterministic demand, there is no significance of the travel cost in any case of the central depots belong inside or outside of demand areas. Therefore, the summary of travel for a whole network is almost equal. However, if we consider individual layer, we probably see that from central depots to depots in Network 2 is lower because the serving depots are more closely located with the second depots and demand points.

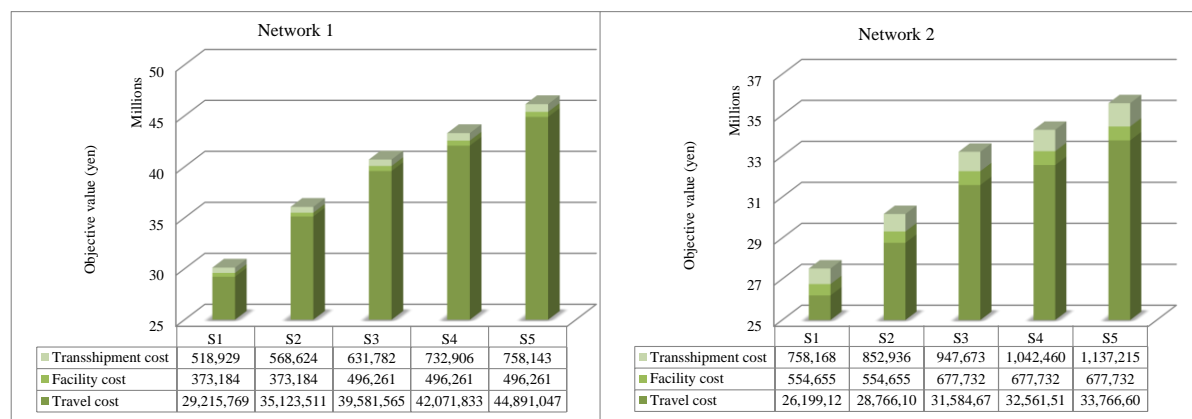


(a) Total delivery cost comparison



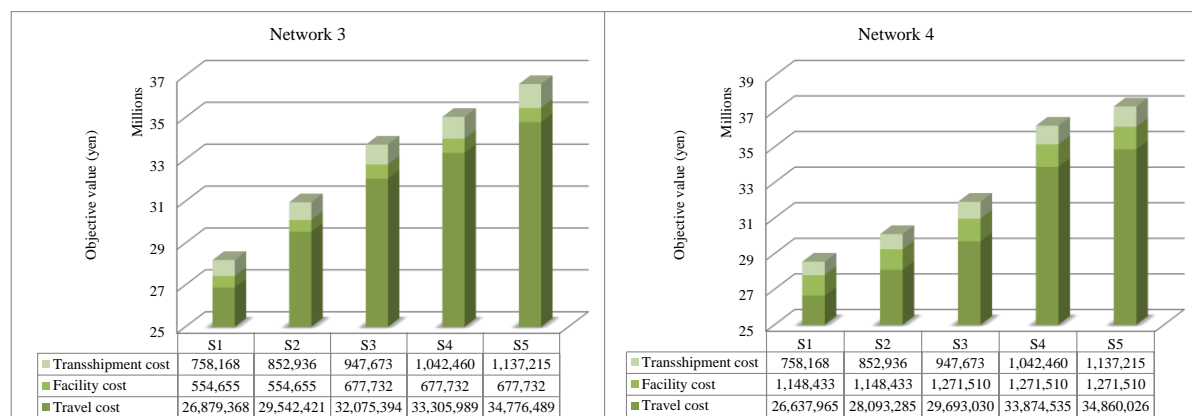
(b) Average total delivery cost

Figure 6-3 Total delivery cost of uncertainty demand



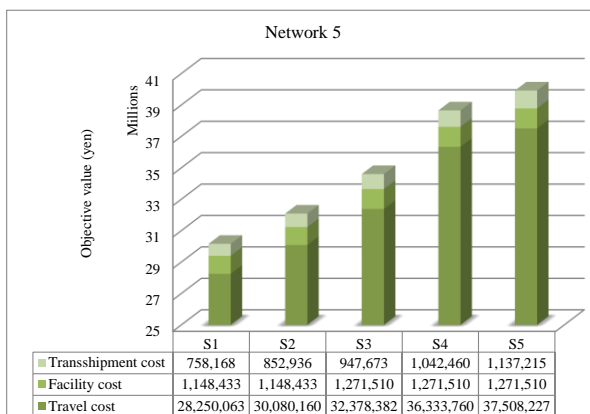
(a) Network 1

(b) Network 2



(c) Network 3

(d) Network 4



(e) Network 5

Figure 6-4 Total delivery cost for each network scenario of uncertainty demand

6.4 Sensitive value

Figure 6-5 illustrates the total delivery cost comparison between deterministic demand and uncertainty demand of five networks. It also shows the sensitive value of objective function for each network. The sensitive value characteristic is represented differential values between the average of samples which shown in the figures 6-5 (right). In fact, the total delivery cost of uncertainty demand is higher than deterministic demand because they consider all possible cases in the uncertainty region and attempt to search the best results that can be represented for all possible demands.

The range of sensitivity value comparison, Network 1 is wider range and higher sensitivity than the others, means that Network 1 is less robust than the other networks. The range scale of Network 1 is approximately 0.1 to 9 million yen while there is approximately 3 to 5 million yen of sensitivity for Network 2 to Network 5.

The deterministic demand and uncertainty demand comparison, network 2 and network 3 are similar that by using robust optimization to handle the uncertainty demand illustrates more robustness than ordinary deterministic demand. In addition, the fluctuation of sensitivity between deterministic demand and uncertainty demand of network 2 is less than network 3. Meaning that network 2 is robust than the other networks.

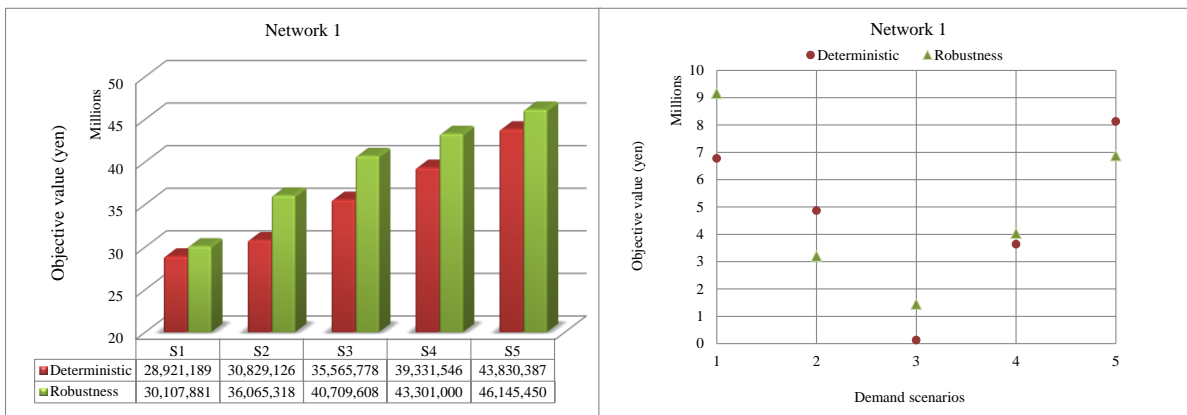


Figure 6-5 (left) Total delivery cost of both deterministic and uncertainty demand
(right) Sensitive value comparison of deterministic and uncertainty demand

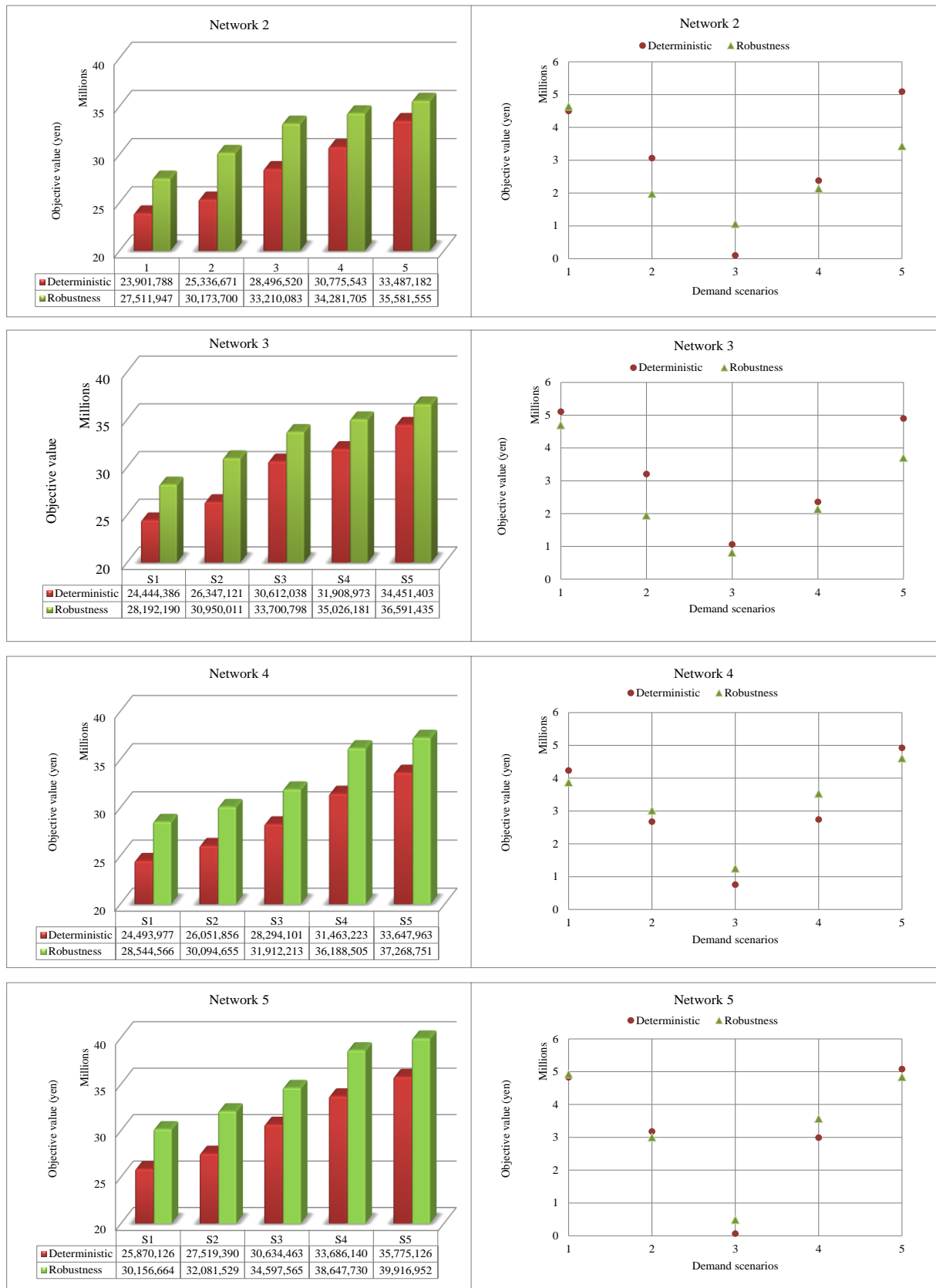


Figure 6-5 (con't) (left) Total delivery cost of both deterministic and uncertainty demand
(right) Sensitive value comparison of deterministic and uncertainty demand

6.5 Truck requirement

As mention before, each network frame includes five demand scenarios thus we report five expectation results for each. In order to identify the network efficiency by total delivery cost minimization and network robustness, hence we compare the total delivery cost of the three networks and indicate the best network structures. Then, we present the sensitivity analysis and compare the robustness of the three networks. Not only mentioned above but we also estimate the fundamental resource requirements, including the number of trucks and total working time of drivers. Therefore, this study can be helping the decision maker to plan for post disaster distribution network and their systems when the circumstance of demand uncertainty occurs.

Figures in this section show the number of truck requirement for all networks and all demand scenarios. The number in the bar chart presents for the number of needed truck for each echelon and also discriminates by the origin suppliers.

Figure 6-6 shows the maximum number of trucks that need to use for relief distribution at each network configuration. From the results, we found that by dispatching with a big lot size at central depots of the Network 2 can be reduced the truck requirements approximately 50 percent. These trucks were about not over than six vehicles at each central depots (echelon 2). This was advantage on the transportation cost by reducing working time of driver and their hire cost. Therefore, the whole system cost was reducing.

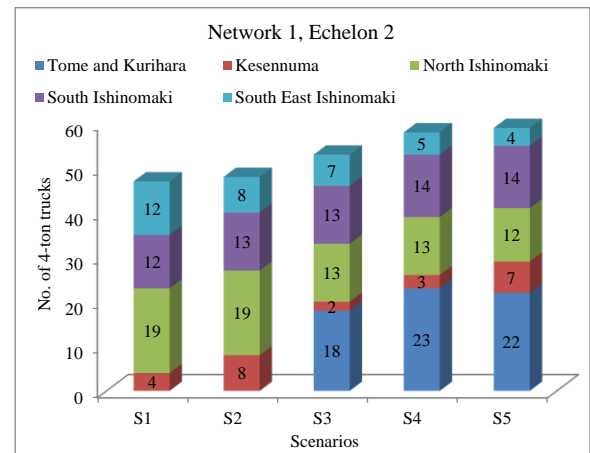
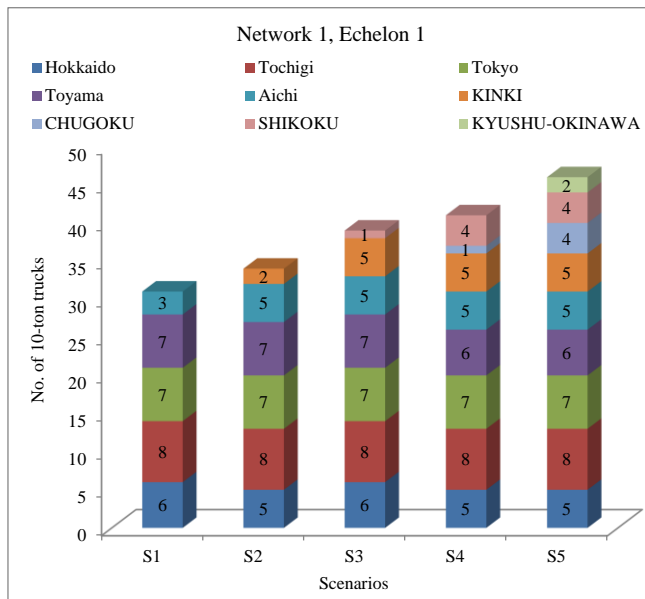


Figure 6-6 Number of truck requirement of deterministic demand, Network 1

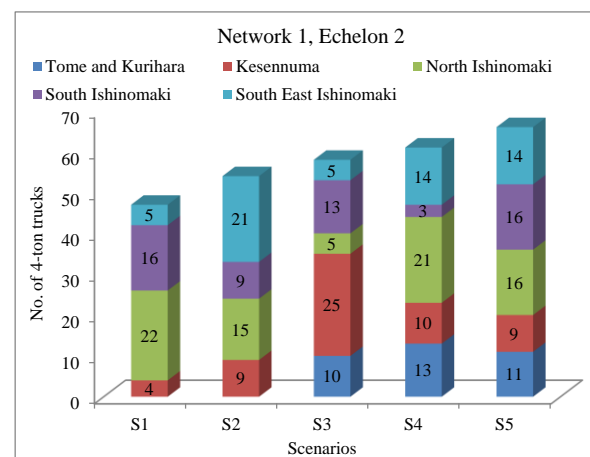
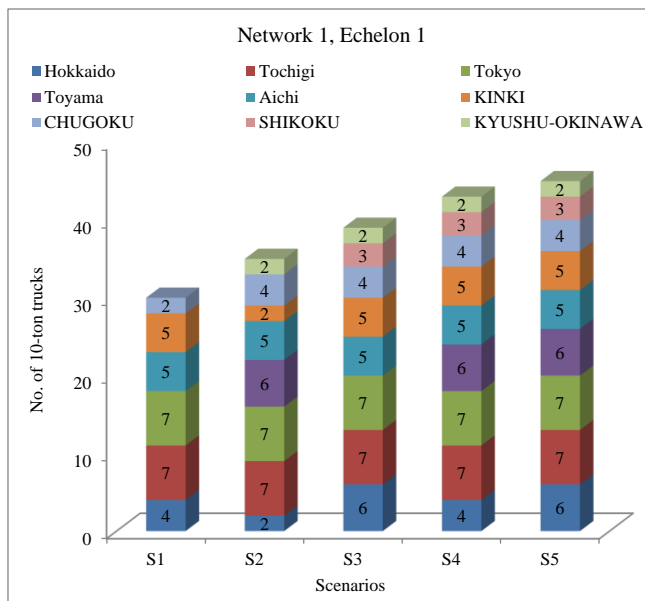


Figure 6-7 Number of truck requirement of uncertainty demand, Network 1

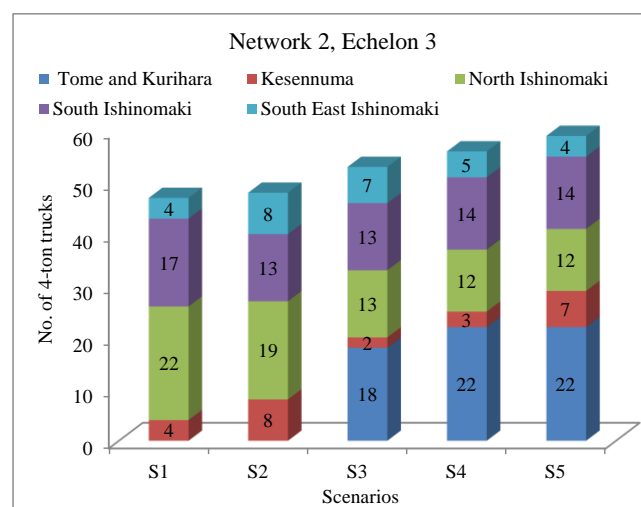
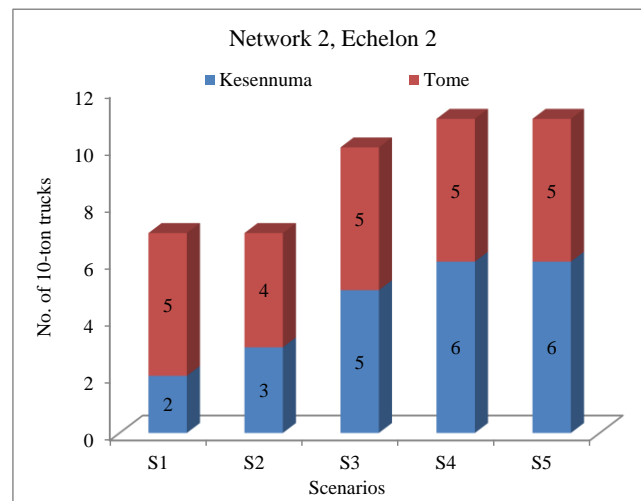
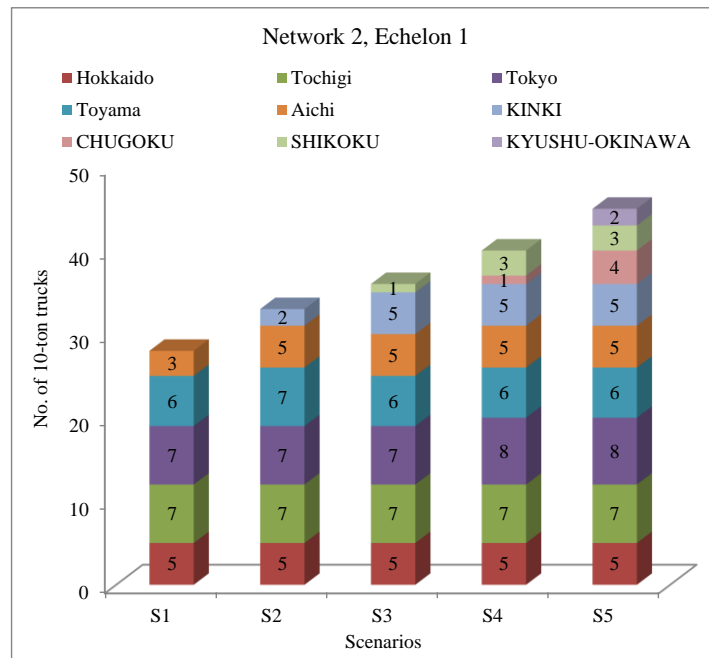


Figure 6-8 Number of truck requirement of deterministic demand, Network 2

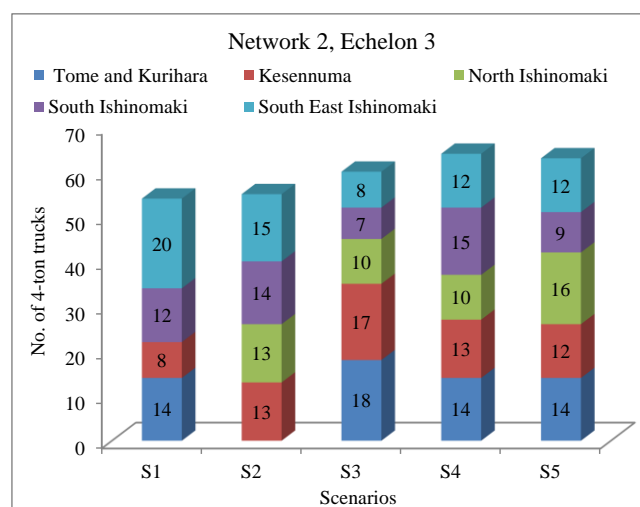
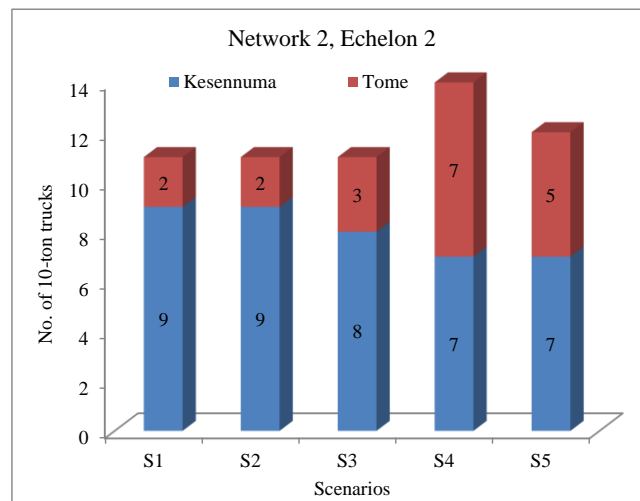
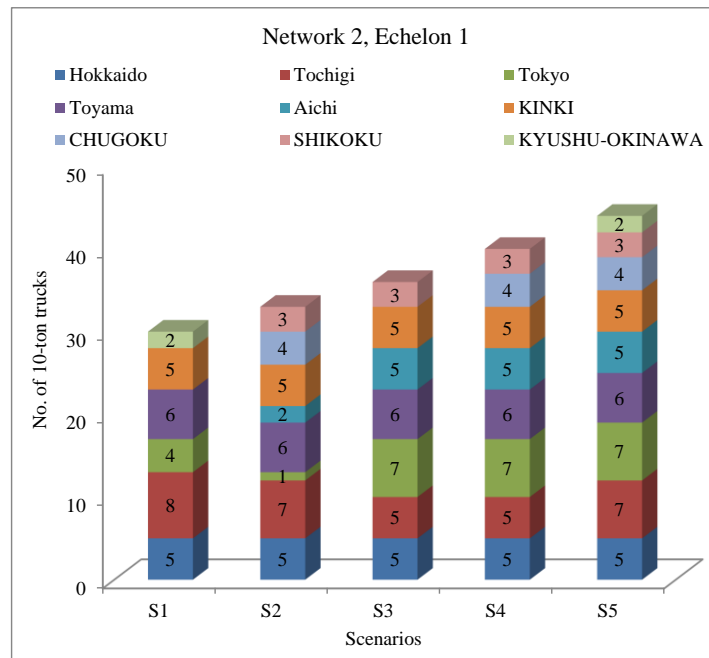


Figure 6-9 Number of truck requirement of uncertainty demand, Network 2

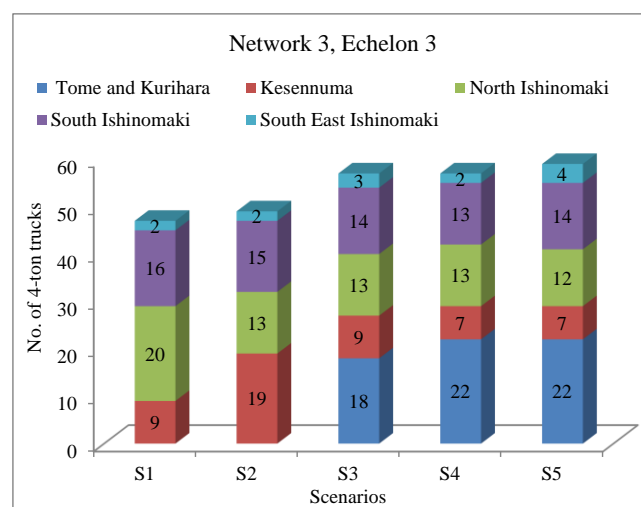
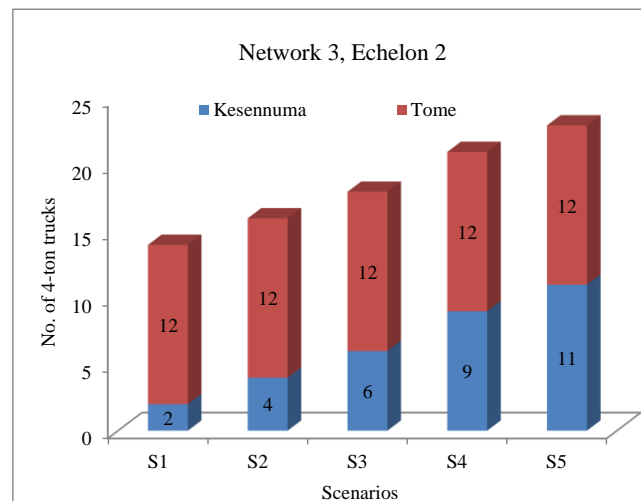
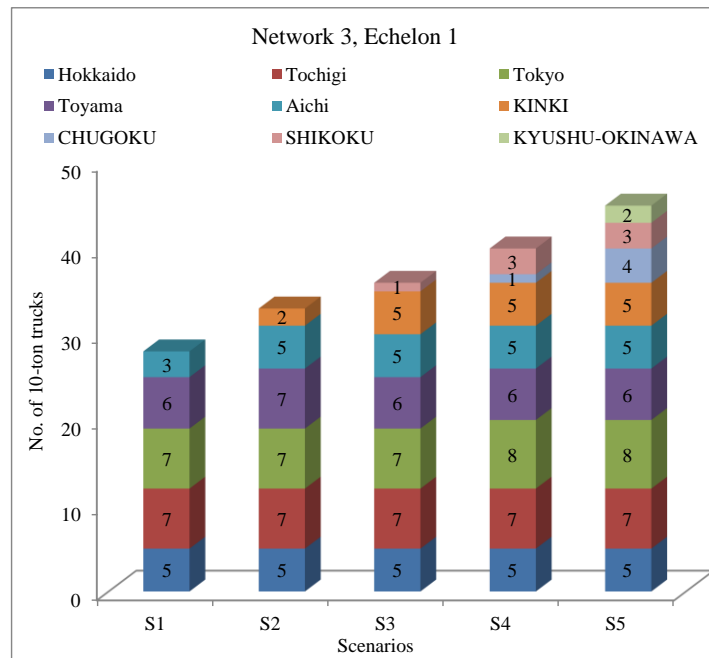


Figure 6-10 Number of truck requirement of deterministic demand, Network 3

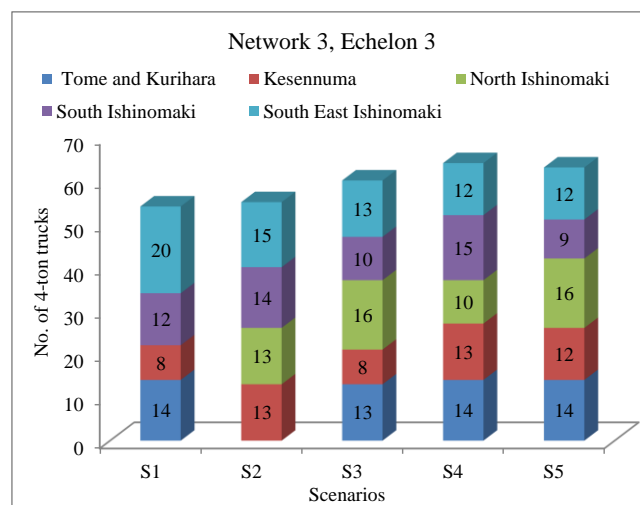
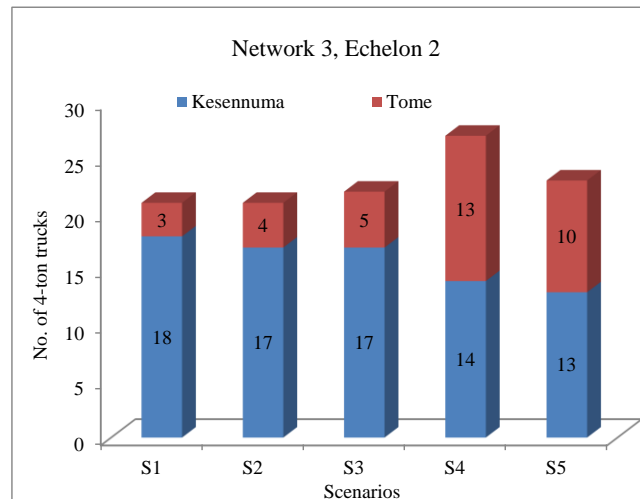
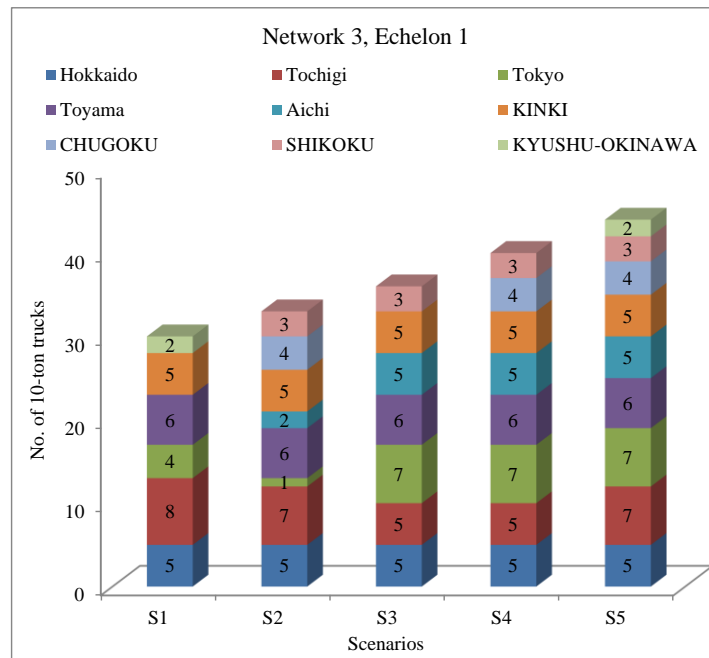


Figure 6-11 Number of truck requirement of uncertainty demand, Network 3

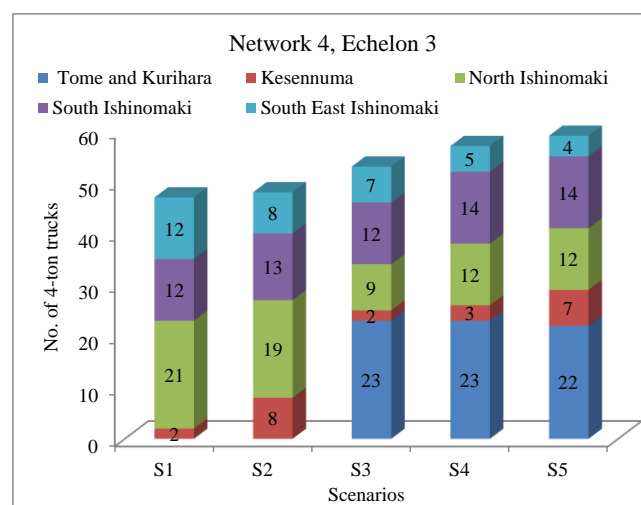
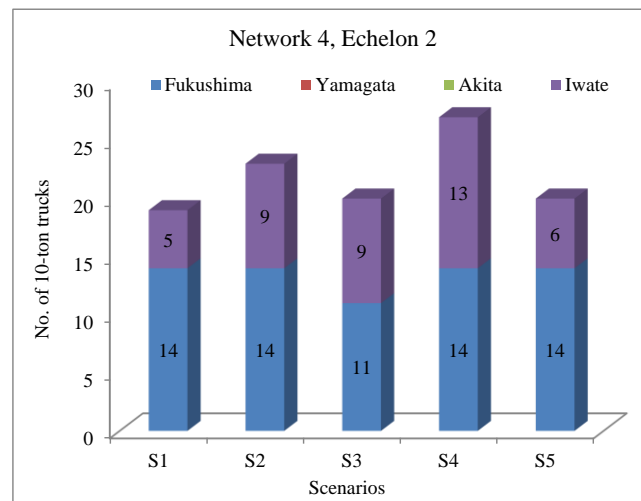
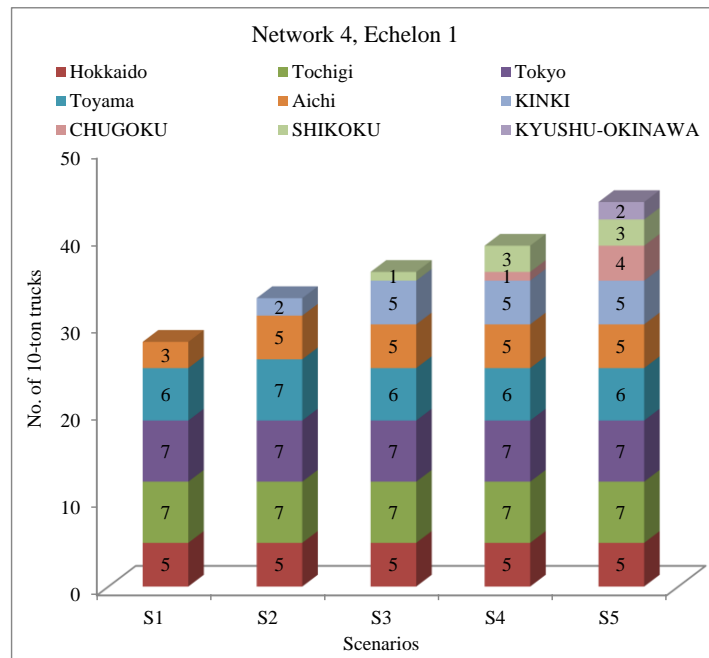


Figure 6-12 Number of truck requirement of deterministic demand, Network 4

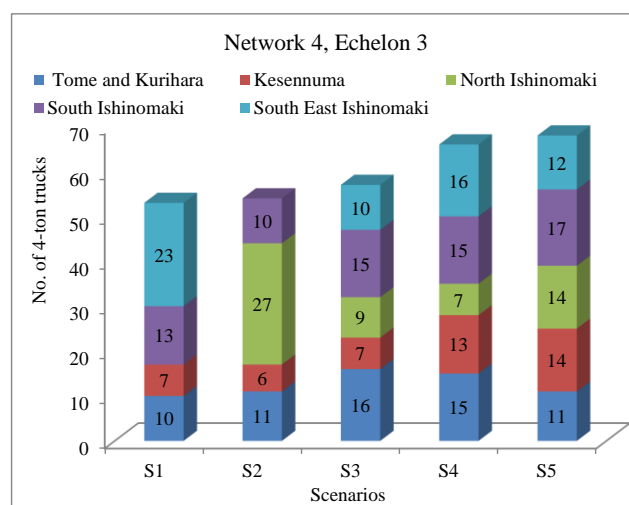
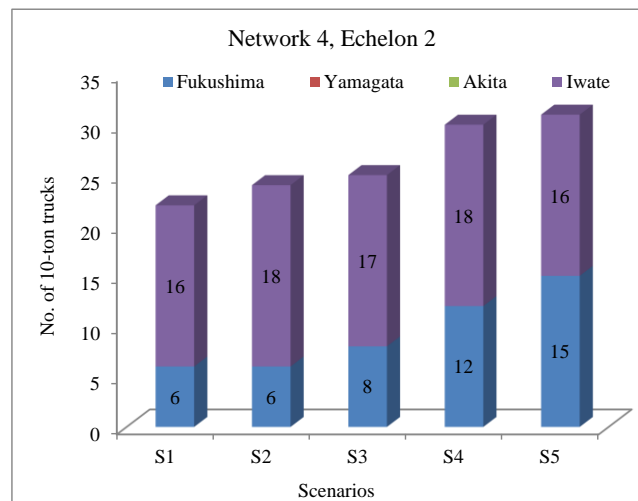
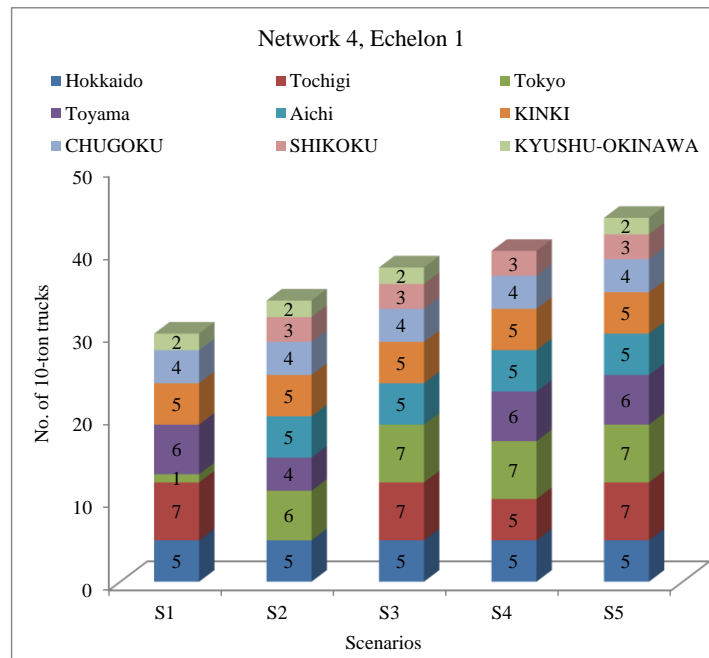


Figure 6-13 Number of truck requirement of uncertainty demand, Network 4

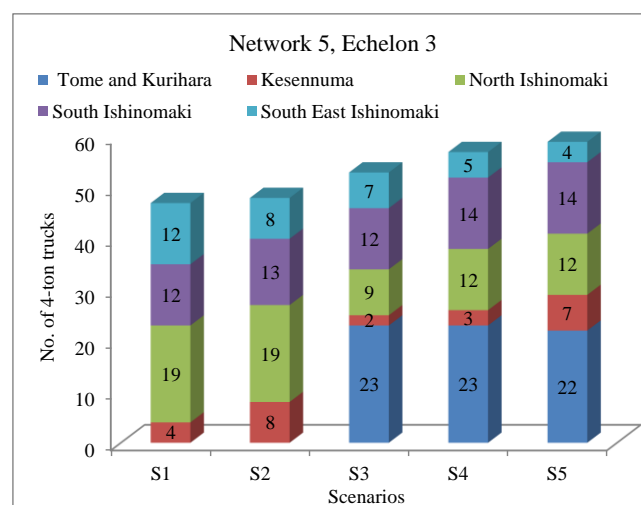
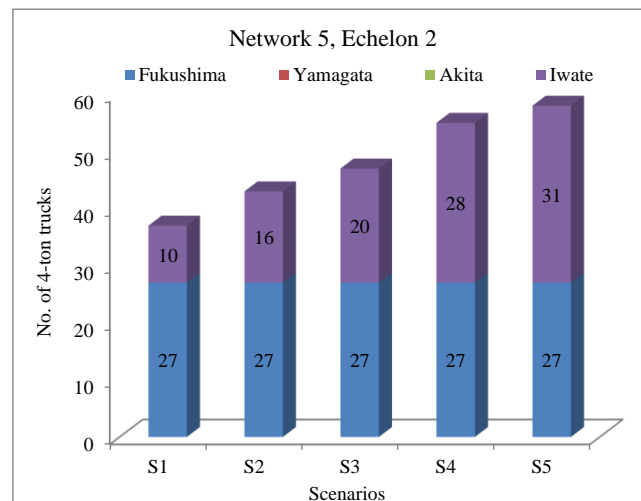
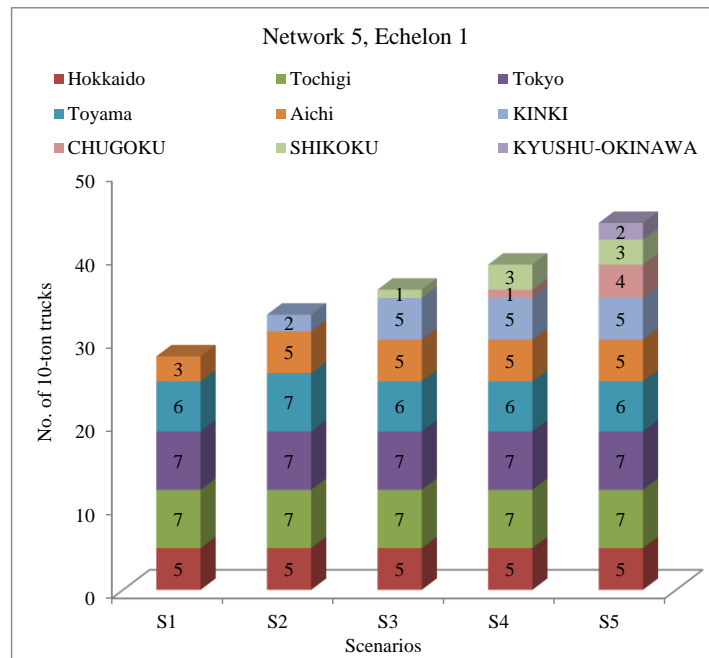


Figure 6-14 Number of truck requirement of deterministic demand, Network 5

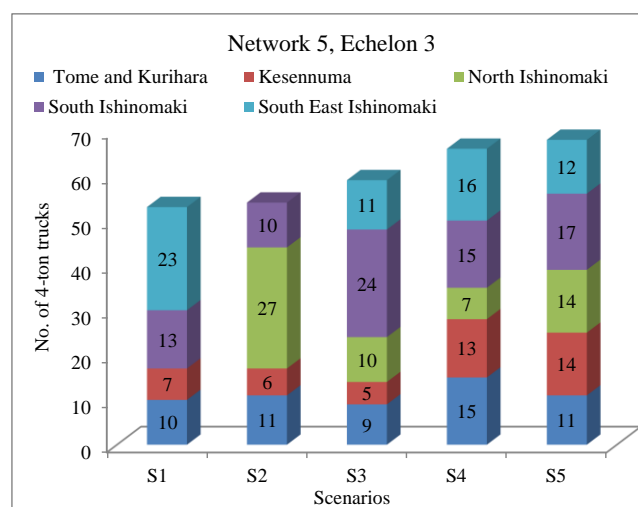
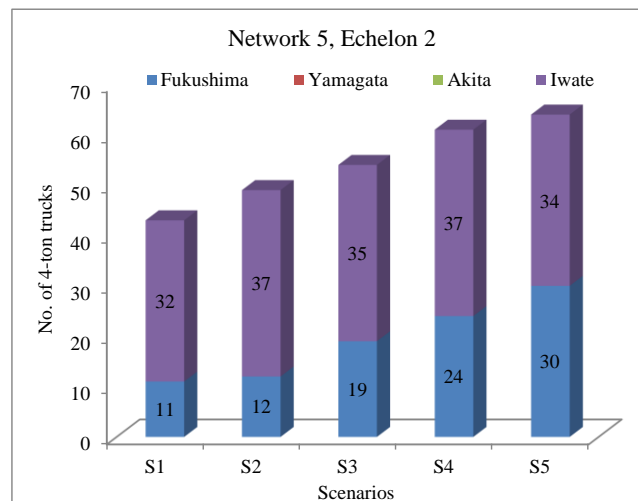
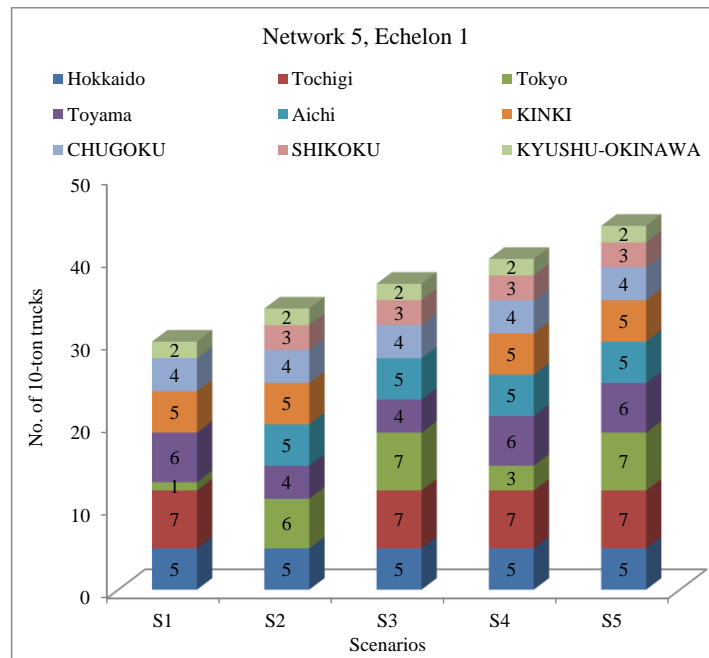


Figure 6-15 Number of truck requirement of uncertainty demand, Network 5

6.6 Working time estimation

This section presents the estimation of total working hours for all networks and scenarios. Each column bar chart is the total working time clarifies by each facility. Obviously, the total working time varies by number of truck and those trucks relate to the travelling distance.

Considering the working time for all networks, a total working time of whole network tends similarly because it is varied directly from the distance. However, we focus on the layer before delivering to shelter demand. Network 2 and network 3 able to spend shorter delivery time in the last two hierarchies. Moreover, network 2 has benefits by using large truck size to deliver a big lot size as a result to save time.

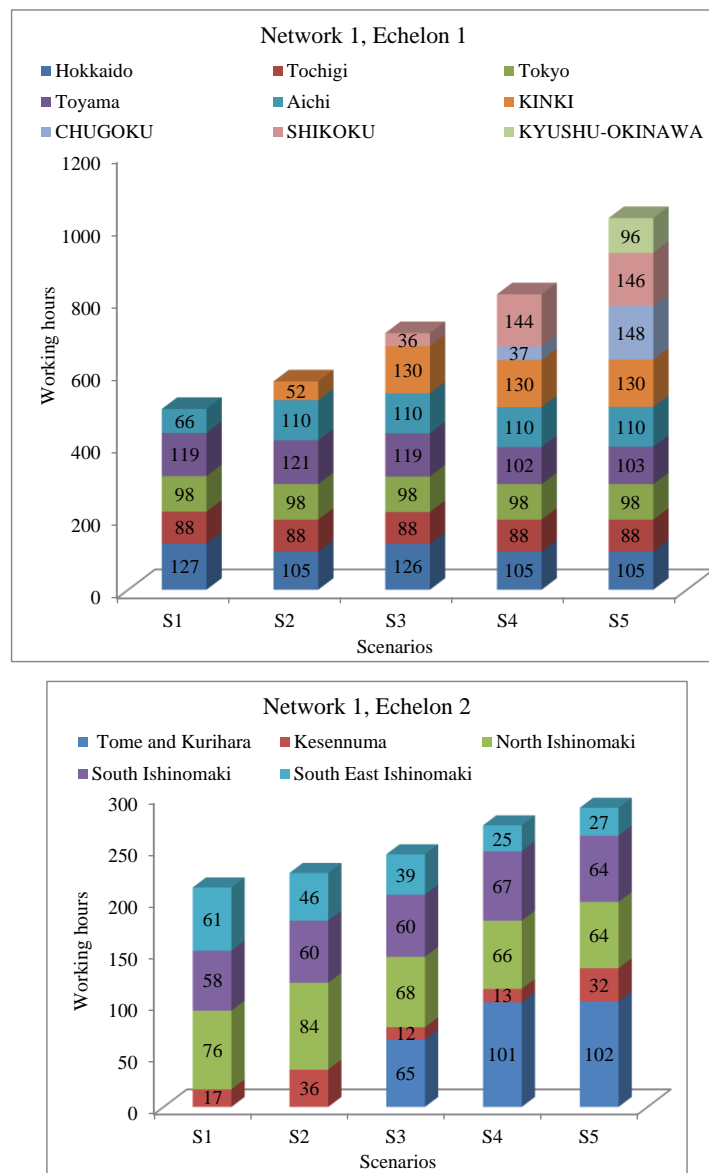


Figure 6-16 Working time of deterministic demand, Network 1

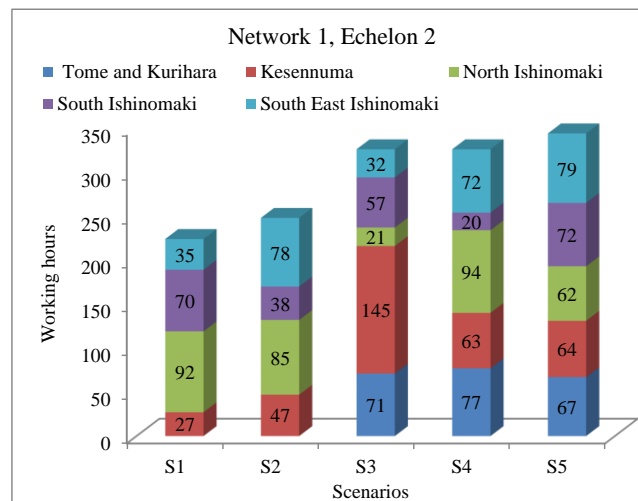
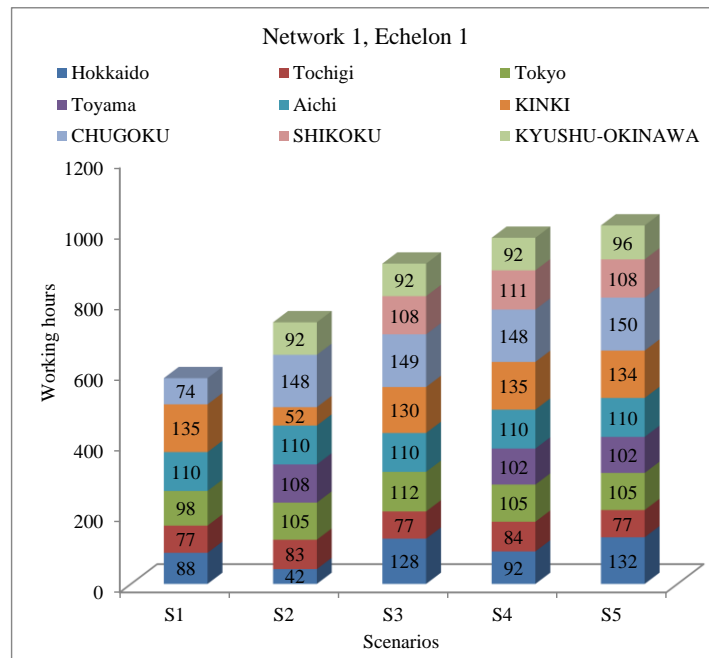


Figure 6-17 Working time of uncertainty demand, Network 1

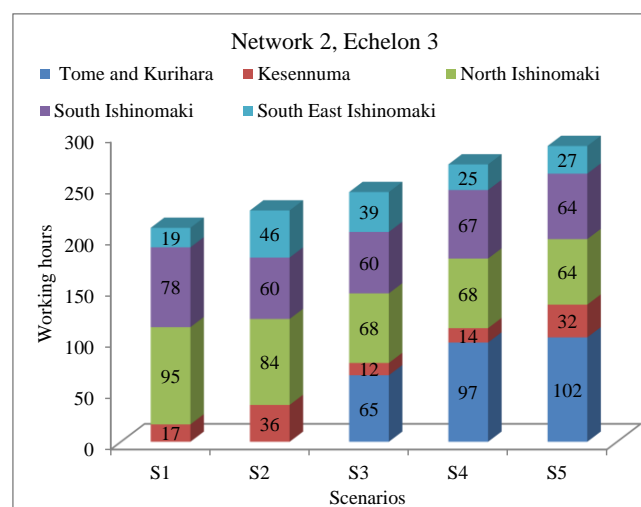
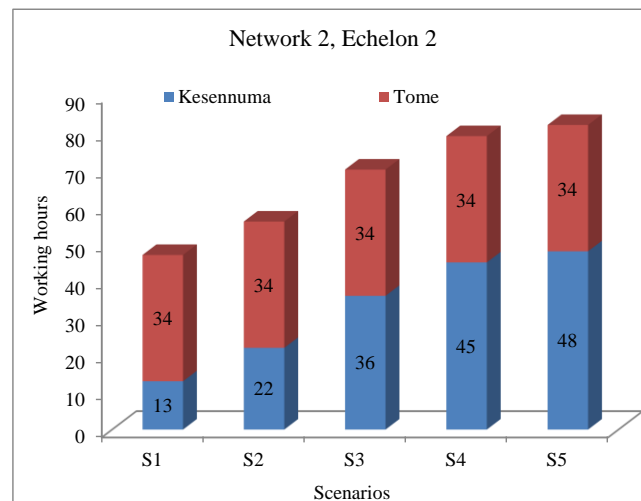
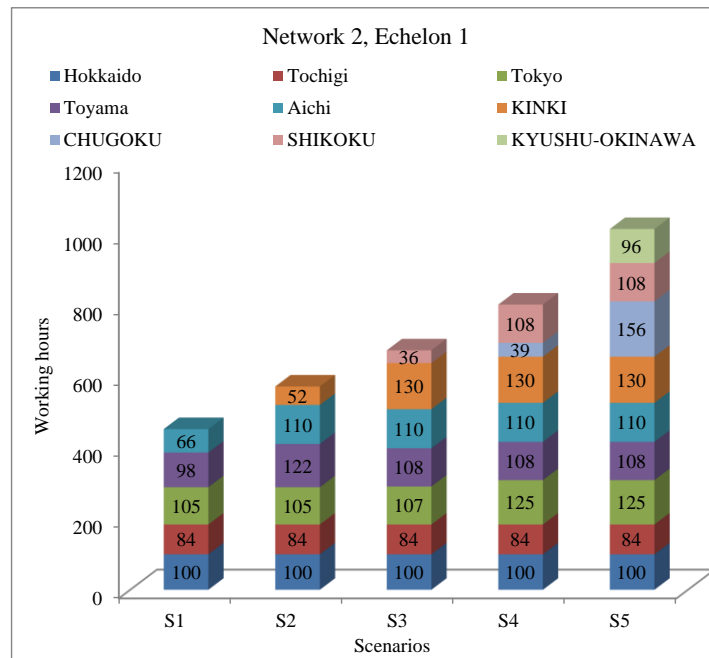


Figure 6-18 Working time of deterministic demand, Network 2

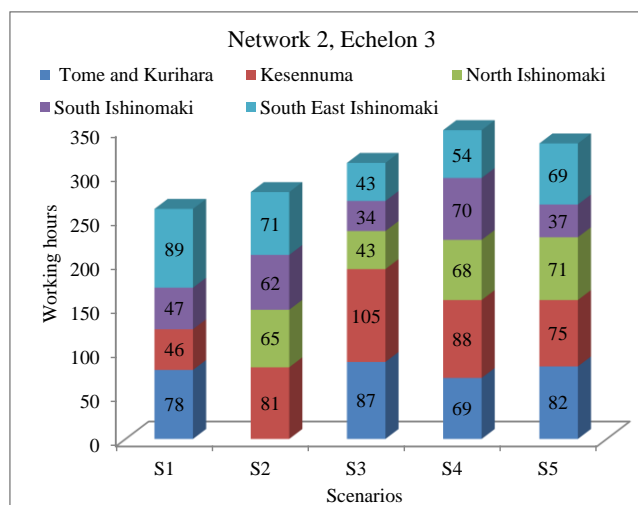
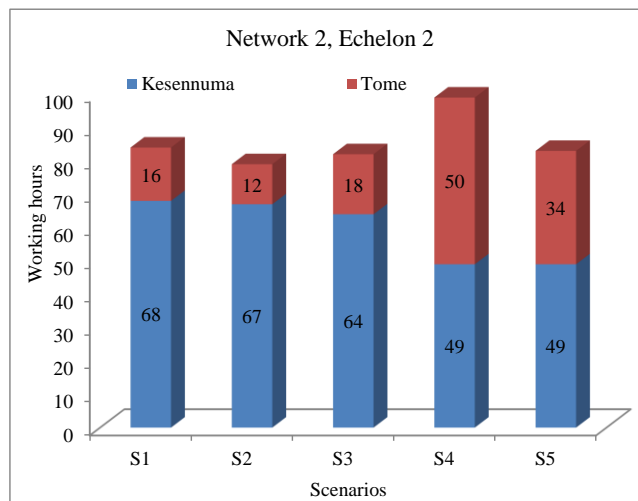
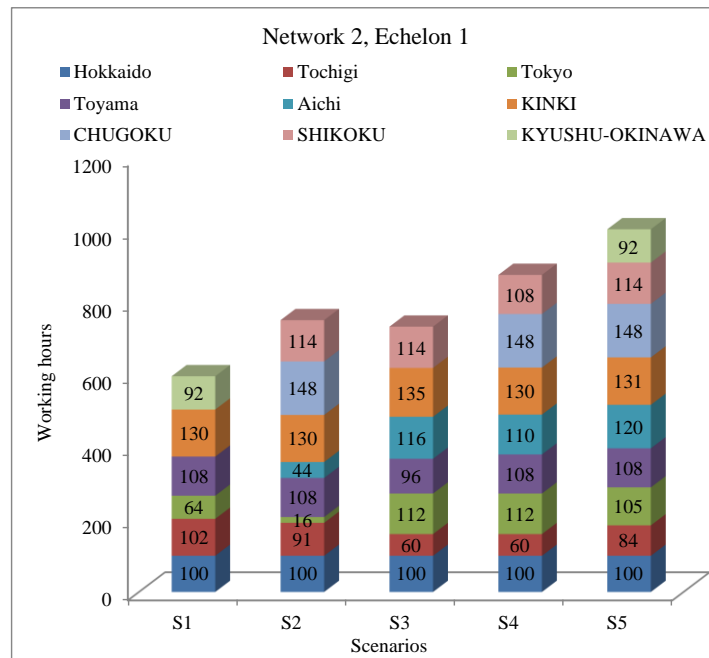


Figure 6-19 Working time of uncertainty demand, Network 2

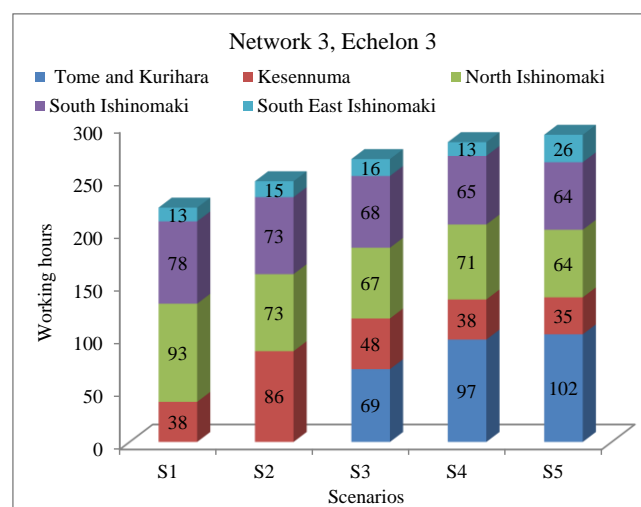
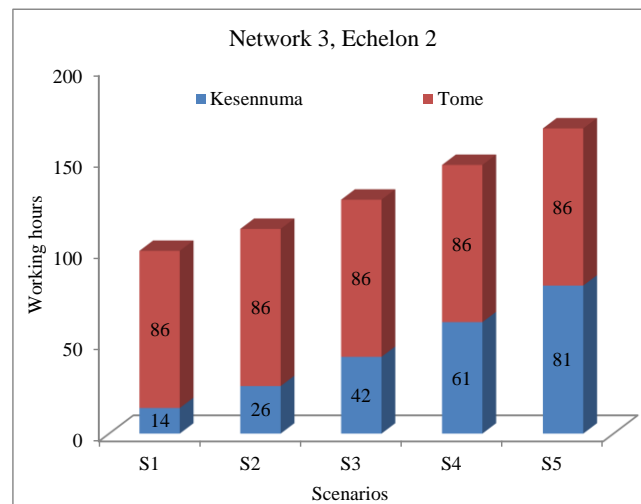
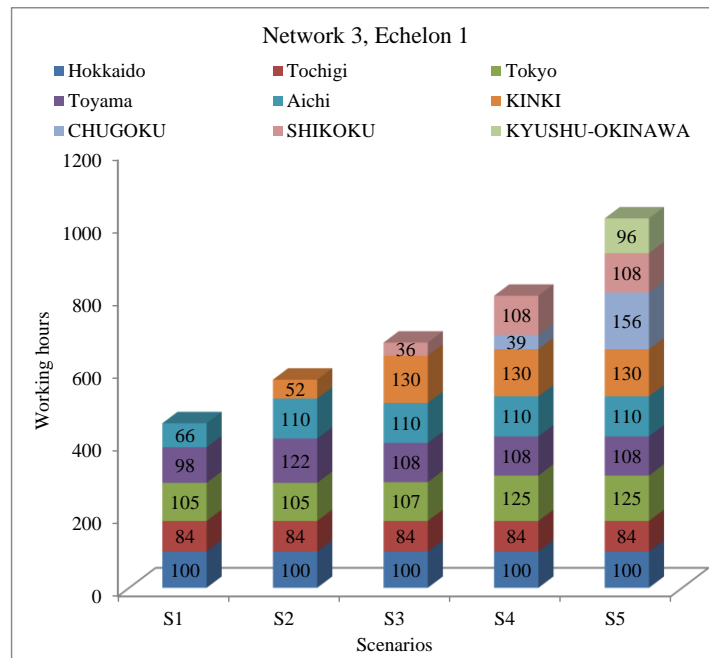


Figure 6-20 Working time of deterministic demand, Network 3

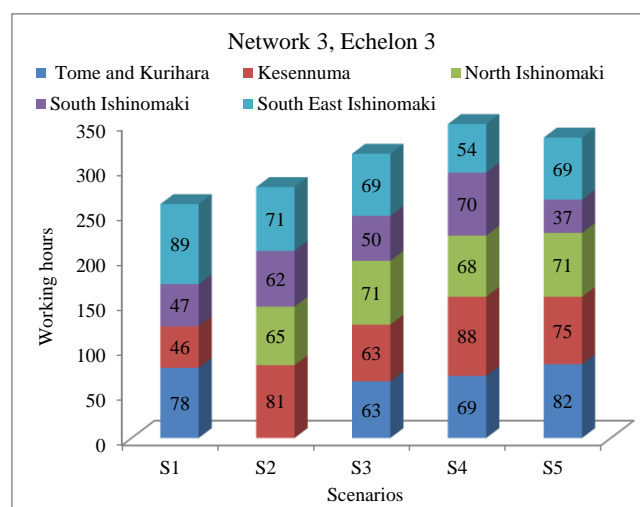
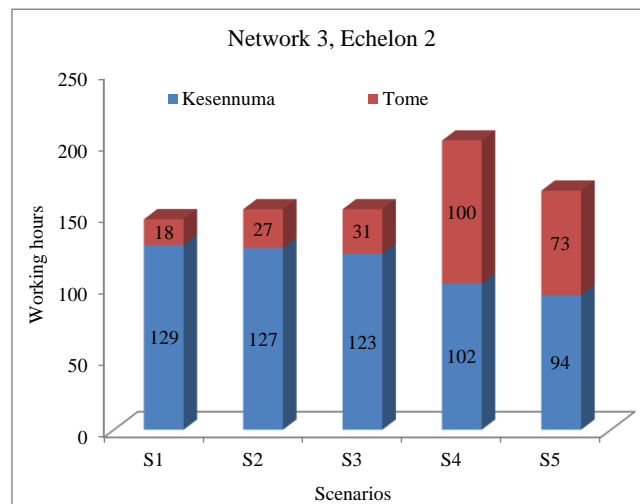
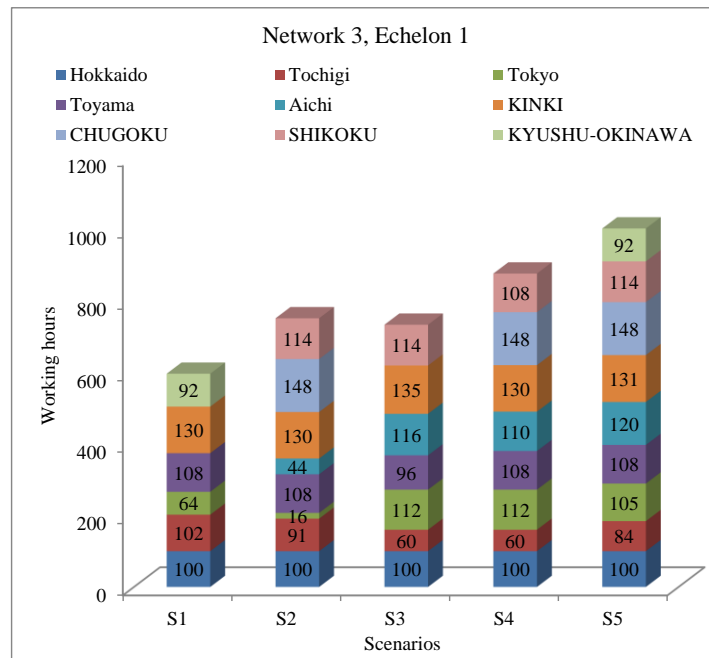


Figure 6-21 Working time of uncertainty demand, Network 3

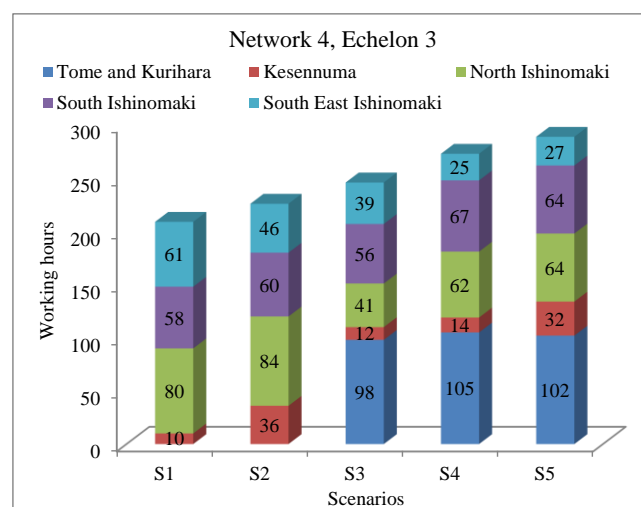
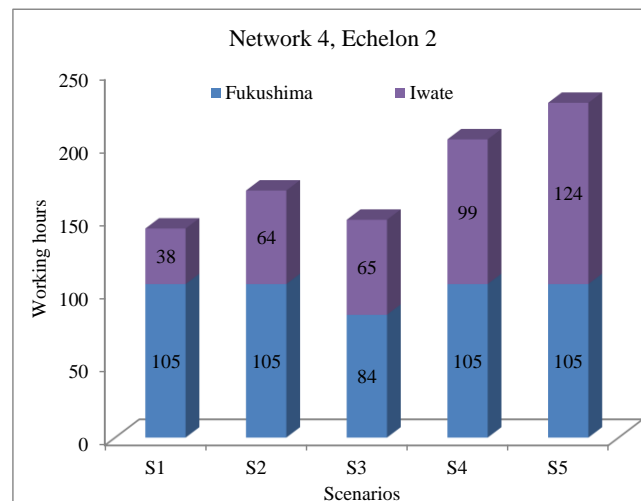
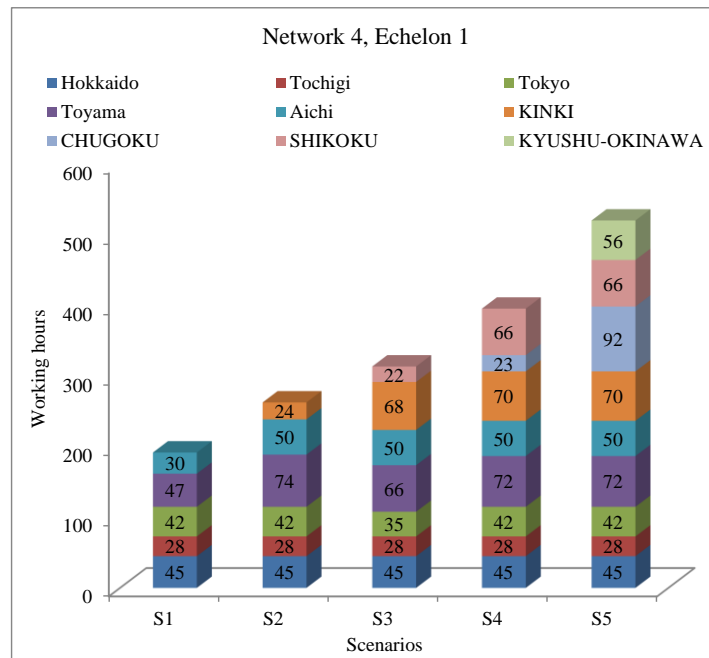


Figure 6-22 Working time of deterministic demand, Network 4

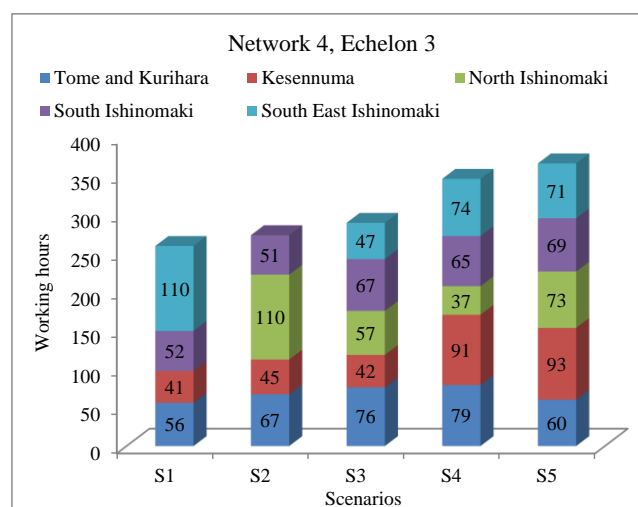
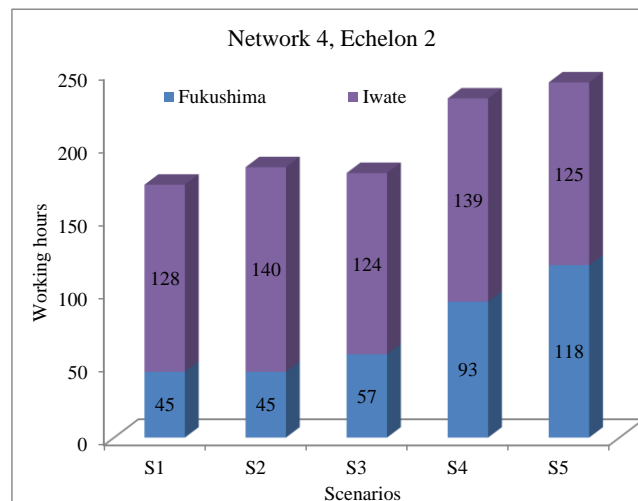
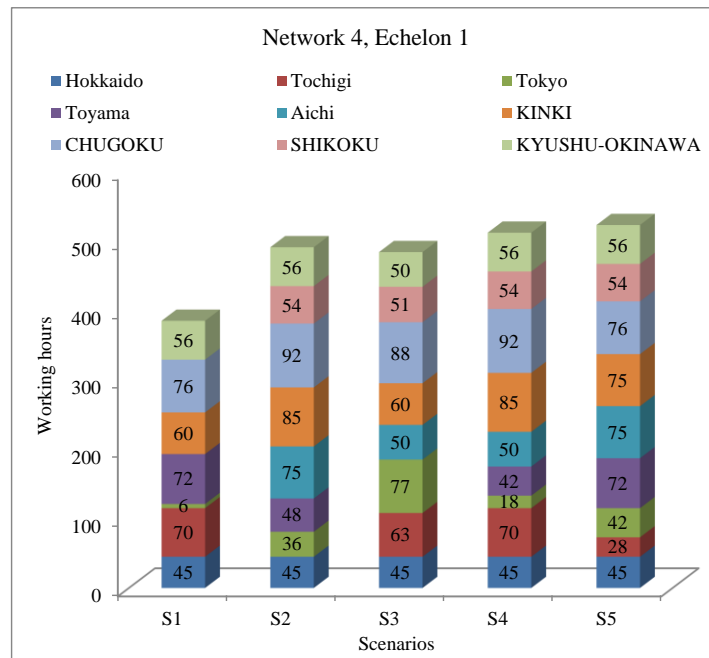


Figure 6-23 Working time of uncertainty demand, Network 4

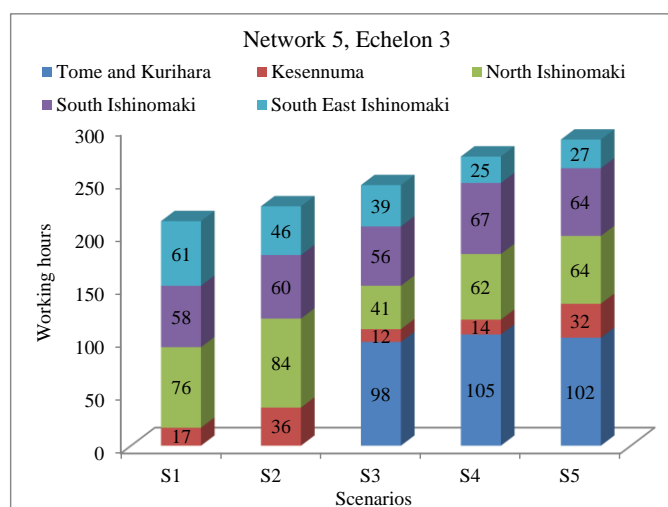
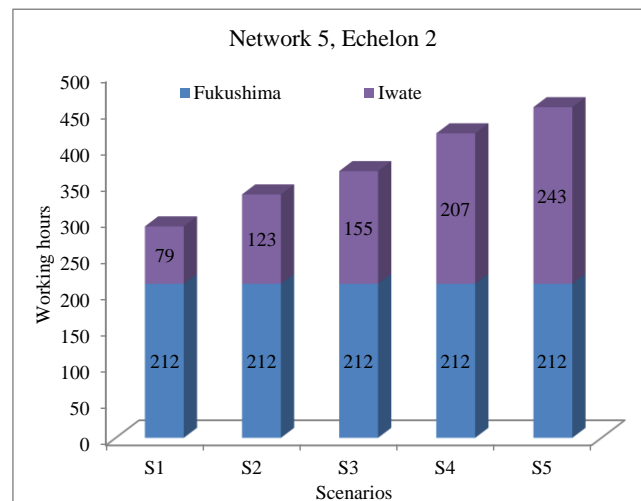
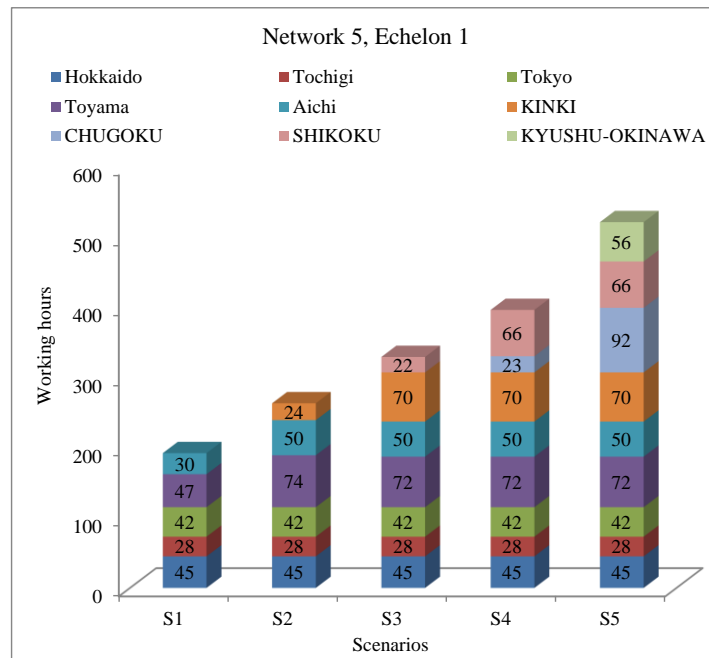


Figure 6-24 Working time of deterministic demand, Network 5

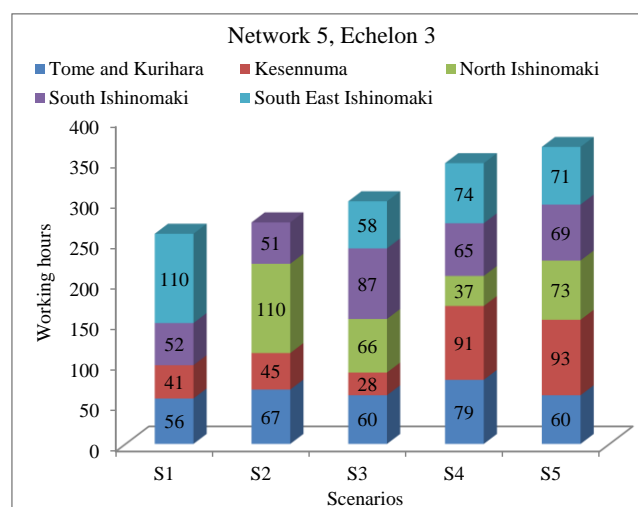
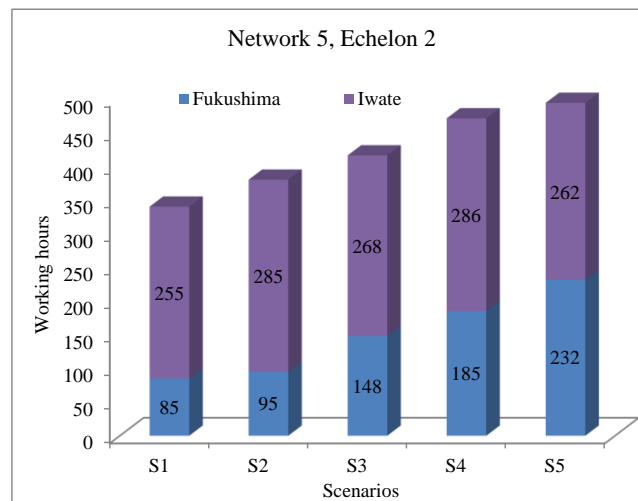
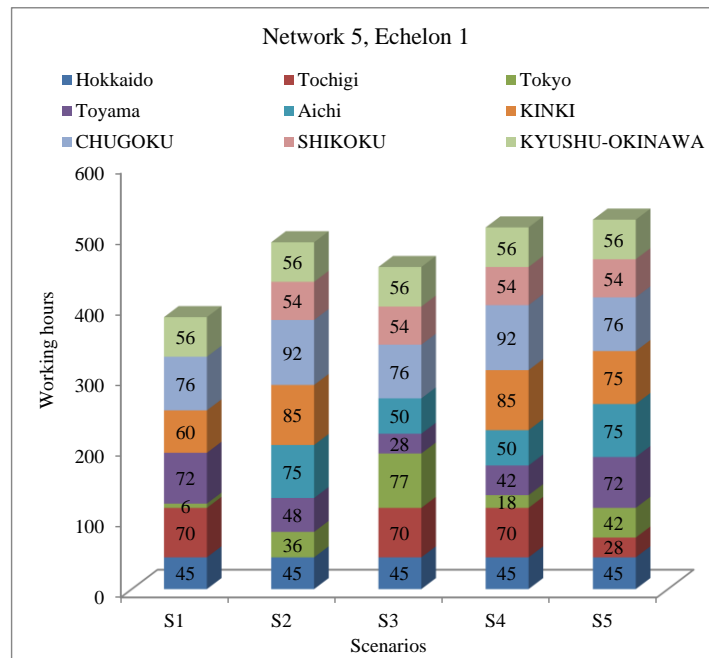


Figure 6-25 Working time of uncertainty demand, Network 5

6.7 Routing implementation

The previous location problem not only located the optimal facility sites but also allocated the optimal link flows. Results indicated that, we can improve the selected networks among five differences by making practical uses of routing. The generic name is Vehicle Routing Problem (VRP) which is a set of routes for a fleet of vehicles based at one or several depots can be resolved for a number of geographically dispersed cities or customers which will be usefulness after located the facility sites by location problem (see figure 6-25). The main purpose of VRP is to deliver known demands of customers on minimum-cost vehicle routes from origin and termination at a depot. Near all of the most commonly used techniques for solving Vehicle Routing Problems are heuristics and metaheuristics because no exact algorithm can be guaranteed to find optimal tours within reasonable computing time when the number of cities is large. This is due to the NP-Hardness of the problem.

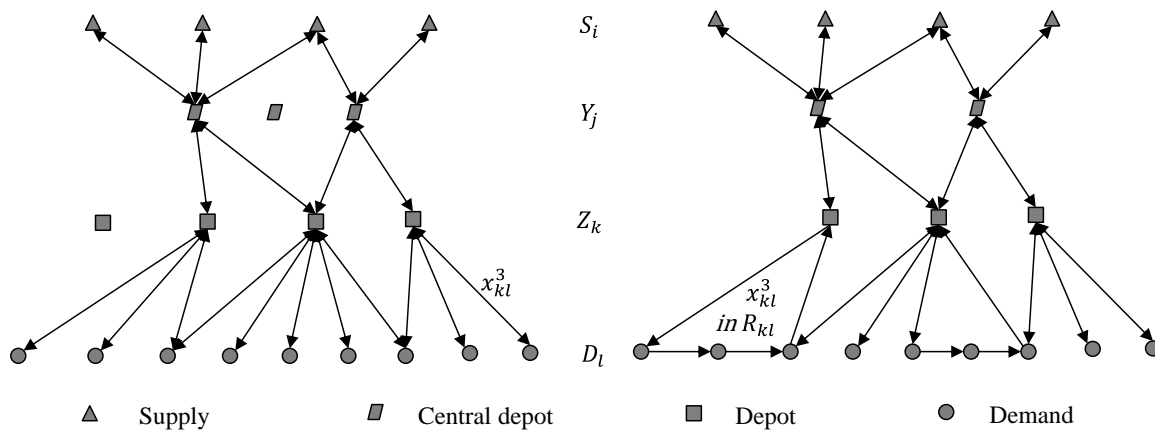


Figure 6-26 Ordinary location problem (left) and implemented routing (right)

The routing infers to the second stage of this study, it is in the part of improving by routing (formulation in section 5.4). The variables in location problem which are the locations and allocation were determined in the primary stage. According to the previous comparisons in section 6.3 and 6.4, by considering their cost efficiency and robustness of the model, network 2 offers the best cost efficiency and highest robustness when the demand becomes uncertainty. Consequently, we choose scenario 3 of this network to be a representative to improve by practical uses of vehicle routing problem. We focus on the last hierarchy of the network elements, from depots to shelters, to apply with routing problems. The optimized routing network of each opened facilities are illustrated in figure

6-26. There are five depots which are selected at the optimal solutions and each depot responds to their link flow allocation. The routing, which visits more than one shelter at one trip, is conducted instead of a single visited trip when those link flows are less than truck capacity. We found that the total delivery cost is reduced for every opened facility sites, the total delivery cost is approximately 30 percent reducing as shown in table 2.

Table 6-5 The total delivery cost reduction by using routing

Selected opening depots	Location problem of echelon 3	Improved by routing	Percentage of cost reduction
Tome and Kurihara	7,027,454	4,163,944	40.75
Kesennuma	6,640,056	3,704,803	44.21
North Ishinomaki	3,903,580	1,766,211	54.75
South Ishinomaki	2,731,894	1,739,353	36.33
South East Ishinomaki	3,124,383	2,587,476	17.18
Sum of echelon 3	23,427,368	13,961,787	
Travel cost of echelon 1 and 2	6,662,229	6,662,229	
Opening cost	677,732	677,732	
Transshipment cost	1,263,564	1,263,564	
Total delivery cost	32,030,892	22,565,312	29.55

Depot location and serving amount: Tome and Kurihara

Depot	Depot	Demand
	Tome and Kurihara	
Responsibility node	Miyagino-ku Sendai	42283
	Taihaku-ku Sendai	42283
	Kurihara	508
	Higashimatsushima	42331
	Zao-machi	127
	Murata town	556
	Shibata town	127
	Matsushima-machi	5701
	Shichigahama town	11614
	Taiwa-cho	40
	Tomiya	1957
	Ohira village	106
	Wakuya town	1264

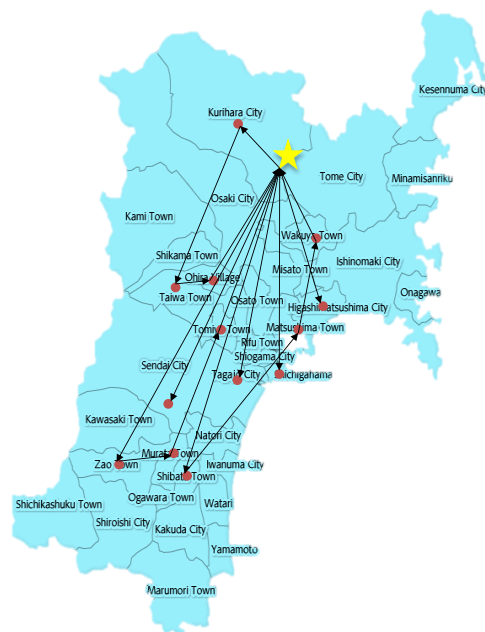


Figure 6-27 Implemented routing construction

Depot location and serving amount: Kesennuma

Depot	Depot	Demand
	Kesennuma	
Responsibility node	Izumi-ku Sendai	42283
	Wakabayashi-ku Sendai	42283
	Natori	11089
	Osaki	9910
	Shichikashuku town	76
	Ogawara-machi	226
	Watari-cho	13687
	Rifu town	313
	Onagawa-cho	4632
	Minamisanriku-cho	29101



Depot location and serving amount: North Ishinomaki

Depot	Depot	Demand
	North Ishinomaki	
Responsibility node	Aoba-ku Sendai	42283
	Ishinomaki	13148
	Kakuda	676
	Tome	14401
	Marumori town	16
	Yamamoto-cho	11794
	Shikama town	55
	Misato	3229



Figure 6-26 (con't) Implemented routing construction

Depot location and serving amount: South Ishinomaki

Depot	Depot	Demand
	South Ishinomaki	
Responsibility node	Ishinomaki	108656
	Shiogama	15238
	Shiroishi	1936
	Iwanuma	15901
	Onagawa-cho	11869



Depot location and serving amount: South East Ishinomaki

Depot	Depot	Demand
	South East Ishinomaki	
Responsibility node	Kesennuma	57064
	Tagajo	32707
	Kawasaki	100
	Osato town	136
	Kami-machi	76

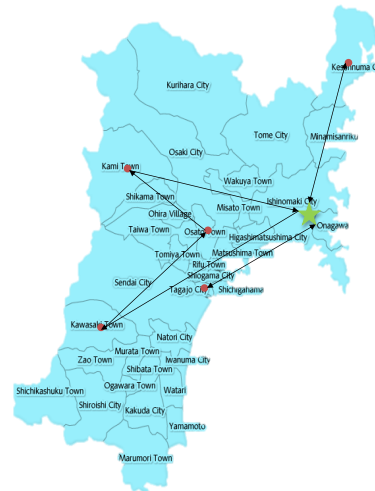


Figure 6-26 (con't) Implemented routing construction

6.8 Time series

Subsequently, the time series are conducted in the model. We expand the model by considering 10 periods of times by a week. The parameters such as demand in the case study in humanitarian logistics much higher change comparing with the ordinary situations. The demand can be rapidly increase or rapidly decrease week by week or even day by day depend on the severity of disaster and recovering systems. Therefore, we design the model to plan when the demand changes. Figure 6-27 is the number of evacuees that vary by the period of time aftermath.

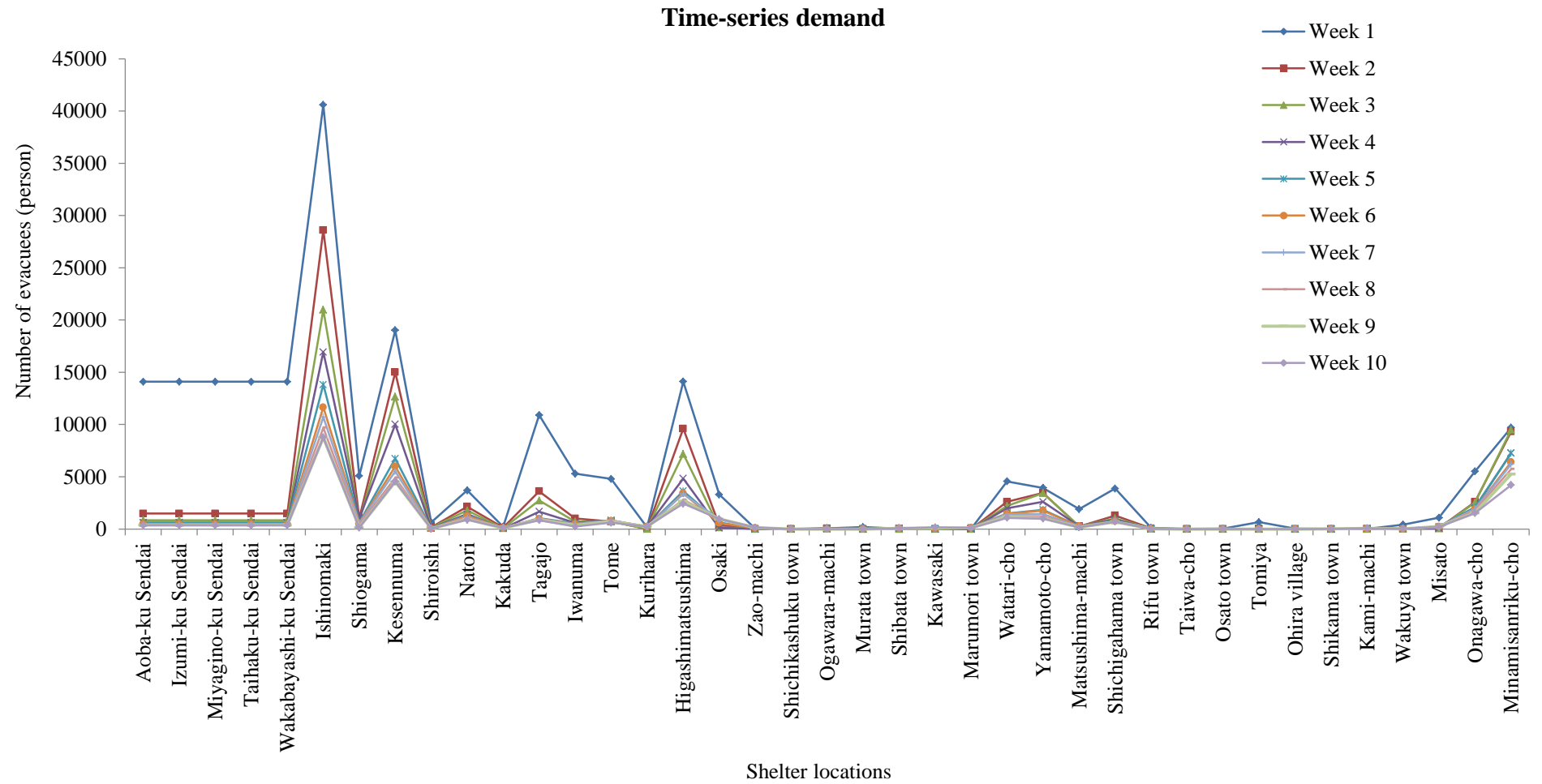


Figure 6-28 Demand for each shelter locations by 10 weeks

6.8.1 Deterministic

Table 6-6 Location facility of deterministic demand by time series

Central depots	Time series									
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Kesennuma	1	1	1	1	1	1	1	1	1	1
Tome	1									
Sendai(Kumagane)										
Yamamoto										
Depots	Time series									
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Tome and Kurihara	1									
Kesennuma	1	1	1	1	1	1	1	1	1	1
North Ishinomaki	1									
South Ishinomaki	1	1	1	1						
South East Ishinomaki	1									
Taiwa Town										
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

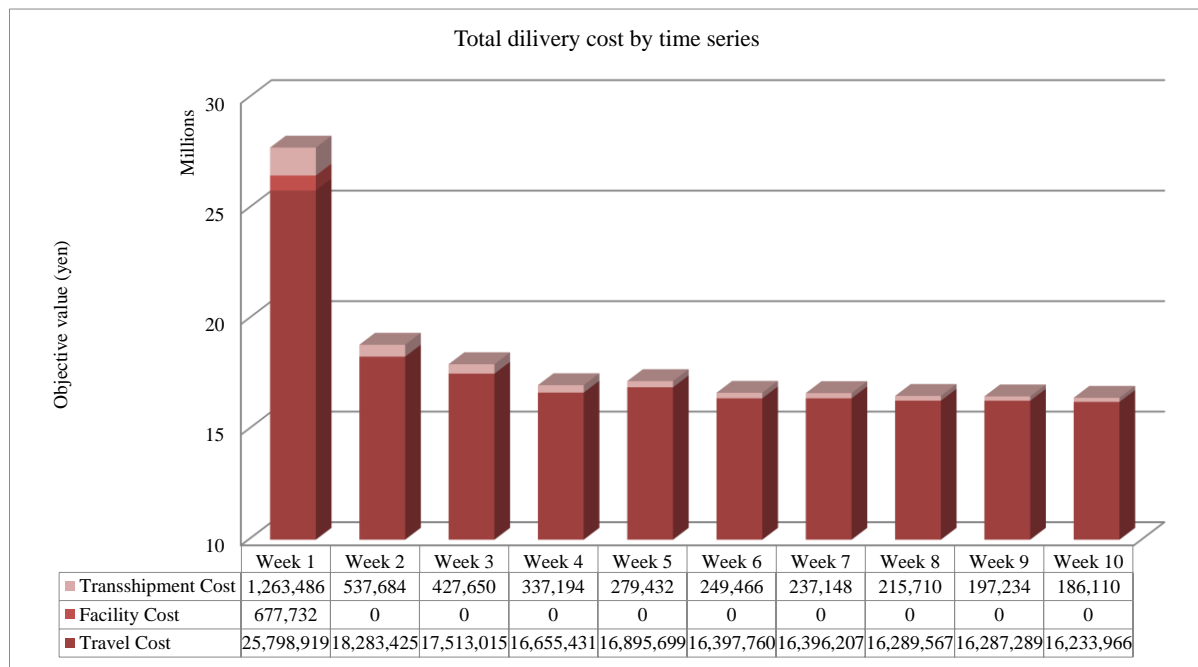


Figure 6-29 Total delivery cost of deterministic demand by time series

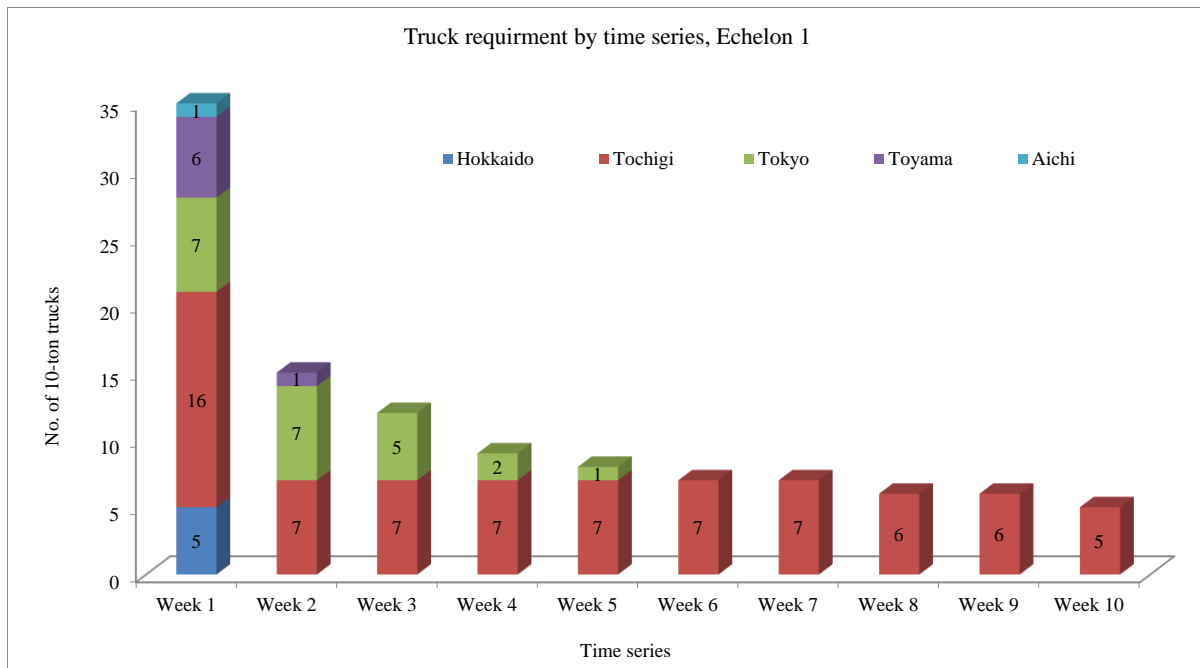


Figure 2-30 Truck requirements of deterministic demand by time series, Echelon 1

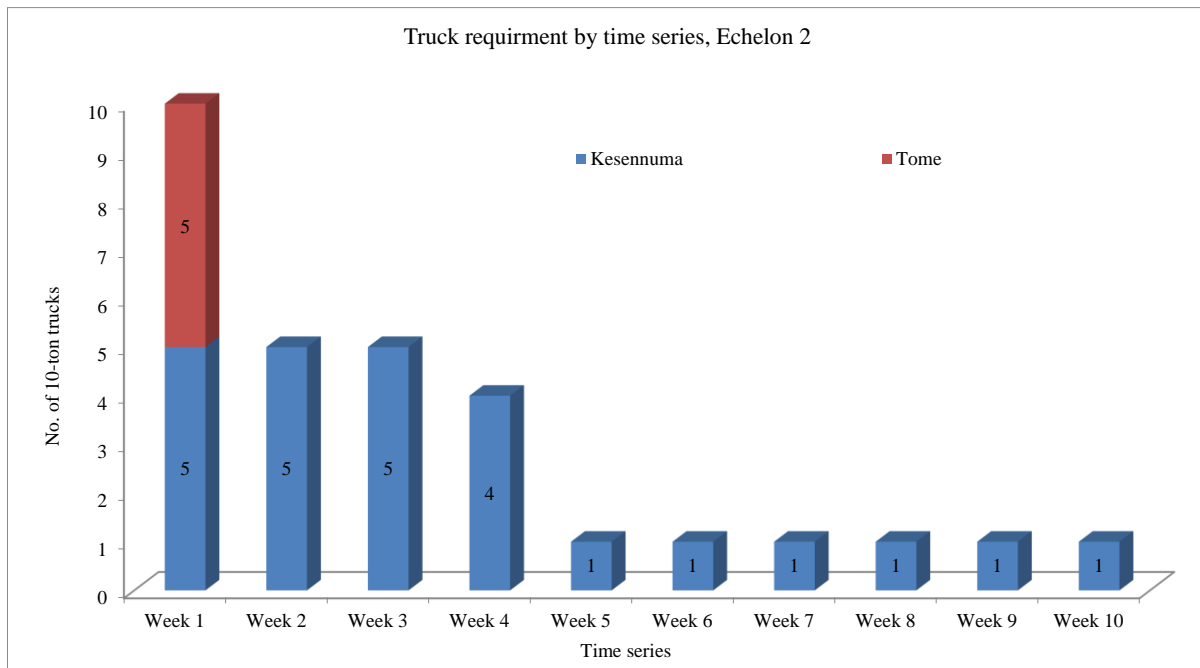


Figure 6-31 Truck requirements of deterministic demand by time series, Echelon 2

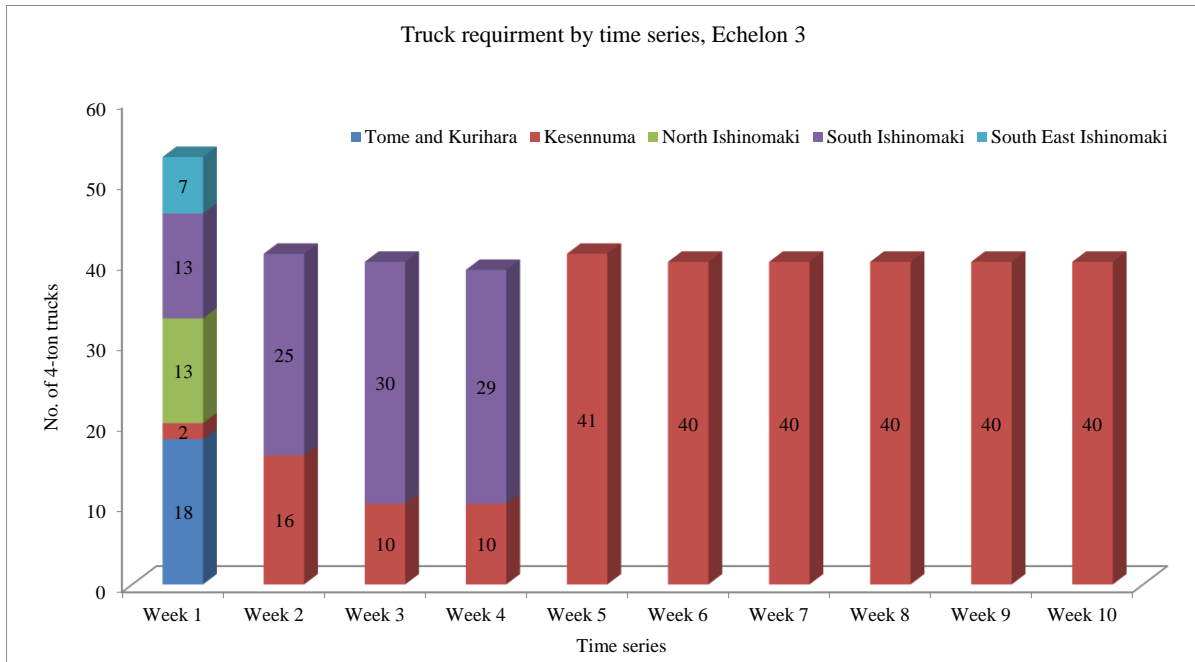


Figure 6-32 Truck requirements of deterministic demand by time series, Echelon 3

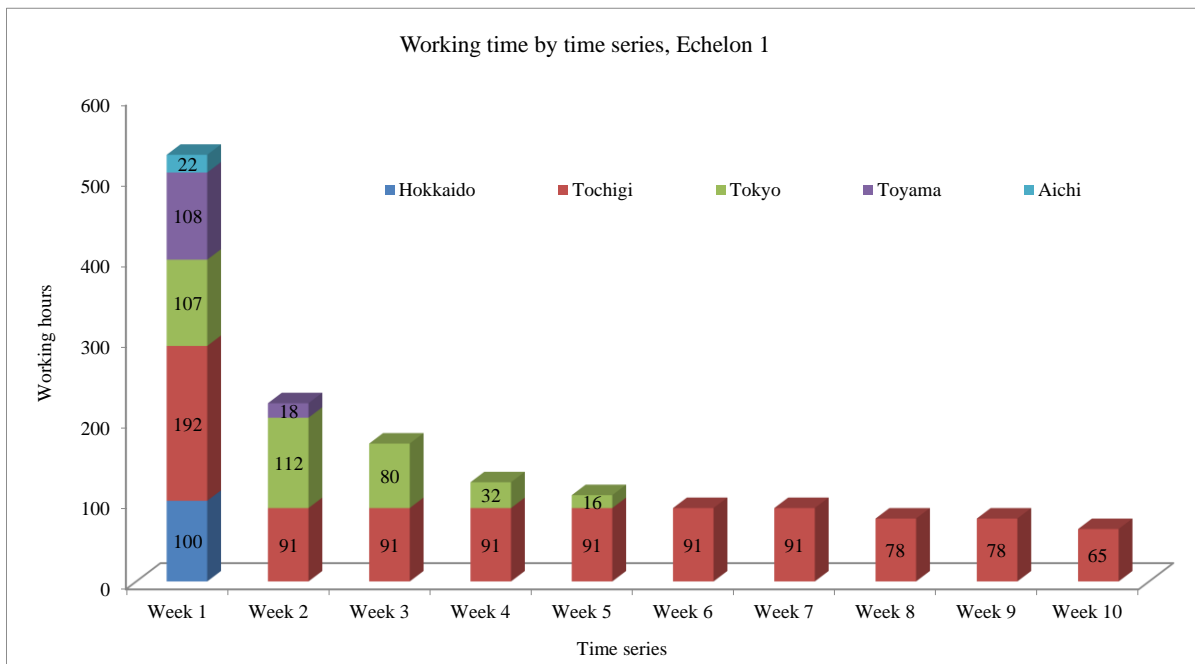


Figure 6-33 Working time of deterministic demand by time series, Echelon 1

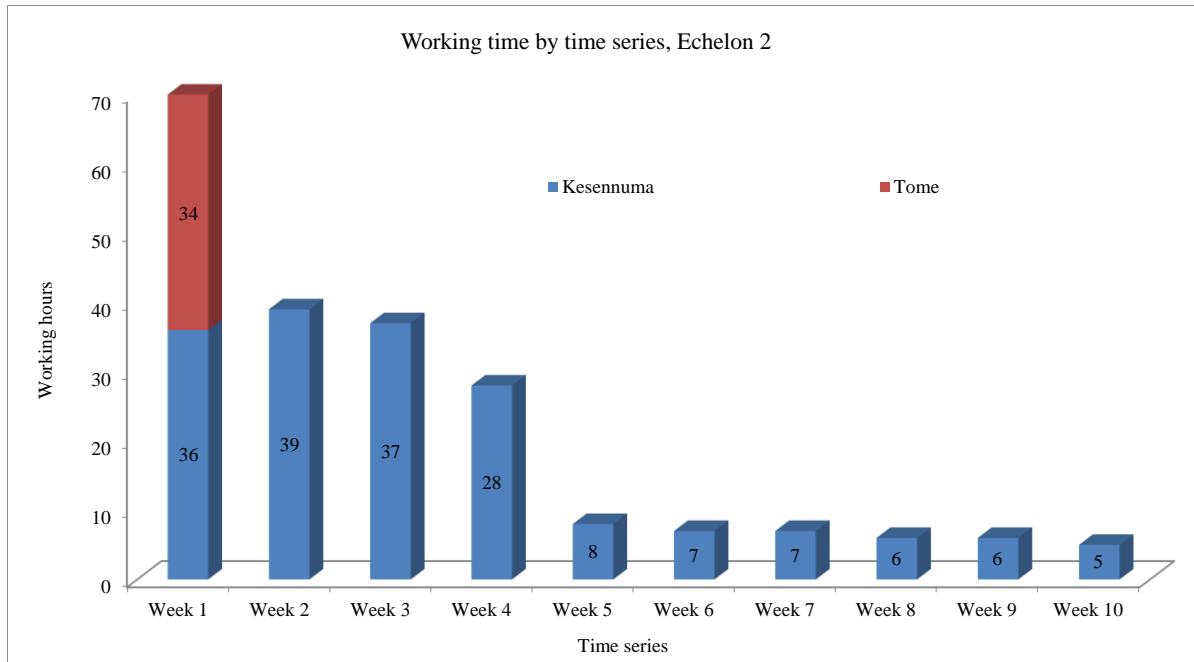


Figure 6-34 Working time of deterministic demand by time series, Echelon 2

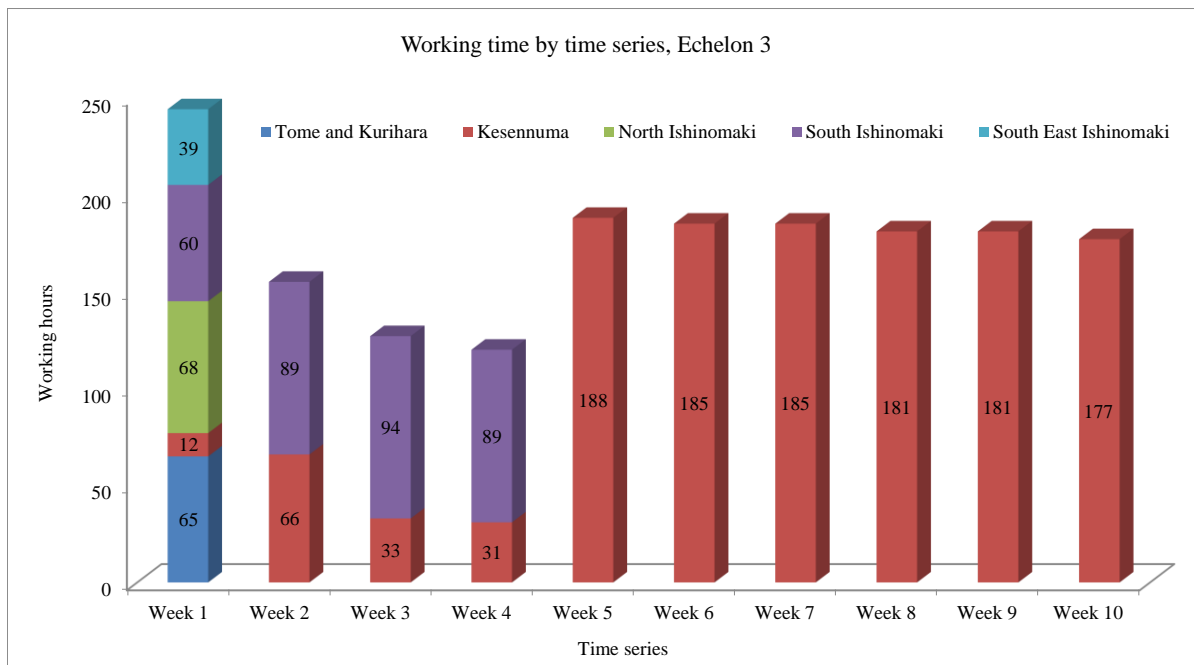


Figure 6-35 Working time of deterministic demand by time series, Echelon 3

6.8.2 Uncertainty

Table 6-7 Location facility of uncertainty demand 10 percent by time series

Central depots	Time series									
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Kesennuma	1	1	1	1	1	1	1	1	1	1
Tome	1									
Sendai(Kumagane)										
Yamamoto										
Depots	Time series									
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Tome and Kurihara	1									
Kesennuma	1	1	1	1	1	1	1	1	1	1
North Ishinomaki	1									
South Ishinomaki	1	1	1	1	1					
South East Ishinomaki	1	1								
Taiwa Town										
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

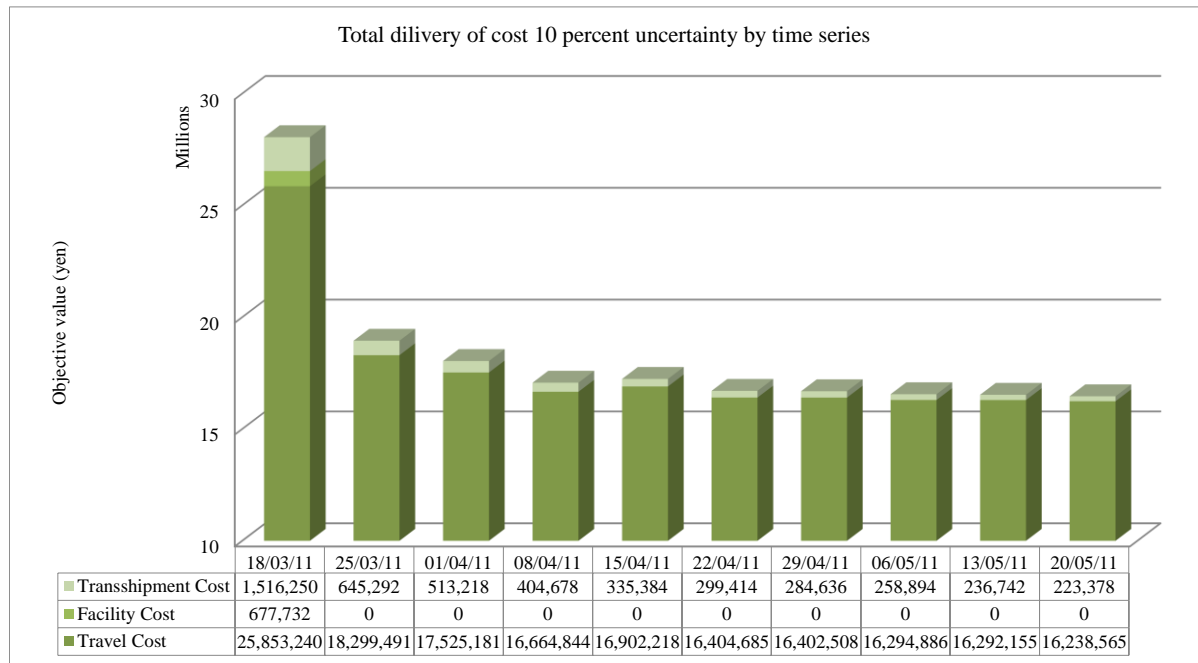


Figure 6-36 Total delivery cost of uncertainty demand 10 percent by time series

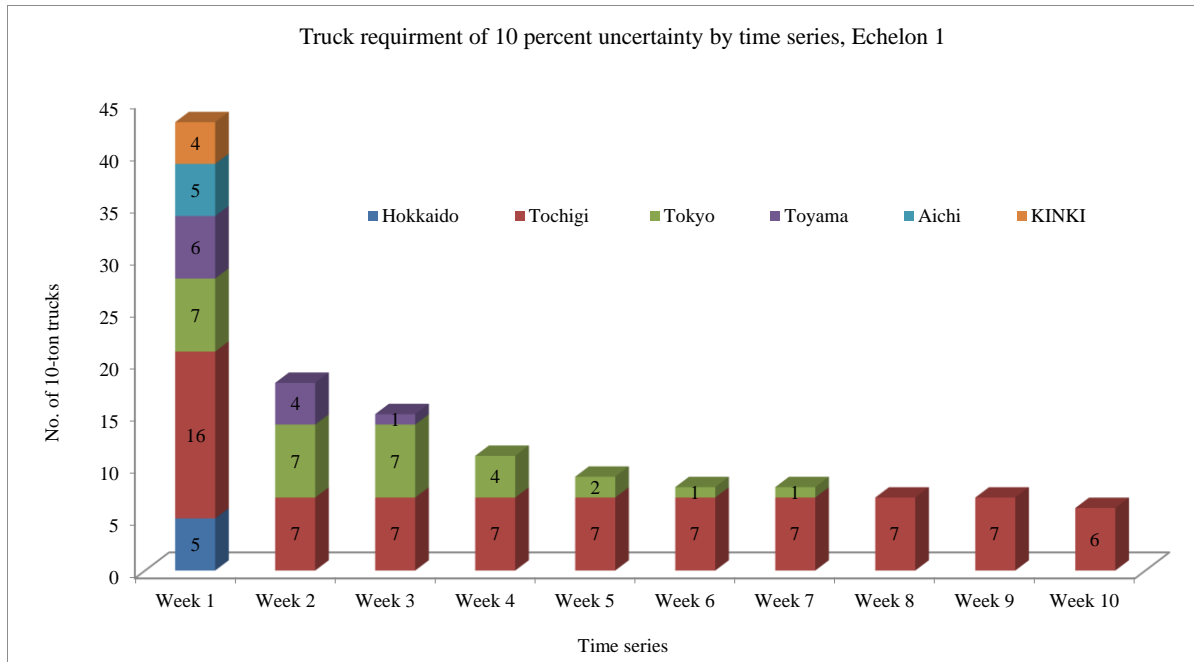


Figure 6-37 Truck requirements of uncertainty demand 10 percent by time series, Echelon 1

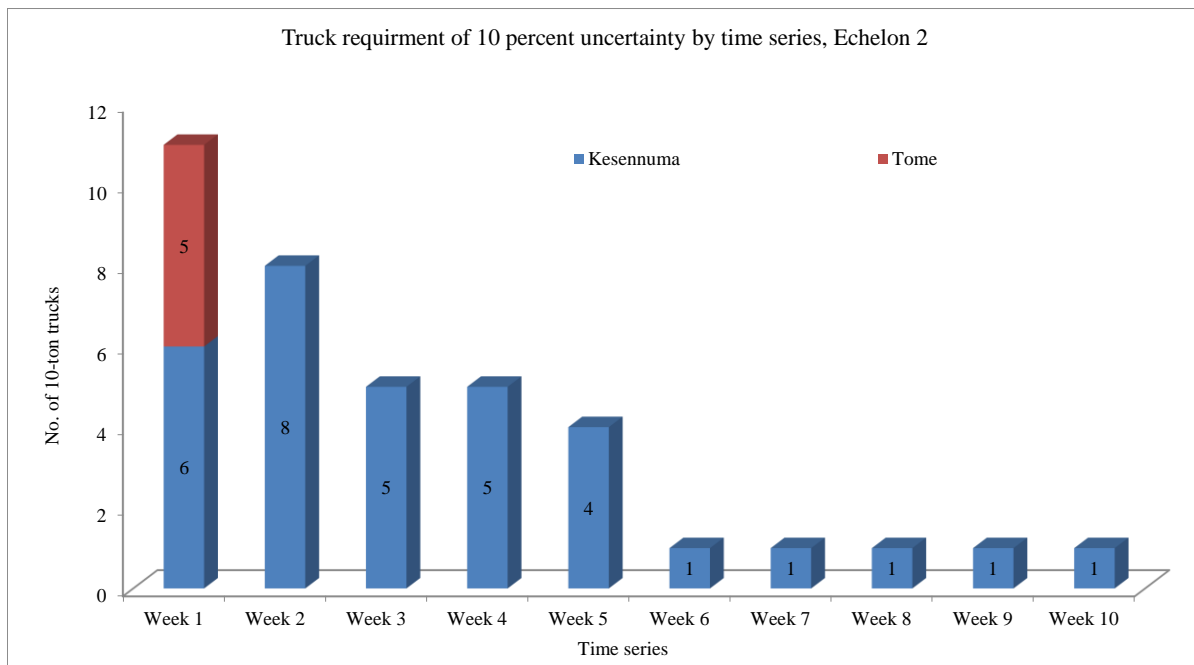


Figure 6-38 Truck requirements of uncertainty demand 10 percent by time series, Echelon 2

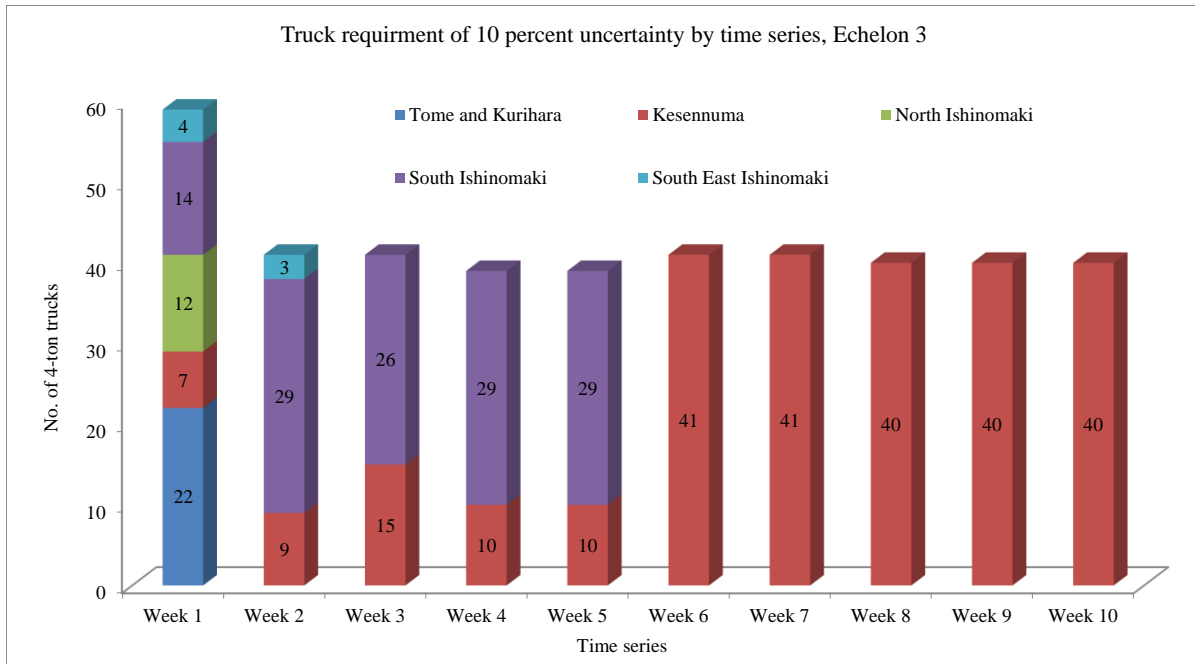


Figure 6-39 Truck requirements of uncertainty demand 10 percent by time series, Echelon 3

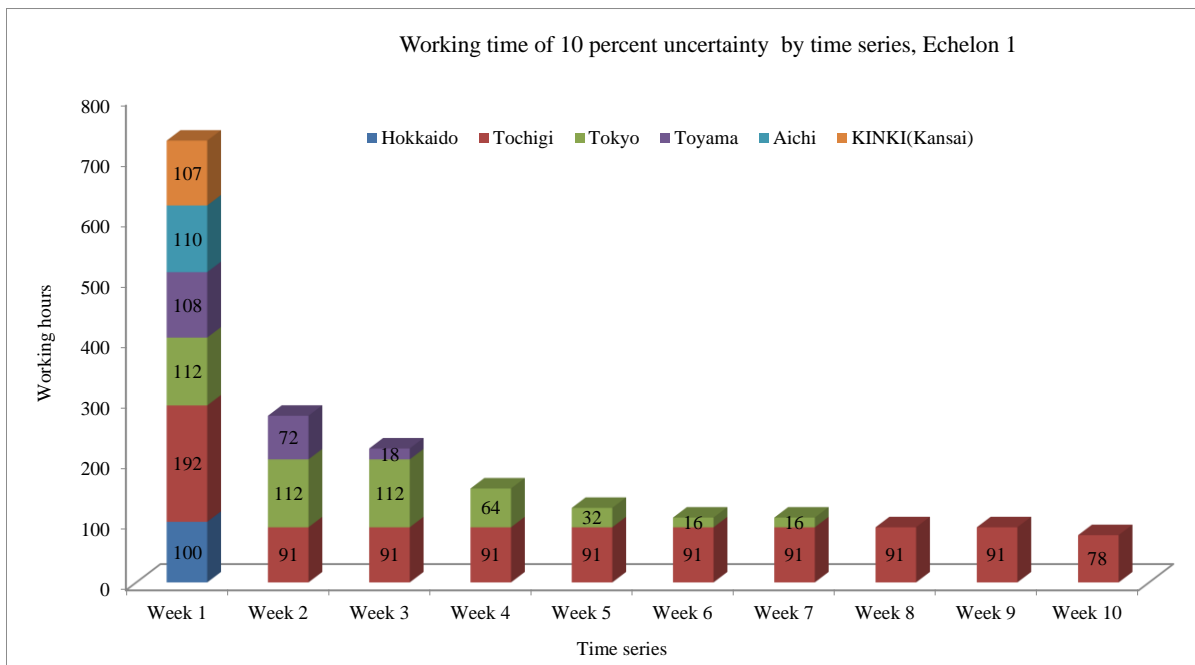


Figure 6-40 Working time of uncertainty demand 10 percent by time series, Echelon 1

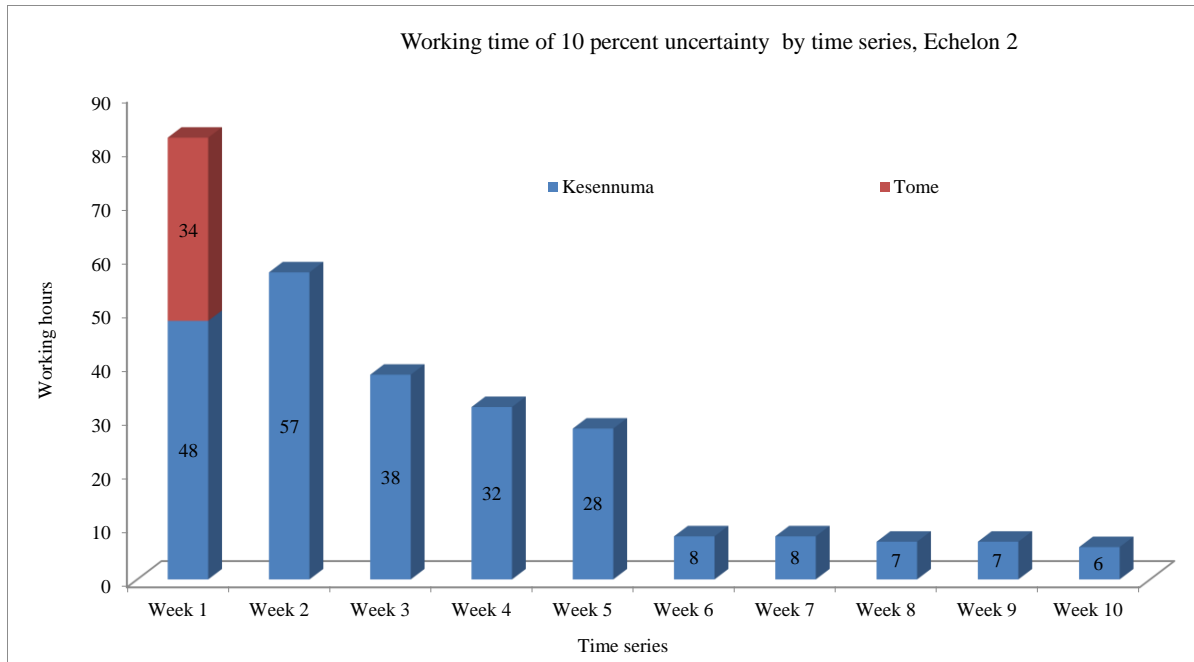


Figure 6-41 Working time of uncertainty demand 10 percent by time series, Echelon 2

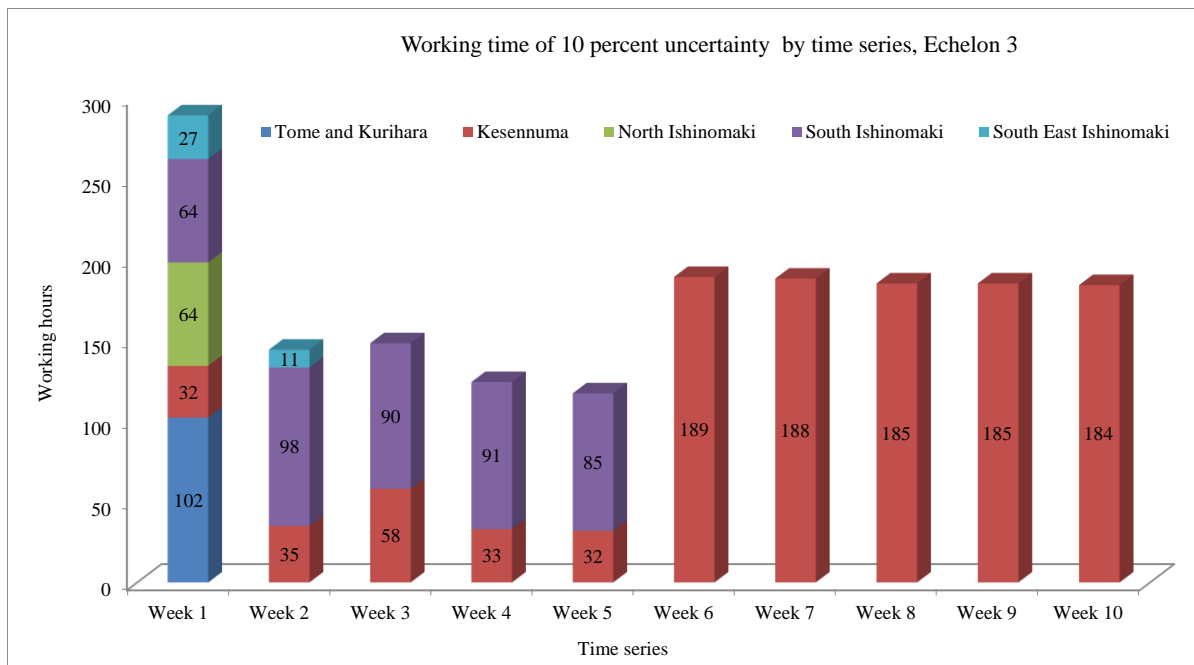


Figure 6-42 Working time of uncertainty demand 10 percent by time series, Echelon 3

Table 6-8 Location facility of uncertainty demand 20 percent by time series

Central depots	Time series									
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Kesennuma	1	1	1	1	1	1	1	1	1	1
Tome	1									
Sendai(Kumagane)										
Yamamoto										

Depots	Time series									
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Tome and Kurihara	1									
Kesennuma	1	1	1	1	1	1	1	1	1	1
North Ishinomaki	1									
South Ishinomaki	1	1	1	1	1	1	1			
South East Ishinomaki	1	1								
Taiwa Town	1									
North West Sendai										
North East Sendai										
Central Sendai										
South East Sendai										
South Sendai										

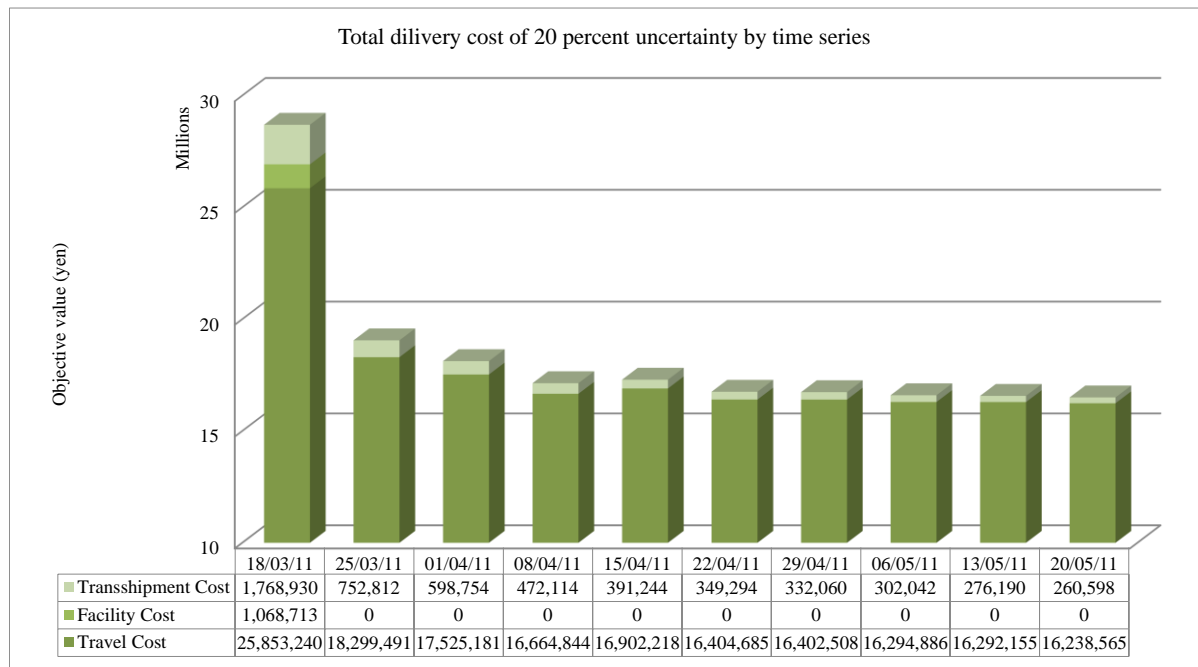


Figure 6-43 Total delivery cost of uncertainty demand 20 percent by time series

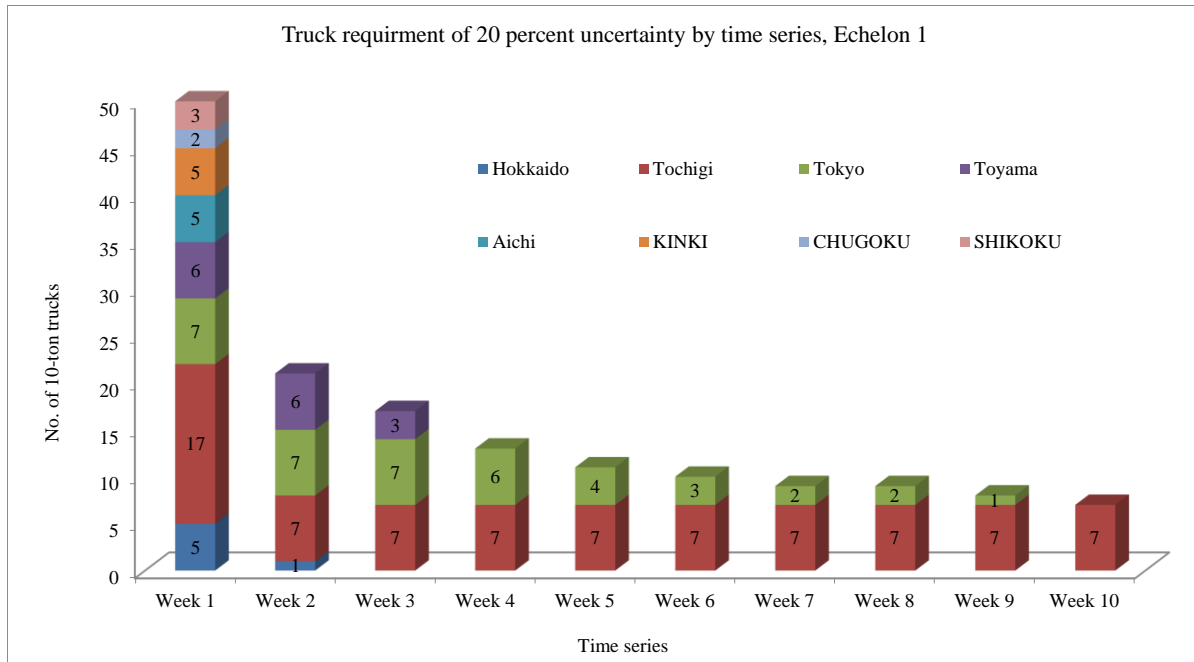


Figure 6-44 Truck requirements of uncertainty demand 20 percent by time series, Echelon 1

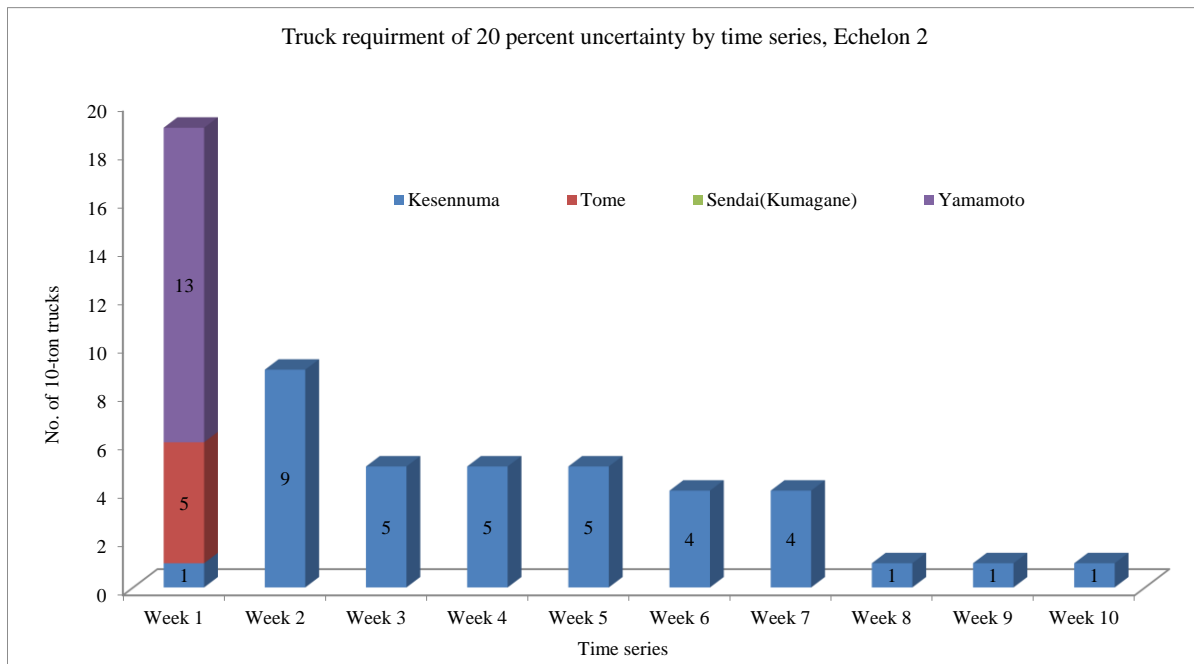


Figure 6-45 Truck requirements of uncertainty demand 20 percent by time series, Echelon 2

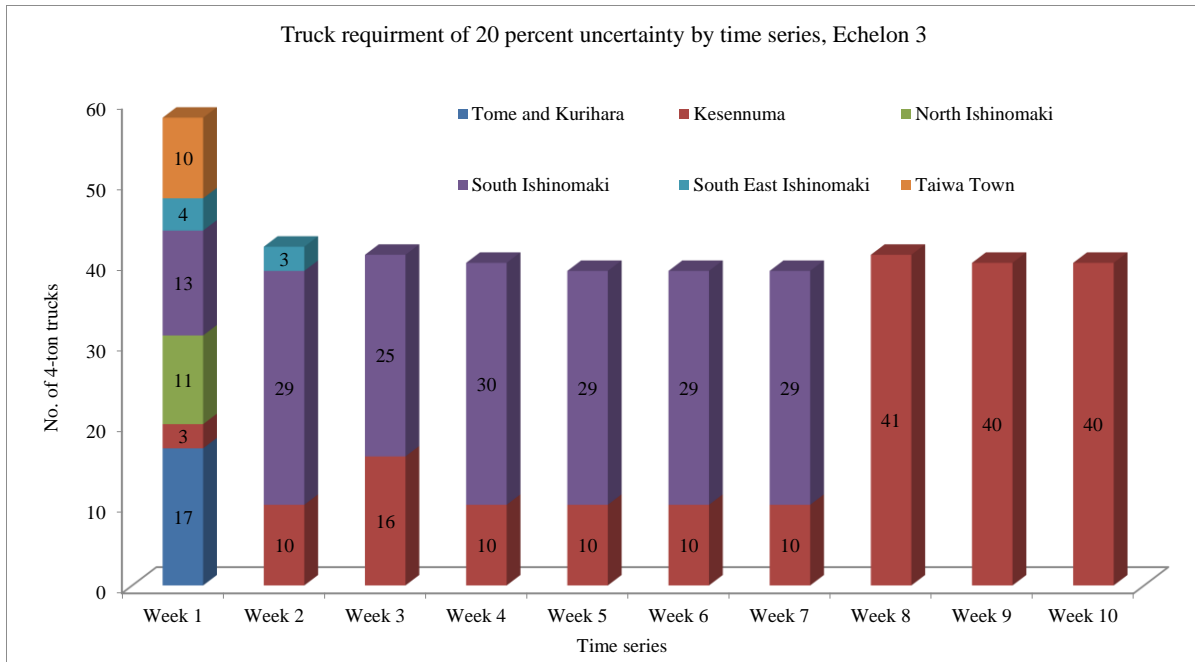


Figure 6-46 Truck requirements of uncertainty demand 20 percent by time series, Echelon 3

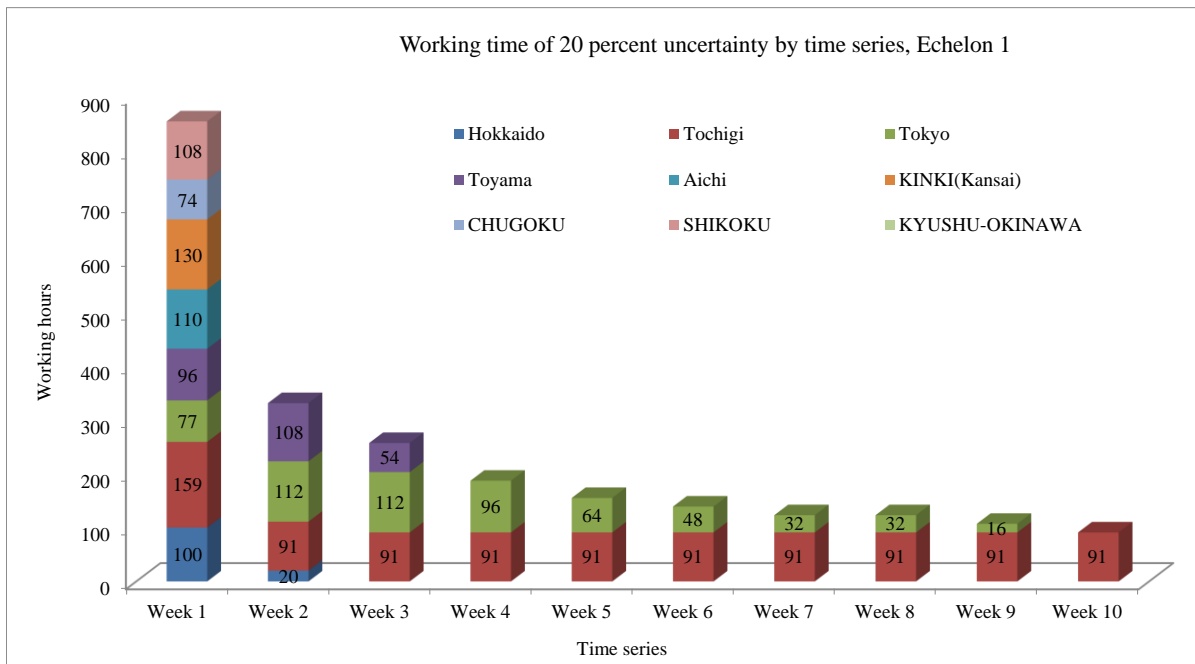


Figure 6-47 Working time of uncertainty demand 20 percent by time series, Echelon 1

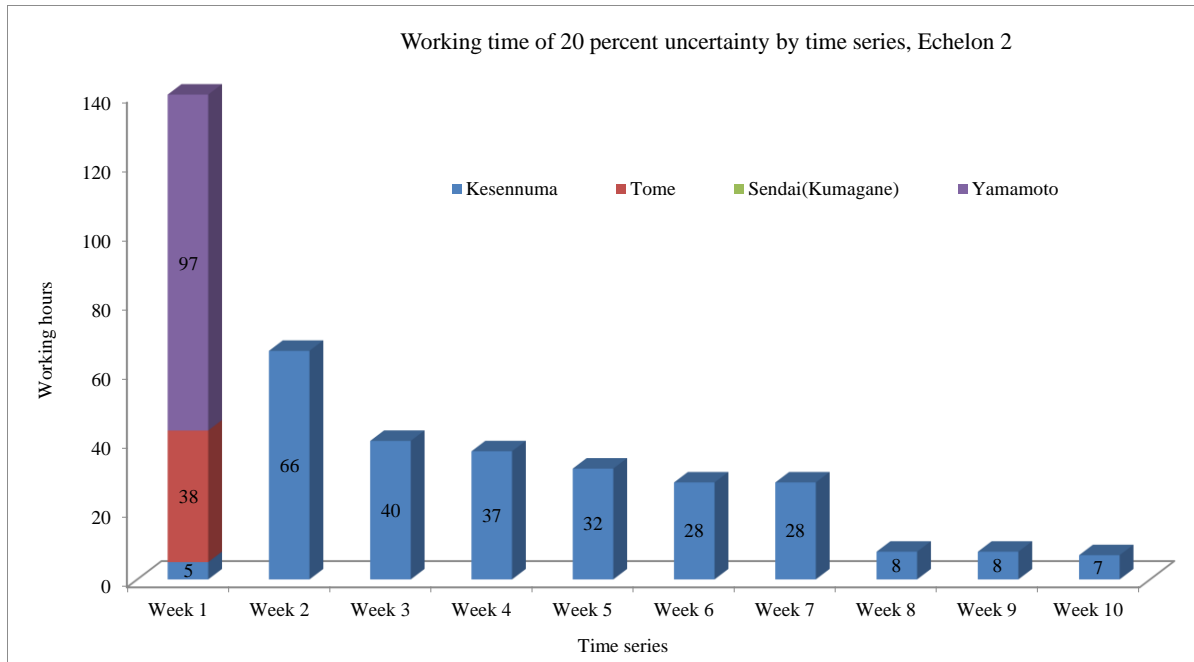


Figure 6-48 Working time of uncertainty demand 20 percent by time series, Echelon 2

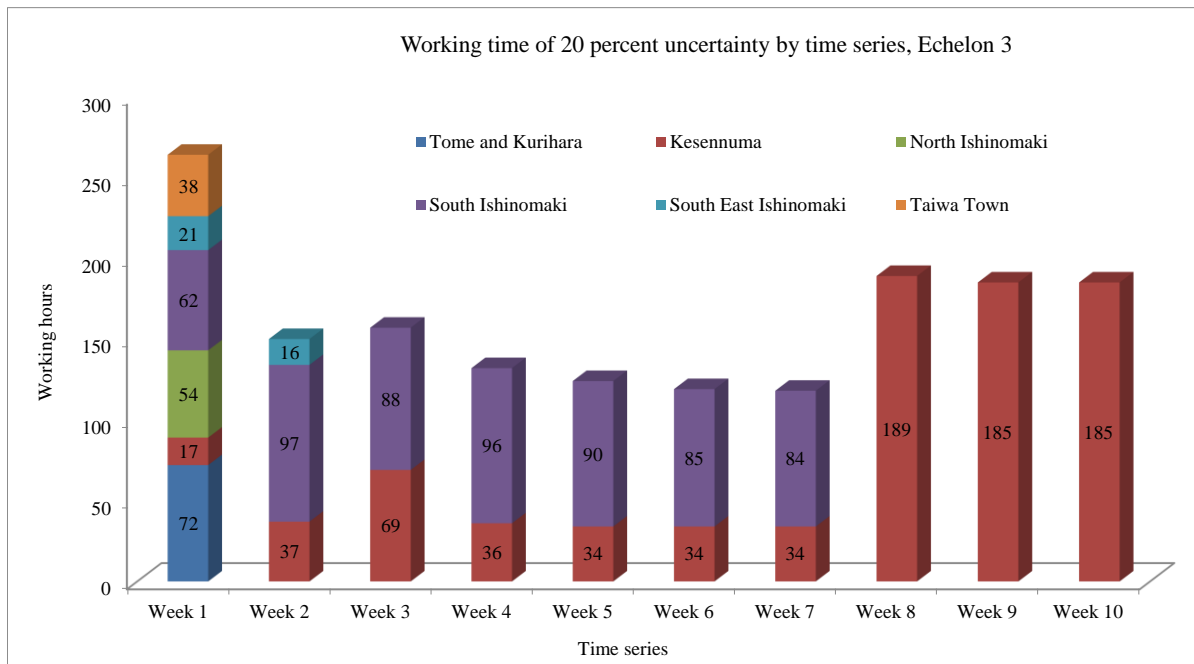


Figure 6-49 Working time of uncertainty demand 20 percent by time series, Echelon 3

CHAPTER 7

Applicability of the Multi-hierarchy network under demand uncertainty by using Ellipsoidal uncertainty set in Robust optimization: Bangkok, Thailand

7.1 Introduction

This chapter is the model application to another case study in Bangkok, Thailand. The proposed model is multi-hierarchy location problem and mainly distribute by large truck, which has contributed with uncertainty demand. Accordingly, the chapter discusses the efficient total cost of the proposed model. The natural disaster is severe flooding occurred during the 2011 monsoon season in Bangkok, Thailand.

7.2 General information and needed data for planning



Figure 7-1 River basins and Bangkok map

The flooding primary began late of July and early December, triggered by the landfall of Tropical Storm Nock-ten. These floods soon spread through the provinces of northern, northeastern, and central Thailand along the Mekong and Chao Phraya river basins, see the river basin's map in figure 7.1 (left). In October floodwaters reached the mouth of the Chao Phraya and inundated parts of the capital city of Bangkok (figure 7.1 right). Flooding persisted in some areas until mid-January 2012, and resulted in a total of 815 deaths (with 3 missing) and 13.6 million people affected. The disaster has been described as "the worst

flooding yet in terms of the amount of water and people affected."

The Royal Thai Armed Forces were mobilized to distribute aid to affected people, and civilian groups and organizations were also involved, with volunteers packing sustenance kits and delivering aid to some areas. A Flood Relief Operations Center (FROC) was set up at Don Mueang Airport to coordinate the delivery of aid, superseding the Emergency Operation Center because it could not exercise adequate authority. The stadium at Rangsit Campus of Thammasat University served as a shelter for evacuees, mostly from Ayutthaya. However, many people in the flooded areas refused to leave their homes for fear of looting. Those operation plans possibly were not determined beforehand because the severe natural disaster is quite less relative issues with Thailand in that period. The operations are usually taken from the resources that have ability without concerning the system efficiency. According to the historical operation, the need data and candidate facility locations in this application study is based on the number of population, The Royal Thai Army based location and municipality in each district.

7.2.1 Demand and shelter location: Population and Administrative Subdivision

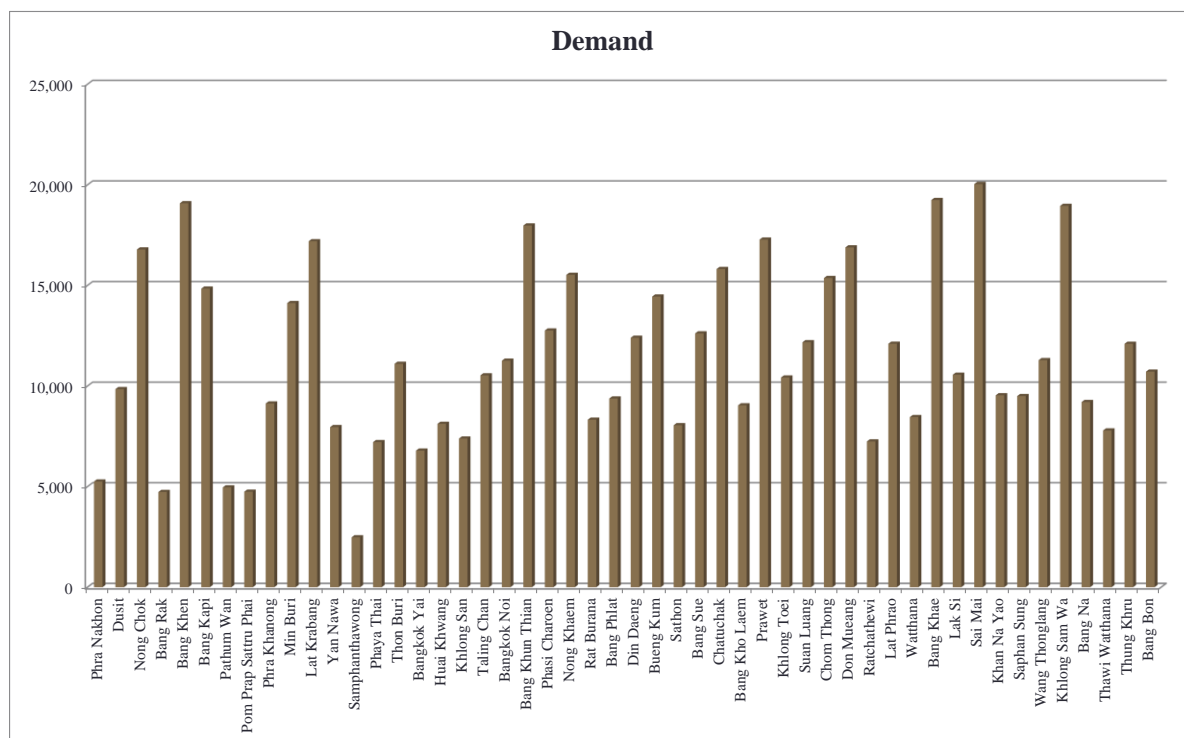


Figure 7-2 The number of expected evacuees in each district of Bangkok

Unfortunately, the amount of demand was not exactly recorded in any Thailand reports. However, the demand can be assumed by the number of population and each district supposed to be the shelters. According to the case study in Japan, the report presents the summarized number of victims who temporarily live in the shelters around 10 percent of the number of population. In a similar way, the demand that used in this application is 10 percent of each district population in Bangkok (figure 7-2).

7.2.2 Identify the facility location

The locations of suppliers are determined based on the historical operation which mainly operated by The Royal Thai Air Forces, located 10 sites in Thailand (figure 7-3). These suppliers have a function to provide and gather the relief items which usually support from government and also donation from private sectors. The advantages to use these facilities are easy to accessible, adequate human resource and available equipment and space.



Figure 7-3 The supply location based on The Royal Thai Air Forces based

Then, the locations of candidate central depots are defined. As same as described in the section 3.4, two assumptions of central depot potential sites is located at inside and outside of demand areas are supposed, as presented in the figure 7-4. The first assumption is that the central depots belong inside the demand areas. Another assumption is to define the central depot belong outside and along the edges of demand areas. In this case there are four boundaries where are connected with Bangkok. Thus, these prefectures, Nakhon Pathom, Nonthaburi, Pathum Thani, Chachoengsao and Samut Sakhon are defined to represent the

candidate central depots.



Figure 7-4 The set of central depot potential sites

Next, the locations of depots are specified by clustering zoning areas and demand size. The candidate depot locations are indicated near to the responded demand sites in total 11 places (figure 7-5).

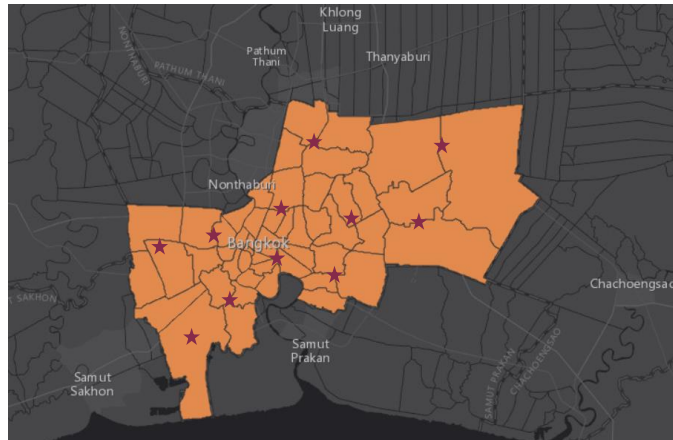
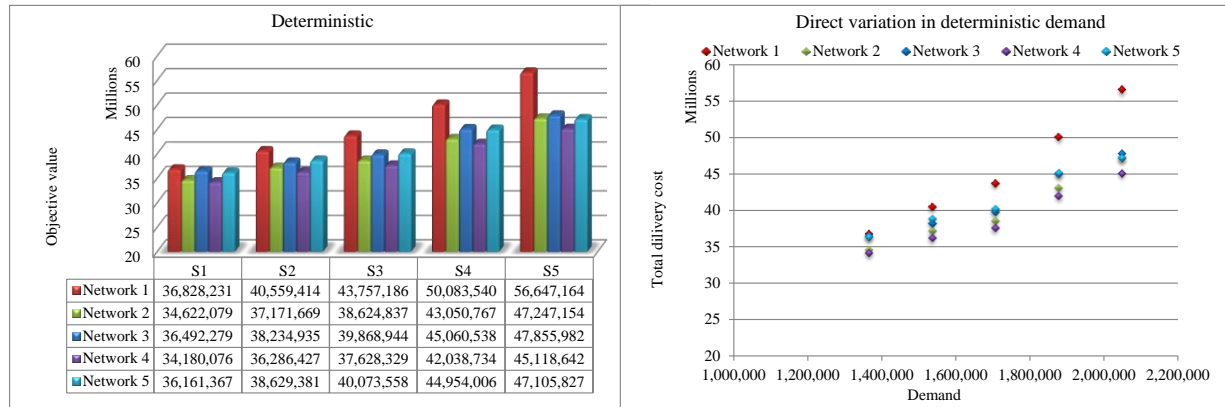


Figure 7-5 The set of depot potential sites

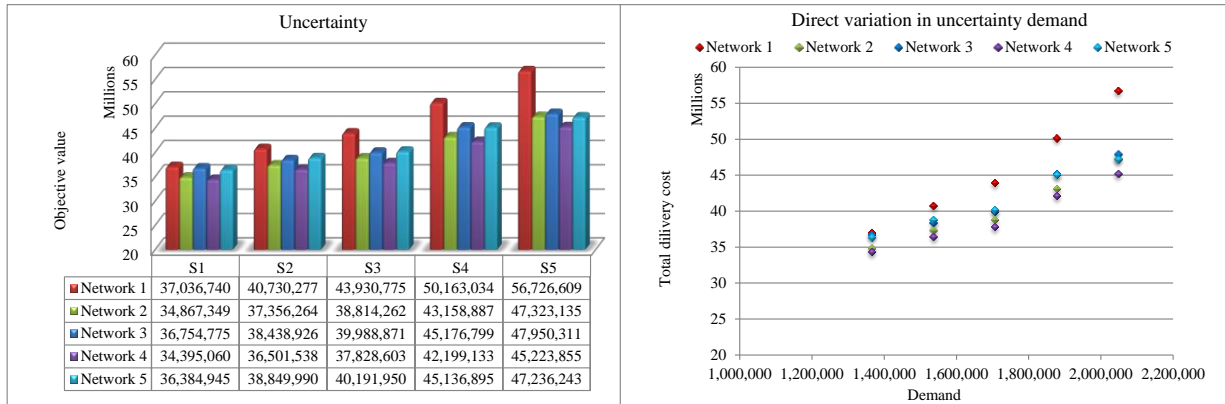
7.3 Computation results

This section presents the results of the application in Bangkok by using the proposed model, multi-hierarchy delivery by large trucks. Even though the topography of Thailand and Japan is totally different however it apparently seen that the multi-hierarchy networks which are network 2 to network 5 are suitable to design. As the results from figure 7-6, left, network 2 and network 4 which are large truck delivering always gives the better result of total delivery cost in any demand scenarios comparing with network 3 and network 5 respectively. Moreover, those four networks are giving not much different total delivery cost while single-

hierarchy, network1, effects rapidly high total delivery cost when the demand becomes pessimistic for both deterministic and uncertainty demand (figure 7-6, right).



a. Total delivery cost (left) and direct variation in deterministic demand (right)



b. Total delivery cost (left) and direct variation in uncertainty demand (right)

Figure 7-6 Total delivery cost for deterministic and uncertainty demand

Figure 7-6 illustrates the total delivery cost comparison between deterministic demand and uncertainty demand of five networks. It also shows the sensitive value of objective function for each network. Total delivery cost of uncertainty demand is higher than deterministic demand because they consider all possible cases in the uncertainty region and attempt to search the best results of worst case that can be represented for all possible demands. However, the total delivery cost of this application for deterministic demand and uncertainty demand are not huge difference for every scenario of all networks.

The range of sensitivity value comparison, Network 1 is wider range and higher sensitivity than the others, means that Network 1 is less robust than the other networks. The range scale of Network 1 is approximately 2 to 11 million yen while there is approximately 1.5 to 7

million yen of sensitivity for Network 2 to Network 5.

The sensitive value of uncertainty demand at each scenario is mostly less than deterministic demand (see figure 7-6 (right)). Therefore, the deterministic demand and uncertainty demand comparison of all networks are similar that by using robust optimization to handle the uncertainty demand illustrates more robustness than ordinary deterministic demand.

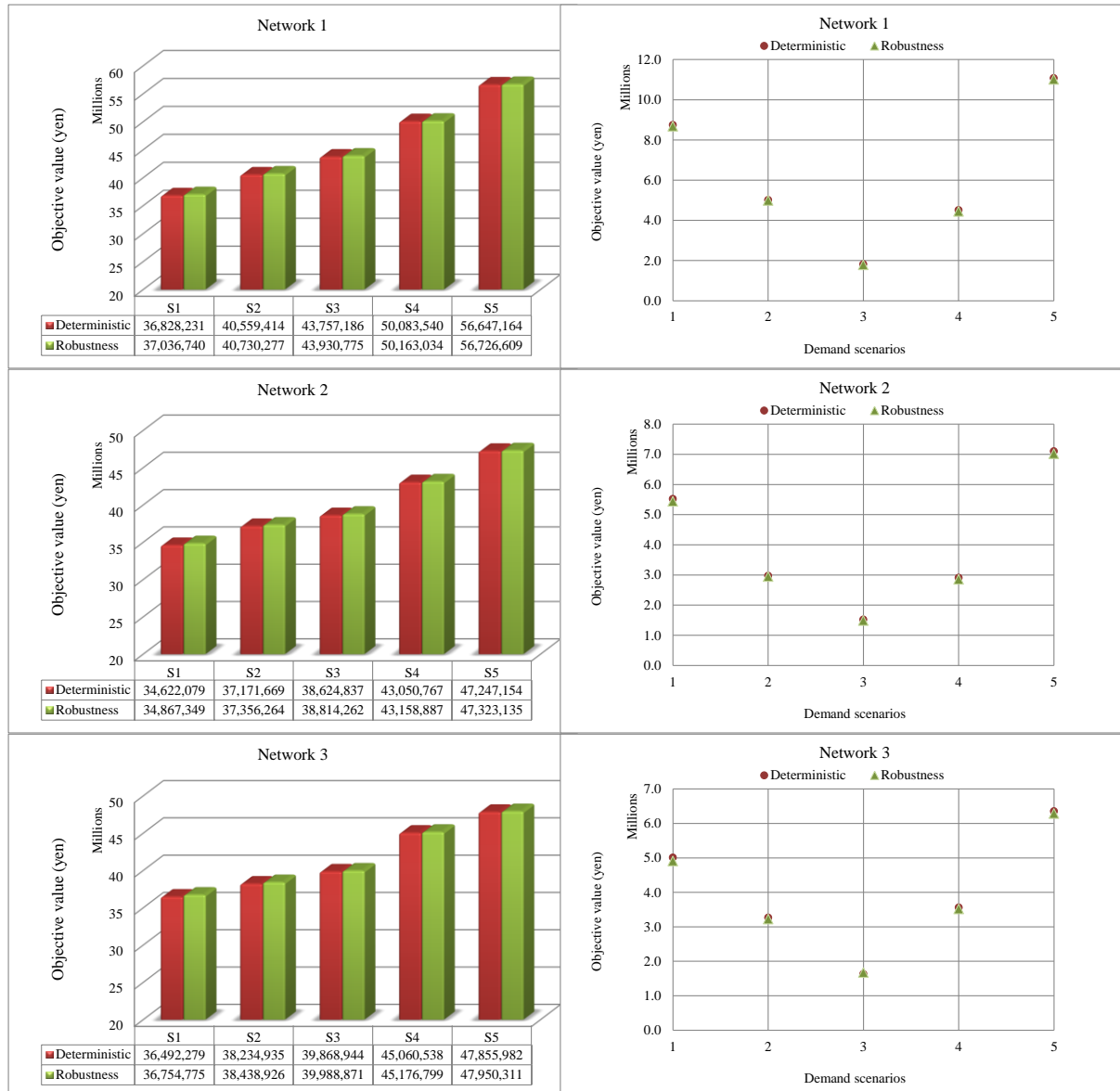


Figure 7-7 Total delivery cost for deterministic and uncertainty demand

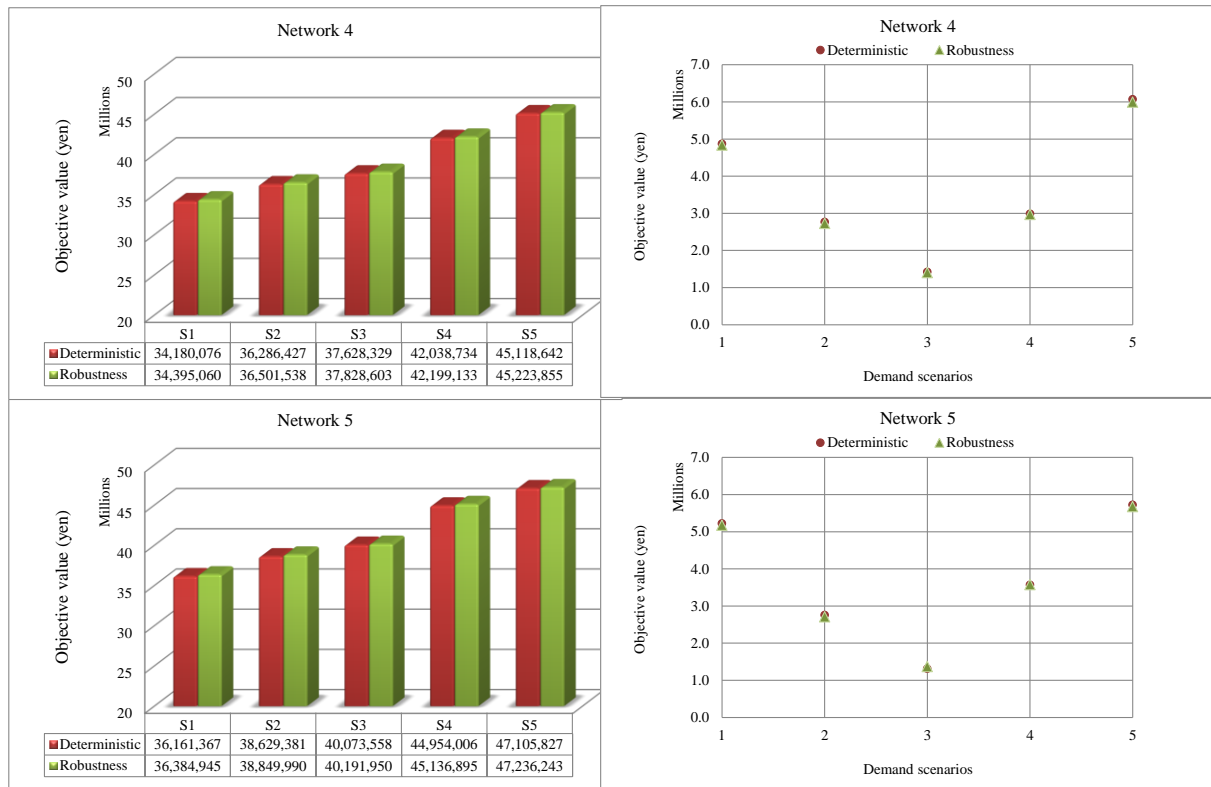


Figure 7-7 (con't) Total delivery cost for deterministic and uncertainty demand

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

8.1 Key findings

First, the calculation results demonstrate that the network configurations are significant with total delivery cost. It can be seen clearly that the total delivery cost of network 2 to network 5 can reduce cost because the travel cost much reduces even though it requires more facility cost and transshipment cost. Further, results indicated that the travel cost has more significance influence than the opening facility cost. Moreover, the truck size operation is significant when the demand is high enough. This study found that large truck is appropriate to deliver both inbound and outbound at the central depots. To apply model, we suggest establishing the central depots and using large truck to deliver both inbound and outbound.

Number of truck requirement and working time by each facility location are also estimated in this study. This estimation can help to prepare the fundamental requirements such as truck, driver and working time in advance. The large trucks can have not only to save the total cost but also can reduce the drivers. This will be the benefit when the situation is insufficient of labors, especially the aftermath circumstance. The working time can show to see the overview of working time whether how they are trend to be. The assumption that to locate the facility inside disaster areas can clearly see that they can quick response to deliver to the victims which is the one of criterion in humanitarian logistics. However, it may unfortunately happen that we are not able to establish those facilities in the disaster areas. Then, our studies also create the case that facilities locate outside. We found that the total delivery cost of these cases is not much difference. Therefore, the facility location sites have no effect to design the network, in other words the location can be the candidate sites in any convenient place upon the severity of disaster circumstance.

Furthermore, we prove that the networks are robust when the demand becomes uncertain or unknown. Here, we tested five different demand scenarios in each network based on the actual number of evacuees during post disaster. After solving the uncertainty demand by using robust optimization, the results prove that the structural networks have an effect on the model robustness. The two hierarchies of facility provide an extra robustness than the single

hierarchy of facility. Moreover, the uncertainty demand model is robust than deterministic demand models. Accordingly, we conclude that the Robust Optimization has an advantage to solve uncertainty models.

Subsequently, we improve the distribution network by routing designation for the second stage. The improved facility location with routing have an advantage to save total delivery cost approximately 30 percent. Evidently, considering routing after location design can have benefits whenever the demand can combine as a tour. Moreover, the fundamental resource requirements can be estimated properly in this procedure. Therefore, this study can be helping the decision maker to plan for the efficient post disaster distribution network when the circumstance of demand uncertainty occurs.

Further, the time series are conducted in the model. We expand the model by considering 10 periods of times by a week. The parameters such as demand in the case study in humanitarian logistics much higher change comparing with the ordinary situations. The demand can be rapidly increase or rapidly decrease week by week or even day by day depend on the severity of disaster and recovering systems. Therefore, we design the model to plan when the demand changes. The proposed model is able to consider the under uncertainty demand level for each week at 10 percent and 20 percent.

Finally, we applied the model to the different case study, here is Bangkok, Thailand. Even though, the geographical distributions of both Japan and Thailand are totally difference however the model can result in the identical behaviors. The multi-hierarchy facility location and using large truck to deliver both inbound and outbound network is the better results than the others. Similarly to Japan application, to set central depots outside or inside effect areas are not decidedly definite. By the reasons that in any applications have to design depending on their own characteristic and parameters for instances the distance from each location pairs and also the parameter of facility cost. As above mentioned the model has described that it satisfied well for both application Japan and Thailand.

8.2 Key contributions

This study contributes to the previous research by considering the worst case scenarios of the multi-facility location problems under uncertainty demand. We diagnose the uncertainty

demand by the reasons that it is quite difficult to predict the post disaster demand. Therefore, study determine the region of uncertainty demand as an ellipsoid uncertainty set that suitable for our situation where only the uncertainty ranges are known and not necessarily the distribution. Moreover, an ellipsoid uncertainty set is a novel approach that has never been fully applied so far to solving on facility location. Accordingly, the main objective of the study is to tackle the facility locations and allocations with demand uncertainty function, besides is to improve by integrating with vehicle routing problems. Moreover, we develop the model to be able to solve with the time series of input demand. We analyze the five network structures including one single-layer facility network and four two-layer facility networks with distinct truck size (large trucks and small trucks).

8.3 Recommendations

The study has contributed with the strategic planning of distribution network which has considered the cost efficiency among different network structures and assumptions of facility locations that possibly happens. Further, this model can deal with the uncertainty demand where only the uncertainty ranges have to determine. This model is recommended to apply with the situations that intend to optimize the whole network starting from the suppliers through the demand. The model is able to assign the amount of items are optimize to serve from each supplier. Moreover, the model has been established with reasonable constraints of the facility capacity and truck capacity. These can be result to the planner to be able to estimate the fundamental resource requirements which are number of trucks, number of drivers and workers and time estimation. The model is available to use when we hold the data following below:

- The historical demand or expected demand which normally estimate based on number of population and severe level of disaster.
- The historical supply or expected supply that will be available to serve.
- The demand locations that is usually known according to the plan.
- The supply location that is available to handle on necessary duty such as ability to have enough space, and to provide vehicles, labors or volunteers.
- The location of candidate central depots that should have enough space to gather the

items of suppliers and aptitude to access by large truck.

- The location of candidate depots that can be represented to cover well at any demand points.
- The parameters that need to estimate the total deliver cost here is the x-y coordinates of all locations, the energy consumption rate for vehicle, the set up facility cost at each facility site, the capacity space of facility sites and the carrying capacity of vehicles.
- The range of uncertainty set that depends on the satisfied level of the researchers. The size of the ellipsoid can increase by the ellipsoid radius δ or the constraint ρ^2 . Increasing the size of the ellipsoid will make the model more robust against (more) uncertainty, however at the cost of a worse solution. Moreover, if the size of the ellipsoid becomes too large then the model might become infeasible.

The limitation of this study is the data analysis and network assumptions. The results and findings are rather effects with this data. The two layers of facility network and the large truck size operation assumptions are probably advantage when they match with the right demand. However, these assumptions and operations can ensure that they properly respond with five scenarios of demand, when they become less and high. The model still provides the same trend of objective values. In addition, according to the model is MISOCP thus it is not able to guarantee the global optimization. However, we use Gurobi solver which has better performance (<http://www.gurobi.com/products/features-benefits>)

Because of some those limitations above, this study has applied the proposed model, multi-hierarchy facility location under demand uncertainty solving by Robust Optimization, to another application in Thailand. The results show that the proposed model can be applied appropriately under uncertainty demand.

Finally, we recommend the interrelated aspects to improve the future work as follows:

(1) We have not considered the other parameters that can be possible to fluctuate during humanitarian logistics, for example the supply amount, the unit transportation cost, the opening facility cost and etc. Therefore, not only the uncertainty demand but also such kind of parameters should be considered simultaneously.

(2) The future work can also consider the multi-objective facility location routing

problem. The model should be more reasonable by investigation both cost and time indicators simultaneously. After that the uncertainty of the demand is assigned to use with the model and then evaluates their model robustness.

(3) This study used the displacement distance which is calculated from x-y coordinate. Therefore, the future work can be considering the model more deep in practical level by dealing with road networks. According to consider this issue, the model probably will be able to track the real time operation such as road interruption during the aftermath.

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Appendices

Allocation

The table below shows the quantity of relief items that deliver from suppliers through the facility locations to 39 demand shelters. In some cases of large amount demand need to serve, for example in table 11 at Ishinomaki is served by only one depot from Central Sendai. However, some of demand sites are served from more than a single depot because the model is relaxed for a single-source constraint especially at demand shelters Aoba-ku Sendai, Izumi-ku Sendai and Miyagino-ku Sendai. Firstly, Aoba-ku Sendai receives the transportation link flow from two depots of Central Sendai and South Sendai. Secondly, Izumi-ku Sendai is delivered from two depots as Tome-Kurihara and Kesennuma. Finally, two depots in Kesennuma and Central Sendai need to dispatch the relief items to the shelter in Miyagino-ku Sendai.

Each table illustrates the transportation amount from suppliers to central depots, central depots to depots and depots to shelter demand respectively. The facility sites that are not selected must be non-value amount of transportation link flow, for example Yamagata and Iwate in table 31. The two opening central depots obtain the amount of goods from suppliers. The central depot at Fukushima gets the amount of items from five suppliers at Tochigi, Tokyo, Namerikawa, NIKKI (Kansai) region and SHIKOKU region and Akita obtains from five suppliers at Hokkaido, Namerikawa, Aichi, CHUGOKU region and KYUSHU-OKINAWA region as shown the quantity of them in the mentioned table. The summation of goods at each central depot is not over than the ability of their capacity. For example, the items is assigned to Fukushima until the amount reach to the limitation capacity because this central depot provides the lowest total cost than the others, then the remaining is filled to the second cheapest choice as Akita.

The right table on the top below is presented the amount of items from central depots to depots where are selected to operate. Same example table 31, there is a difference of capacity limitation between these two facility layers. The central depots are general ideal to keep more the amount of items or more capacity. The depots at Tome-Kurihara, Taiwa Town, Central Sendai and South Sendai present the amount of items that deliver from two central depots.

Central Sendai and South Sendai receive from Fukushima and Tome-Kurihara and Taiwa Town get the items from Akita as followed in the table.

Table bottom table shows the amount of link flow from opening depots to shelter demand. This study allows that the shelter demand can receive goods from any number of depots or multi-source facility location. The demand shelter is received the relief items from four selected depots at Tome-Kurihara, Taiwa Town, Central Sendai and South Sendai. There are 39 nodes of shelter demand which are separated for three tables, each table consists 13 demand areas. The zero value illustrates that there is no transportation amount from those depots to those shelters.

Here, five suppliers from Hokkaido, Toyama (Namerikawa), Aichi, CHUGOKU and KYUSHU-OKINAWA dispatch the relief items to Kesennuma. Moreover, five suppliers from Tochigi, Tokyo, KINKI (Kansai) region, CHUGOKU region, and SHIKOKU region deliver the remaining demand to Yamamoto.

1. Deterministic, Network 1, Scenario 1

Network 1 Scenario 1 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido		80,857	6,579								
Tochigi				99,284	32,426						
Tokyo					121,174						
Toyama			110,770	77							
Aichi				54,239							
KINKI											
CHUGOKU											
SHIKOKU											
KYUSHU-OKINAWA											

Network 1 Scenario 1 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamanoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisannriku-cho		
Tome and Kurihara																																									
Kesennuma								45,651							11,520	406																									23,280
North Ishinomaki	33,826	33,826	31,332														7,928	60					80				4,560		250	32	108	1,565	84	44	60	1011	2,583				
South Ishinomaki			2,494	33,826	33,826		12,190			1,399		26165				33,864	101			444								9,291													
South East Ishinomaki						97,443			1,548	7,472	540		12,720						180	101		12	10,949	9,435															13,200		
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

2. Uncertainty, Network 1, Scenario 1

Network 1 Scenario 1 Echelon 1		Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai																																																									
Hokkaido		62,392																																																																			
Tochigi		131,710																																																																			
Tokyo		121,174																																																																			
Toyama																																																																					
Aichi		91,208																																																																			
KINKI		81,026																																																																			
CHUGOKU		31,419																																																																			
SHIKOKU																																																																					
KYUSHU-OKINAWA																																																																					
Network 1 Scenario 1 Echelon 2		Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho																													
Tome and Kurihara																																																																					
Kesennuma		12,191 59,136											407																																																								
North Ishinomaki		33,827	33,827												1,549											33,865 7,929 102 181 445 102 81 13 10,950											4,561 251											85 45 61 1,012 2,584											22,130										
South Ishinomaki		33,827 33,827 8,997											8,872 541 26,166 12,721 11,521											61											33 109 1,566											13,201 1,151																							
South East Ishinomaki		33,827	88,447																						9,436																																												
Taiwa Town																																																																					
North West Sendai																																																																					
North East Sendai																																																																					
Central Sendai																																																																					
South East Sendai																																																																					
South Sendai																																																																					

3. Deterministic, Network 1, Scenario 2

Network 1 Scenario 2 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido	87,436										
Tochigi			99,284	32,426							
Tokyo				121,174							
Toyama	20,349	90,498									
Aichi		36,892	54,316								
KINKI		26,210									
CHUGOKU											
SHIKOKU											
KYUSHU-OKINAWA											

Network 1 Scenario 2 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho					
Tome and Kurihara																																												
Kesennuma								51,357						12,960	457		8,919																											
North Ishinomaki	38,054	38,054	38,054	27,698														114	68								5,130		281	36	122	1,761	95				1,137	2,906						
South Ishinomaki				10,356	38,054		13,714		1,742	9,980		29,436	952			38,097			203	500	114							10,452																
South East Ishinomaki						109,623					608		13,358												14	12,318	10,614															7,065		
Taiwa Town																																												
North West Sendai																																												
North East Sendai																																												
Central Sendai																																												
South East Sendai																																												

4. Uncertainty, Network 1, Scenario 2

Network 1 Scenario 2 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido	27,773										
Tochigi		42,753		62,392							
Tokyo			121,174								
Toyama		110,847									
Aichi				91,208							
KINKI			32,426								
CHUGOKU	59,088										
SHIKOKU											
KYUSHU-OKINAWA	20,963										

Network 1 Scenario 2 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisariku-cho		
Tome and Kurihara					38,055			18,336				29,437		12,961			8,920	115																							
Kesennuma	38,055					53,659		33,022	1,743	9,981	609		14,311		458																										
North Ishinomaki				38,055		55,965										38,098														37					50	69	1,138		20,188		
South Ishinomaki	38,055		38,055				13,715												69	204	501	115	91	15	12,319	10,615	5,131	10,453	282	123			96				2,907	14,851	6,003		
South East Ishinomaki																																									
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

5. Deterministic, Network 1, Scenario 3

Network 1 Scenario 3 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido	1,273	86,163									
Tochigi				99,284	32,426						
Tokyo					121,174						
Toyama	83,507		27,340								
Aichi			36,892	54,316							
KINKI			81,026								
CHUGOKU											
SHIKOKU			8,342								
KYUSHU-OKINAWA											

Network 1 Scenario 3 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Tathaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watairi-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
	Tome and Kurihara	11,235	42,282											14,400	507		9,909	126	75	555			99						39	135	1,956	105	54	75		3,228		29,100		
	Kesennuma							57,063																																
	North Ishinomaki	31,047		42,282	42,282	30,714																					5,700		312						1,263					
	South Ishinomaki					11,568		15,237		1,935	11,088		32,706	15,900			42,330			225	126				10,872			11,613												
	South East Ishinomaki						121,803				675														15	2,814	11,793											16,500		
	Taiwa Town																																							
	North West Sendai																																							
	North East Sendai																																							
	Central Sendai																																							
South East Sendai																																								
South Sendai																																								

6. Uncertainty, Network 1, Scenario 3

Network 1 Scenario 3 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
	Hokkaido	72,574	14,767		95						
	Tochigi				131,710						
	Tokyo		121,174								
	Toyama										
	Aichi				91,208						
	KINKI	81,026									
	CHUGOKU		17,659		41,429						
	SHIKOKU			22,367		16,810					
	KYUSHU-OKINAWA				20,963						

Network 1 Scenario 3 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
	Tome and Kurihara	7,481				42,283		15,238	1,936			32,707			508	42,331		127	76	226		127	100		1,293		5,701						106	55	76		3,229		
	Kesennuma									11,089	676						9,910				556									136									
	North Ishinomaki		42,283	42,283									15,901													11,794	11,614	313		1,957				1,264		16,501	9,690		
	South Ishinomaki	34,802			42,283				57,064																				40										
	South East Ishinomaki						121,804							14,401								16	12,394																
	Taiwa Town																																						
	North West Sendai																																						
	North East Sendai																																						
	Central Sendai																																						
South East Sendai																																							
South Sendai																																							

7. Deterministic, Network 1, Scenario 4

Network 1 Scenario 4 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido	87,436										
Tochigi			99,284	32,426							
Tokyo				121,174							
Toyama	110,847										
Aichi			36,892	54,316							
KINKI			81,026								
CHUGOKU	15,976										
SHIKOKU	19,875		35,682								
KYUSHU-OKINAWA											

Network 1 Scenario 4 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho					
	Tome and Kurihara	46,511	46,511	17,153					2,129						15,840	558		10,900	139	83	611		109							43	149	2,152	116	60	83		3,551							
Kesennuma						62,770																														24,666								
North Ishinomaki		46,511	29,358	46,511		15,872																									6,270		344						1,390	7,344				
South Ishinomaki						889					12,197	743	35,977	17,490					46,563					248	139	17	15,055	11,507	12,775															
South East Ishinomaki						133,984																											1,466											18,150
Taiwa Town																																												
North West Sendai																																												
North East Sendai																																												
Central Sendai																																												
South East Sendai																																												
South Sendai																																												

8. Uncertainty, Network 1, Scenario 4

Network 1 Scenario 4 Echelon 1	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido					61,333						
Tochigi			131,710								
Tokyo	121,174										
Toyama				110,847							
Aichi					91,208						
KINKI		81,026									
CHUGOKU	16,335			42,753							
SHIKOKU		55,557									
KYUSHU-OKINAWA			20,963								

Network 1 Scenario 4 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara	46,512		46,512	24,215														84	249							12,974							6,963								
Kesennuma						16,762										46,564	10,901			612		110																18,151	43,483		
North Ishinomaki			46,512	22,297					2,130	12,198	744		17,491	15,841	559			140					18	15,056		6,271	12,776	345		150			61	84							
South Ishinomaki						153,600																																			
South East Ishinomaki	46,512							62,771				35,978									140								44	2,153				1,391	3,552						
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

9. Deterministic, Network 1, Scenario 5

Network 1 Scenario 5 Echelon 1	Network 1 Scenario 5 Echelon 1										
	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
	Hokkaido	87,436									
	Tochigi			99,284	32,426						
	Tokyo				121,174						
	Toyama	94,512	16,335								
	Aichi			36,892	54,316						
	KINKI			81,026							
	CHUGOKU	59,088									
	SHIKOKU		19,875	35,682							
KYUSHU-OKINAWA		20,058									

Network 1 Scenario 5 Echelon 2	Network 1 Scenario 5 Echelon 2																																							
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
	Tome and Kurihara	50,739	50,739	29,561					2,322						609		11,891	152	90	666	0	119								47	162	2,348	126	65	90		3,874			
	Kesennuma					1,712		68,476						17,280																							1,516	19,800	34,920	
	North Ishinomaki		50,739	21,178	50,739		18,285						5,444															6,840		375										
	South Ishinomaki									13,306	810	33,804	19,080		50,796			270	152	18	16,424	5,004					13,936													
	South East Ishinomaki					144,452																					9,148													
	Taiwa Town																																							
	North West Sendai																																							
	North East Sendai																																							
Central Sendai																																								
South East Sendai																																								
South Sendai																																								

10. Uncertainty, Network 1, Scenario 5

Network 1 Scenario 5 Echelon 1																																												
	Tome and Kurihara			Kesennuma			North Ishinomaki			South Ishinomaki			South East Ishinomaki			Taiwa Town			North West Sendai			North East Sendai			Central Sendai			South East Sendai			South Sendai													
	Hokkaido			44,683						42,753																																		
	Tochigi													131,710																														
	Tokyo	120,308																																										
	Toyama													110,847																														
	Aichi													91,208																														
	KINKI			62,158								18,868																																
	CHUGOKU	33,292		25,796																																								
	SHIKOKU													55,557																														
	KYUSHU-OKINAWA			20,963																																								
Network 1 Scenario 5 Echelon 2	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho					
	Tome and Kurihara							18,286	12,880			13,307	39,249	19,081			50,797														7,435													
	Kesennuma					146,165				7,405					610	11,892														16,425	14,153	6,841	6,502			163	2,349			1,517	3,875			34,921
	North Ishinomaki					40,112					2,323	811			17,281			153	91			667	153			19														127	66			19,801
	South Ishinomaki					50,740	10,628	50,740																								376	48			91								
	South East Ishinomaki					50,740	50,740		48,192																					271		120												
	Taiwa Town																																											
	North West Sendai																																											
	North East Sendai																																											
	Central Sendai																																											
	South East Sendai																																											
	South Sendai																																											

11. Deterministic, Network 2, Scenario 1

Network 2 Scenario 1 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		131,710		
Tokyo		121,174		
Toyama	17,970	92,877		
Aichi		54,239		
KINKI				
CHUGOKU				
SHIKOKU				
KYUSHU-OKINAWA				

Network 2 Scenario 1 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma		80,857			24,549						
Tome			153,600	153,600	92,800						
Sendai(Kumagane)											
Yamamoto											
Sum Inventory		80,857	153,600	153,600	117,349						

Network 2 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yanamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
Tome and Kurihara																																								
Kesennuma								45,651						11,520	406																									23,280
North Ishinomaki	33,826	33,826	33,826	33,656													7,928	101	60					80			4,560		250	32	108	1,565	84	44	60	1011	2,583			
South Ishinomaki					170	33,826	12,190		1,548	8,871	540	26165	12,720			33,864			180	444	101		12	10,949	2,729		9,291													
South East Ishinomaki						97,443																				6,706													13,200	
Taiwa Town																																								
North West Sendai																																								
North East Sendai																																								
Central Sendai																																								
South East Sendai																																								
South Sendai																																								

12. Uncertainty, Network 2, Scenario 1

Network 2 Scenario 1 Echelon 1					Network 2 Scenario 1 Echelon 2																
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto		Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai					
Hokkaido	87,436																				
Tochigi	97,137	34,573																			
Tokyo	73,463																				
Toyama	110,847																				
Aichi																					
KINKI		81,026																			
CHUGOKU																					
SHIKOKU																					
KYUSHU-OKINAWA		20,963																			

Network 2 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onaga wa-cho	Minamisanriku-cho		
Tome and Kurihara				33,827	33,827			45,652	1,549		541		12,721		407		7,929																								
Kesennuma	33,827					18,420																				9,436															
North Ishinomaki																																									
South Ishinomaki			33,827			79,024								11,521								102	13	214		4,561								45	1012			23,281			
South East Ishinomaki	33,827					12,191			8,872		26166					33,865		102	61	181	445		81	10,736			9,292	251	33		1,566	85		61		2,584	13,201				
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

13. Deterministic, Network 2, Scenario 2

Network 2 Scenario 2 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		131,710		
Tokyo		121,174		
Toyama	81,149	29,698		
Aichi		91,208		
KINKI		26,210		
CHUGOKU				
SHIKOKU				
KYUSHU-OKINAWA				

Network 2 Scenario 2 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma		107,785			60,800						
Tome			153,600	153,600	92,800						
Sendai(Kumagane)											
Yamamoto											
Sum Inventory		107,785	153,600	153,600	153,600						

Network 2 Scenario 2 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho							
	Tome and Kurihara																																													
							51,357				12,960				457		8,919										5,130								49		68		7,785		26,190					
	North Ishinomaki		38,054	38,054	38,054	27,698															114		68								281		36		122		1,761		95				1,137		2,906	
	South Ishinomaki				10,356	38,054	13,714		1,742		9,980		29,436		952		38,097				203		500		114						10,452															
	South East Ishinomaki					109,623										608		13,358								14		12,318		10,614										7,065						
	Taiwa Town																																													
	North West Sendai																																													
	North East Sendai																																													
	Central Sendai																																													
South East Sendai																																														
South Sendai																																														

14. Uncertainty, Network 2, Scenario 2

Network 2 Scenario 2 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi	131,710			
Tokyo	14,450			
Toyama	110,847			
Aichi		28,510		
KINKI		81,026		
CHUGOKU		59,088		
SHIKOKU	55,557			
KYUSHU-OKINAWA				

Network 2 Scenario 2 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma		121,181		153,600	125,219						
Tome			140,243		28,381						
Sendai(Kumagane)											
Yamamoto											

Network 2 Scenario 2 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watarai-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho														
	Tome and Kurihara																																																				
							109,624		9,981								69		204		115								50		1138																						
	North Ishinomaki					38,055			51,358		29437				458		13,543								15		484		5,131				1,762																				
	South Ishinomaki		38,055	38,055		38,055							1,743								24,555		115		501								12,319				37		96		69												
	South East Ishinomaki			38,055								13,715				609		14,311		12,961								8,920								91		10,131		10,453		282		123				2,907		14,851		26,191	
	Taiwa Town																																																				
	North West Sendai																																																				
	North East Sendai																																																				
	Central Sendai																																																				
South East Sendai																																																					
South Sendai																																																					

15. Deterministic, Network 2, Scenario 3

Network 2 Scenario 3 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		131,710		
Tokyo	33,460	87,714		
Toyama	110,847			
Aichi		91,208		
KINKI		81,026		
CHUGOKU				
SHIKOKU		8,342		
KYUSHU-OKINAWA				

Network 2 Scenario 3 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma	84,780	86,163			60,800						
Tome			153,600	153,600	92,800						
Sendai(Kumagane)											
Yamamoto											
Sum Inventory	84,780	86,163	153,600	153,600	153,600						

Network 2 Scenario 3 Echelon 3	Aoba-ku Sendai	Izumi-i-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watarai-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
Tome and Kurihara	11,235	42,282												14,400	507		9,909	126	75	555	99								39	135	1,956	105	54	75		3,228		29,100		
Kesennuma								57,063																																
North Ishinomaki	31,047		42,282	42,282	30,714																					5,700		312							1263					
South Ishinomaki						11,568	15,237		1,935	11,088		32,706	15,900			42,330			225	126		10,872				11,613														
South East Ishinomaki						121,803					675											15	2,814	11,793														16,500		
Taiwa Town																																								
North West Sendai																																								
North East Sendai																																								
Central Sendai																																								
South East Sendai																																								
South Sendai																																								

16. Uncertainty, Network 2, Scenario 3

Network 2 Scenario 3 Echelon 1					Network 2 Scenario 3 Echelon 2											
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto		Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Hokkaido	87,036															
Tochigi		85,444				Kesennuma	153,600		153,600	90,083						
Tokyo	120,154					Tome	148,897	85,602								
Toyama		111,757				Sendai(Kumagane)										
Aichi	54,507	37,298				Yamamoto										
KINKI	80,029															
CHUGOKU																
SHIKOKU	55,557															
KYUSHU-OKINAWA																

Network 2 Scenario 3 Echelon 3																
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima
Tome and Kurihara			42,283	42,283											508	42,331
Kesennuma	42,283				42,283				11,089							9,910
North Ishinomaki	42,283					13,148				676			14,401			127
South Ishinomaki						108,656	15,238		1,936			15,901				556
South East Ishinomaki								57,064			32,707					127
Taiwa Town																
North West Sendai																
North East Sendai																
Central Sendai																
South East Sendai																
South Sendai																

Network 2 Scenario 3 Echelon 3																
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima
Tome and Kurihara			42,283	42,283											508	42,331
Kesennuma	42,283				42,283				11,089							9,910
North Ishinomaki	42,283					13,148				676			14,401			127
South Ishinomaki						108,656	15,238		1,936			15,901				556
South East Ishinomaki								57,064			32,707					127
Taiwa Town																
North West Sendai																
North East Sendai																
Central Sendai																
South East Sendai																
South Sendai																

17. Deterministic, Network 2, Scenario 4

Network 2 Scenario 4 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		131,710		
Tokyo	80,675	40,499		
Toyama	110,847			
Aichi		91,208		
KINKI		81,026		
CHUGOKU	15,976			
SHIKOKU		55,557		
KYUSHU-OKINAWA				

Network 2 Scenario 4 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma	139,354	94,780			60,800						
Tome			153,600	153,600	92,800						
Sendai(Kumagane)											
Yamamoto											
Sum Inventory	139,354	94,780	153,600	153,600	153,600						

Network 2 Scenario 4 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
Tome and Kurihara	46,511	46,511		9,809					2,129					15,840	558		10,900	139	83	611	109									43	149	2,152	116	60	83	3,551			
Kesennuma								62,770																															32,010
North Ishinomaki		46,511	36,702	46,511			15,872																				6,270	344							1390				
South Ishinomaki							889			12,197	743	35977	17,490		46,563				248		139		17	15,055	11,507		12,775												
South East Ishinomaki						133,984																				1,466													18,150
Taiwa Town																																							
North West Sendai																																							
North East Sendai																																							
Central Sendai																																							
South East Sendai																																							
South Sendai																																							

18. Uncertainty, Network 2, Scenario 4

Network 2 Scenario 4 Echelon 1	Network 2 Scenario 4 Echelon 2			
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		88,637		
Tokyo	121,174			
Toyama	110,847			
Aichi		91,208		
KINKI		81,026		
CHUGOKU		59,088		
SHIKOKU		55,557		
KYUSHU-OKINAWA				

Network 2 Scenario 4 Echelon 3	Network 2 Scenario 4 Echelon 2																																											
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho					
Tome and Kurihara	46,512							3,700					35,978	17,491	15,841	559																												
Kesennuma						133,985			2,130													140	18	15,056				1,611																
North Ishinomaki		46,512		46,512				59,071																				1,505																
South Ishinomaki			46,512			16,762										46,564		140	84				110			12,974	9,660	345		2,153		61	84						18,151					
South East Ishinomaki	46,512									12,198	744						10,901		249	612						6,271			44	150							3,552							
Taiwa Town																																												
North West Sendai																																												
North East Sendai																																												
Central Sendai																																												
South East Sendai																																												
South Sendai																																												

19. Deterministic, Network 2, Scenario 5

[illegible]

20. Uncertainty, Network 2, Scenario 5

[illegible]

21. Deterministic, Network 3, Scenario 1

Network 3 Scenario 1 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
	Hokkaido	87,436		
	Tochigi		131,710	
	Tokyo		121,174	
	Toyama	17,970	92,877	
	Aichi		54,239	
	KINKI			
	CHUGOKU			
	SHIKOKU			
	KYUSHU-OKINAWA			

Network 3 Scenario 1 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
	Kesennuma	105,406									
	Tome		153,600	153,600	92,800						
	Sendai(Kumagane)										
	Yamamoto										

Network 3 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahana town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
	Tome and Kurihara																																								
	Kesennuma					3,317		45,651						11,520	406		7,928																								
	North Ishinomaki	33,826	33,826	33,826	33,826	7,862												101	60					80			4,560		250	32	108	1,565	84		44	60			13,200	23,280	
	South Ishinomaki					25,964	1,326	12,190		1,548	8,871	540	26165	12,720		33,864			180	444	101		12	10,949	9,435		9,291										1011	2,583			
	South East Ishinomaki						92,800																																		
	Taiwa Town																																								
	North West Sendai																																								
	North East Sendai																																								
	Central Sendai																																								
South East Sendai																																									
South Sendai																																									

22. Uncertainty, Network 3, Scenario 1

[illegible]

23. Deterministic, Network 3, Scenario 2

Network 3 Scenario 2 Echelon 1					Network 3 Scenario 2 Echelon 2											
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai	
Hokkaido	87,436															
Tochigi		131,710														
Tokyo		121,174														
Toyama	81,149	29,698														
Aichi		91,208														
KINKI		26,210														
CHUGOKU																
SHIKOKU																
KYUSHU-OKINAWA																

Network 3 Scenario 2 Echelon 3																																										
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho			
Tome and Kurihara																																										
Kesennuma	30,765					1,838		51,357						12,960	457		8,919							90						36	122	1,761	95	49	68	1137	2,906	14,850	26,190			
North Ishinomaki	38,054	7,289	38,054	38,054	26,556													114	68							5,130		281														
South Ishinomaki					11,498		13,714		1,742	9,980	608	29436	14,310		38,097				203	500	114		14	12,318	10,614		10,452															
South East Ishinomaki						107,785																																				
Taiwa Town																																										
North West Sendai																																										
North East Sendai																																										
Central Sendai																																										
South East Sendai																																										
South Sendai																																										

24. Uncertainty, Network 3, Scenario 2

Network 3 Scenario 2 Echelon 1					Network 3 Scenario 2 Echelon 2															
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai					
Hokkaido	87,436																			
Tochigi	131,710																			
Tokyo	14,450																			
Toyama	110,847																			
Aichi		28,510																		
KINKI		81,026																		
CHUGOKU		59,088																		
SHIKOKU	55,557																			
KYUSHU-OKINAWA																				

Network 3 Scenario 2 Echelon 3																																									
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara																																									
Kesennuma						109,624				9,981								69	204	115																					
North Ishinomaki						38,055		51,358				29437			458	13,543								15		484	5,131				1,762										
South Ishinomaki	38,055		38,055	38,055					1,743							24,555		115		501					12,319					37			96		69						
South East Ishinomaki		38,055					13,715				609		14,311	12,961			8,920						91			10,131		10,453	282	123							2,907	14,851	26,191		
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

25. Deterministic, Network 3, Scenario 3

Network 3 Scenario 3 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		131,710		
Tokyo	33,460	87,714		
Toyama	110,847			
Aichi		91,208		
KINKI		81,026		
CHUGOKU				
SHIKOKU		8,342		
KYUSHU-OKINAWA				

Network 3 Scenario 3 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma	78,143	153,600									
Tome			153,600	153,600	92,800						
Sendai(Kumagane)											
Yamamoto											

Network 3 Scenario 3 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara	17,198	42,282							1,935						507		9,909	126	75	555			99																		
Kesennuma	4,342					30,797		57,063						14,400																135							1263		16,500	29,100	
North Ishinomaki	20,742		42,282	42,282	42,282																					5,700		312													
South Ishinomaki						15,237			11,088	675	32,706	15,900			42,330				225	126	15	13,686	9,999			11,613															
South East Ishinomaki						91,006																			1,794																
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

26. Uncertainty, Network 3, Scenario 3

Network 3 Scenario 3 Echelon 1					Network 3 Scenario 3 Echelon 2																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto		Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									
Hokkaido	87,436																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								

27. Deterministic, Network 3, Scenario 4

Network 3 Scenario 4 Echelon 1	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto
Hokkaido	87,436			
Tochigi		131,710		
Tokyo	80,675	40,499		
Toyama	110,847			
Aichi		91,208		
KINKI		81,026		
CHUGOKU	15,976			
SHIKOKU		55,557		
KYUSHU-OKINAWA				

Network 3 Scenario 4 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Kesennuma	140,820	153,600			514						
Tome			153,600	153,600	92,800						
Sendai(Kumagane)											
Yamamoto											

Network 3 Scenario 4 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara	46,511	46,511		11,275					2,129					15,840	558		10,900	139	83		611	109								43	149	2,152	116	60	83		3,551				
Kesennuma						40,670		62,770																															18,150	32,010	
North Ishinomaki		46,511	35,236	46,511		16,761						577															6,270	344							1390						
South Ishinomaki										12,197	743	35400	17,490		46,563			248	139		17	15,055	12,973			12,775															
South East Ishinomaki						93,314																																			
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

28. Uncertainty, Network 3, Scenario 4

[illegible]

29. Deterministic, Network 3, Scenario 5

Network 3 Scenario 5 Echelon 1																	
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai		
Hokkaido	87,436																
Tochigi		131,710															
Tokyo	80,675	40,499															
Toyama	110,847																
Aichi		91,208															
KINKI		81,026															
CHUGOKU	59,088																
SHIKOKU		55,557															
KYUSHU-OKINAWA	20,058																

Network 3 Scenario 5 Echelon 3																	
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki
Tome and Kurihara	50,739	50,739		29,561					2,322						609		11,891
Kesennuma						11,608		68,476						17,280			152
North Ishinomaki	50,739	21,178	50,739			18,285						5,444					90
South Ishinomaki										13,306	810	33,804	19,080		50,796		270
South East Ishinomaki						134,556											152
Taiwa Town																	18
North West Sendai																	16,424
North East Sendai																	5,004
Central Sendai																	13,936
South East Sendai																	
South Sendai																	

Network 3 Scenario 5 Echelon 3																	
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki
Tome and Kurihara	50,739	50,739		29,561					2,322						609		11,891
Kesennuma						11,608		68,476						17,280			152
North Ishinomaki	50,739	21,178	50,739			18,285						5,444					90
South Ishinomaki										13,306	810	33,804	19,080		50,796		270
South East Ishinomaki						134,556											152
Taiwa Town																	18
North West Sendai																	16,424
North East Sendai																	5,004
Central Sendai																	13,936
South East Sendai																	
South Sendai																	

30. Uncertainty, Network 3, Scenario 5

Network 3 Scenario 5 Echelon 1					Network 3 Scenario 5 Echelon 2															
	Kesennuma	Tome	Sendai(Kumagane)	Yamamoto	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai					
Hokkaido	87,436																			
Tochigi		131,710				Kesennuma	50,943	153,600	153,600											
Tokyo		121,174				Tome	92,800	153,600	153,600											
Toyama	110,847					Sendai(Kumagane)														
Aichi	91,208					Yamamoto														
KINKI	13,095	67,931																		
CHUGOKU		58,222																		
SHIKOKU	55,557																			
KYUSHU-OKINA WA		20,963																		

Network 3 Scenario 5 Echelon 3																																									
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanniku-cho		
Tome and Kurihara	50,740		50,740					27,309	13,307					610		10,417	11,892	153	271				120		493		14,153														
Kesennuma						52,995		41,168					19,081																											3,875	
North Ishinomaki	50,740									811	39249		17,281		40,380		91	667											376	48	2,349			91	1517						
South Ishinomaki						93,170	18,286												153							6,841		163				66							34,921		
South East Ishinomaki			50,740	50,740				2,323																15,932		13,937			127									19,801			
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

31. Deterministic, Network 4, Scenario 1

Network 4 Scenario 1 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi	131,710			
Tokyo	121,174			
Toyama	92,877			17,970
Aichi	54,239			
KINKI				
CHUGOKU				
SHIKOKU				
KYUSHU-OKINAWA				

Network 4 Scenario 1 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima			92,800	153,600	153,600						
Yamagata											
Akita											
Iwate		68,931	36,475								

Network 4 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
Tome and Kurihara																																								
Kesennuma								45,651						11,520	406		7,928	60		80					4,560		250	32	108	1,565	84	44	60	1011	2,583				23,280	
North Ishinomaki	33,826	33,826	31,332																																					
South Ishinomaki			2,494	33,826	33,826	12,190				1,399	26165					33,864	101		444								9,291													
South East Ishinomaki						97,443			1,548	7,472	540		12,720						180	101	12	10,949	9,435																13,200	
Taiwa Town																																								
North West Sendai																																								
North East Sendai																																								
Central Sendai																																								
South East Sendai																																								
South Sendai																																								

32. Uncertainty, Network 4, Scenario 1

Network 4 Scenario 1 Echelon 1	Fukushima	Yamagata	Akita	Iwate
	Hokkaido			87,436
	Tochigi			131,710
	Tokyo	14,375		
	Toyama			110,847
	Aichi			
	KINKI	81,026		
	CHUGOKU	59,088		
	SHIKOKU			
	KYUSHU-OKINAWA			20,963

Network 4 Scenario 1 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
	Fukushima	889			153,600						
	Yamagata										
	Akita										
	Iwate	139,701	57,655		153,600						

Network 4 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Toniya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
	Tome and Kurihara	7,252			33,827	97,444																		81	13			4,561	7,319	251			85								
	Kesennuma				33,827													102		445																				23,281	
	North Ishinomaki																																								
	South Ishinomaki	33,827					12,191			8,872	541	26166	12,721			33,865											4,561	7,319	251				85						13,201		
	South East Ishinomaki	26,575	33,827					45,652	1,549					11,521	407		7,929	61	181		102			10,950	9,436				33	109	1,566		45	61	1012	2,584					
	Taiwa Town																																								
	North West Sendai																																								
	North East Sendai																																								
	Central Sendai																																								
South East Sendai																																									
South Sendai																																									

33. Deterministic, Network 4, Scenario 2

Network 4 Scenario 2 Echelon 1					Network 4 Scenario 2 Echelon 2																
	Fukushima	Yamagata	Akita	Iwate		Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai					
Hokkaido				87,436																	
Tochigi	131,710																				
Tokyo	121,174					Fukushima		92,800	153,600	153,600											
Toyama	29,698			81,149		Yamagata															
Aichi	91,208					Akita															
KINKI	26,210					Iwate		107,785	60,800												
CHUGOKU																					
SHIKOKU																					
KYUSHU-OKINAWA																					

Network 4 Scenario 2 Echelon 3																						
	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town
Tome and Kurihara																						
Kesennuma								51,357						12,960	457		8,919					
North Ishinomaki	38,054	38,054	38,054	27,698														114	68		90	
South Ishinomaki				10,356	38,054	13,714			1,742	9,980		29,436	952		38,097					203	500	114
South East Ishinomaki						109,623					608		13,358									
Taiwa Town																		14	12,318	10,614		
North West Sendai																						
North East Sendai																						
Central Sendai																						
South East Sendai																						
South Sendai																						

34. Uncertainty, Network 4, Scenario 2

Network 4 Scenario 2 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi				
Tokyo	113,067			
Toyama				60,279
Aichi				91,208
KINKI				81,026
CHUGOKU				59,088
SHIKOKU	55,557			
KYUSHU-OKINAWA				20,963

Network 4 Scenario 2 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima	16,824			151,800							
Yamagata											
Akita											
Iwate	136,776	109,624	153,600								

Network 4 Scenario 2 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho			
Tome and Kurihara			38,055		38,055				1,743			29437					8,920																									
Kesennuma						109,624																																				
North Ishinomaki		38,055		38,055						9,981			14,311	12,961	458			115	69	204	501			91	15	12,319	10,615	5,131	603	282	37		1,762	96	50	69	1138	2,907	3,775			
South Ishinomaki	38,055						13,715	51,358		609						38,098												9,850														
South East Ishinomaki																																										
Taiwa Town																																										
North West Sendai																																										
North East Sendai																																										
Central Sendai																																										
South East Sendai																																										
South Sendai																																										

35. Deterministic, Network 4, Scenario 3

Network 4 Scenario 3 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi	131,710			
Tokyo	121,174			
Toyama				110,847
Aichi	91,208			
KINKI	55,908			25,118
CHUGOKU				
SHIKOKU				8,342
KYUSHU-OKINAWA				

Network 4 Scenario 3 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima			92,800	153,600	153,600						
Yamagata											
Akita											
Iwate	145,580	86,163									

Network 4 Scenario 3 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Waari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
Tome and Kurihara	42,282	42,282		27,818					1,935					14,400	507		9,909	126	75	555		99								39	135	1,956	105	54	75		3,228		
Kesennuma								57,063																															29,100
North Ishinomaki		42,282	14,464	28,779																						5,700		312								1263			
South Ishinomaki				13,503		15,237			11,088	32,706	15,900				42,330			225	126				10,872			11,613													
South East Ishinomaki					121,803					675													15	2,814	11,793													16,500	
Taiwa Town																																							
North West Sendai																																							
North East Sendai																																							
Central Sendai																																							
South East Sendai																																							
South Sendai																																							

36. Uncertainty, Network 4, Scenario 3

Network 4 Scenario 3 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi				131,710
Tokyo				121,174
Toyama				
Aichi	91,208			
KINKI	81,026			
CHUGOKU				59,088
SHIKOKU	55,557			
KYUSHU-OKINAWA	3,991			592

Network 4 Scenario 3 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima	17,241	60,941		153,600							
Yamagata											
Akita											
Iwate	136,359		130,423		133,218						

Network 4 Scenario 3 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watai-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
Tome and Kurihara			38,797											14,401	42,331				76	226							11,614		40	1,957	106					1264			29,101
Kesennuma	42,283					15,238																								136				55			3,229		
North Ishinomaki	42,283	3,486				57,064			11,089																														16,501
South Ishinomaki				42,283		48,880			1,936		676	32,707	15,901		508		9,910			556	127	100	16																
South East Ishinomaki			42,283			72,924												127								11,794	5,701		313						76				
Taiwa Town																																							
North West Sendai																																							
North East Sendai																																							
Central Sendai																																							
South East Sendai																																							
South Sendai																																							

37. Deterministic, Network 4, Scenario 4

Network 4 Scenario 4 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi	131,710			
Tokyo	121,174			
Toyama				110,847
Aichi	91,208			
KINKI	55,908			25,118
CHUGOKU				15,976
SHIKOKU				55,557
KYUSHU-OKINAWA				

Network 4 Scenario 4 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima			92,800	153,600	153,600						
Yamagata											
Akita											
Iwate	153,600	94,780	46,554								

Network 4 Scenario 4 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
Tome and Kurihara	46,511	46,511		24,055					2,129					15,840	558		10,900	139	83	611	109									43	149	2,152	116	60	83		3,551			32,010
Kesennuma								62,770																																
North Ishinomaki		46,511	22,456	46,511		15,872																				6,270	344								1,390					
South Ishinomaki						889			12,197	743	35,977	17,490			46,563			248	139	17	15,055	11,507		12,775																
South East Ishinomaki						133,984																			1,466														18,150	
Taiwa Town																																								
North West Sendai																																								
North East Sendai																																								
Central Sendai																																								
South East Sendai																																								
South Sendai																																								

38. Uncertainty, Network 4, Scenario 4

Network 4 Scenario 4 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi				131,710
Tokyo	57,138			
Toyama	110,847			
Aichi	91,208			
KINKI				81,026
CHUGOKU				59,088
SHIKOKU	55,557			
KYUSHU-OKINAWA				20,963

Network 4 Scenario 4 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima	7,550	153,600		153,600							
Yamagata											
Akita											
Iwate	146,050		80,573		153,600						

Network 4 Scenario 4 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
Tome and Kurihara	46,512		20,858	46,512					2,130					15,841																44								3,552	18,151
Kesennuma		18,530				133,985												140	84	249	612																		
North Ishinomaki			25,654		16,830	16,762																			15,056	6,271													
South Ishinomaki		27,982						62,771							559	46,564	10,901					140	18				3,012							117	61	84	1391		
South East Ishinomaki					29,682					12,198	744	35978	17,491									110			12,974	9,764	345	150	2,153										32,011
Taiwa Town																																							
North West Sendai																																							
North East Sendai																																							
Central Sendai																																							
South East Sendai																																							
South Sendai																																							

39. Deterministic, Network 4, Scenario 5

Network 4 Scenario 5 Echelon 1	Fukushima	Yamagata	Akita	Iwate																																			
	Hokkaido				87,436																																		
	Tochigi				131,710																																		
	Tokyo				121,174																																		
	Toyama				110,847																																		
	Aichi				91,208																																		
	KINKI				55,908																																		
	CHUGOKU				59,088																																		
	SHIKOKU				55,557																																		
	KYUSHU-OKINAWA				20,058																																		
Network 4 Scenario 5 Echelon 2					Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai																								
	Fukushima					92,800	153,600	153,600																															
	Yamagata																																						
	Akita																																						
	Iwate				153,600	143,704	60,800																																
Network 4 Scenario 5 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Manumori town	Waari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
	50,739	50,739		29,561					2,322						609		11,891	152	90	666	119								47	162	2,348	126	65	90			3,874		
	Kesennuma					1,712	68,476						17,280																										
	North Ishinomaki				50,739	21,178	50,739	18,285				5444																											
	South Ishinomaki								13,306	810	33804	19,080		50,796			270	152	18	16,424	5,004		13,936																
	South East Ishinomaki						144,452																																
	Taiwa Town																																						
	North West Sendai																																						
	North East Sendai																																						
	Central Sendai																																						
South East Sendai																																							
South Sendai																																							

40. Uncertainty, Network 4, Scenario 5

Network 4 Scenario 5 Echelon 1	Fukushima	Yamagata	Akita	Iwate
	Hokkaido87,436			
	Tochigi131,710			
	Tokyo121,174			
	Toyama110,847			
	Aichi91,208			
	KINKI33,33747,689			
	CHUGOKU58,222			
	SHIKOKU55,557			
	KYUSHU-OKINAWA20,963			

Network 4 Scenario 5 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
	Fukushima153,600		96,703		149,697						
	Yamagata										
	Akita										
	Iwate	153,600		153,600	50,943						

Network 4 Scenario 5 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
	Tome and Kurihara131,212					14,953	17,653	19,081			50,797							376			2,349		66		19,801														
	Kesennuma50,740						633	39,249			11,892		153	271		6,841			376																				
	South Ishinomaki50,740	50,740	6,919						811	17,281		610			91	667	120	13,937			48	163	127	1517		3,875													
	South East Ishinomaki68,477					2,323	13,307											16,425		14,153						91		34,921											
	Taiwa Town																																						
	North West Sendai																																						
	North East Sendai																																						
	Central Sendai																																						
	South East Sendai																																						

41. Deterministic, Network 5, Scenario 1

Network 5 Scenario 1 Echelon 1	Fukushima	Yamagata	Akita	Iwate	Network 5 Scenario 1 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai																									
Hokkaido				87,436	Fukushima			92,800	153,600	153,600																															
Tochigi	131,710				Yamagata																																				
Tokyo	121,174				Akita																																				
Toyama	92,877			17,970	Iwate		80,857	24,549																																	
Aichi	54,239																																								
KINKI																																									
CHUGOKU																																									
SHIKOKU																																									
KYUSHU-OKINAWA																																									
Network 5 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara																																									
Kesennuma								45,651						11,520	406			7,928	60		80				4,560	250	32	108	1,565	84	44	60	1011	2,583						23,280	
North Ishinomaki	33,826	33,826	31,332																																						
South Ishinomaki		2,494	33,826	33,826		12,190			1,399	26165						33,864	101		444							9,291															
South East Ishinomaki						97,443			1,548	7,472	540		12,720					180	101	12	10,949	9,435																		13,200	
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

42. Uncertainty, Network 5, Scenario 1

Network 5 Scenario 1 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi				131,710
Tokyo	14,375			
Toyama				110,847
Aichi				
KINKI	81,026			
CHUGOKU	59,088			
SHIKOKU				
KYUSHU-OKINAWA				20,963

Network 5 Scenario 1 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima	889				153,600						
Yamagata											
Akita											
Iwate	139,701	57,655		153,600							

Network 5 Scenario 1 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Manumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara	7,252				33,827	97,444																	81	13				1,973													
Kesennuma			33,827															102		445																				23,281	
North Ishinomaki																																									
South Ishinomaki	33,827						12,191			8,872	541	26166	12,721			33,865										4,561	7,319	251					85						13,201		
South East Ishinomaki	26,575	33,827						45,652	1,549					11,521	407		7,929	61	181	102			10,950	9,436					33	109	1,566		45	61	1012	2,584					
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

43. Deterministic, Network 5, Scenario 2

Network 5 Scenario 2 Echelon 1	Fukushima	Yamagata	Akita	Iwate	Network 5 Scenario 2 Echelon 2														
					Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai				
	Hokkaido			87,436	Fukushima		92,800	153,600	153,600										
	Tochigi	131,710			Yamagata														
	Tokyo	121,174			Akita														
	Toyama	29,698		81,149	Iwate	107,785	60,800												
	Aichi	91,208																	
	KINKI	26,210																	
	CHUGOKU																		
	SHIKOKU																		
KYUSHU-OKINAWA																			

Network 5 Scenario 2 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho			
	Tome and Kurihara																																									
	Kesennuma																																									
	North Ishinomaki																																									
	South Ishinomaki																																									
	South East Ishinomaki																																									
	Taiwa Town																																									
	North West Sendai																																									
	North East Sendai																																									
	Central Sendai																																									
South East Sendai																																										
South Sendai																																										

44. Uncertainty, Network 5, Scenario 2

Network 5 Scenario 2 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi				
Tokyo	113,067			
Toyama				60,279
Aichi				91,208
KINKI				81,026
CHUGOKU				59,088
SHIKOKU	55,557			
KYUSHU-OKINAWA				20,963

Network 5 Scenario 2 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima	16,824			151,800							
Yamagata											
Akita											
Iwate	136,776	109,624	153,600								

Network 5 Scenario 2 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara			38,055		38,055				1,743			29437					8,920														123								11,076	26,191	
Kesennuma						109,624																																			
North Ishinomaki		38,055		38,055						9,981			14,311	12,961	458			115	69	204	501			91	15	12,319	10,615	5,131		603	282	37		1,762	96	50	69	1138	2,907	3,775	
South Ishinomaki	38,055						13,715	51,358			609					38,098						115							9,850												
South East Ishinomaki																																									
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

45. Deterministic, Network 5, Scenario 3

Network 5 Scenario 3 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi	131,710			
Tokyo	121,174			
Toyama				110,847
Aichi	91,208			
KINKI	55,908			25,118
CHUGOKU				
SHIKOKU				8,342
KYUSHU-OKINAWA				

Network 5 Scenario 3 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima			92,800	153,600	153,600						
Yamagata											
Akita											
Iwate	145,580	86,163									

Network 5 Scenario 3 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Wanai-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho		
Tome and Kurihara	42,282	42,282		27,818					1,935					14,400	507		9,909	126	75	555				99																	
Kesennuma								57,063																																29,100	
North Ishinomaki		42,282	14,464	28,779																						5,700		312									1263				
South Ishinomaki					13,503		15,237			11,088		32706	15,900			42,330			225	126		10,872				11,613															
South East Ishinomaki						121,803					675												15	2,814	11,793														16,500		
Taiwa Town																																									
North West Sendai																																									
North East Sendai																																									
Central Sendai																																									
South East Sendai																																									
South Sendai																																									

46. Uncertainty, Network 5, Scenario 3

Network 5 Scenario 3 Echelon 1				Network 5 Scenario 3 Echelon 2														
	Fukushima	Yamagata	Akita	Iwate	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai			
Hokkaido				87,436														
Tochigi				131,710														
Tokyo				121,174														
Toyama	64,646																	
Aichi	91,208																	
KINKI																		
CHUGOKU	59,088																	
SHIKOKU	55,557																	
KYUSHU-OKINAWA				20,963														

Network 5 Scenario 3 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
Tome and Kurihara				42,283		103,680			1,936																		5,701													
Kesennuma										11,089			15,901		508																									
North Ishinomaki	42,283		42,283		36,327							32,707																												
South Ishinomaki														10,258		42,331	9,910	127	76	226	556	127	100	16	13,687	11,794		11,614	313	40	136	1,957	106	55	76	1264	3,229	16,501	29,101	
South East Ishinomaki		42,283			5,956	18,124	15,238	57,064			676			4,143																										
Taiwa Town																																								
North West Sendai																																								
North East Sendai																																								
Central Sendai																																								
South East Sendai																																								
South Sendai																																								

47. Deterministic, Network 5, Scenario 4

Network 5 Scenario 4 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi	131,710			
Tokyo	121,174			
Toyama				110,847
Aichi	91,208			
KINKI	55,908			25,118
CHUGOKU				15,976
SHIKOKU				55,557
KYUSHU-OKINAWA				

Network 5 Scenario 4 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima			92,800	153,600	153,600						
Yamagata											
Akita											
Iwate	153,600	94,780	46,554								

Network 5 Scenario 4 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Manumori town	Wajari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
Tome and Kurihara	46,511	46,511		24,055					2,129					15,840	558		10,900	139	83	611		109								43	149	2,152	116	60	83		3,551		
Kesennuma								62,770																															32,010
North Ishinomaki		46,511	22,456	46,511			15,872																			6,270		344								1390			
South Ishinomaki							889			12,197	743	35977	17,490			46,563			248	139		17	15,055	11,507		12,775													
South East Ishinomaki							133,984																		1,466														18,150
Taiwa Town																																							
North West Sendai																																							
North East Sendai																																							
Central Sendai																																							
South East Sendai																																							
South Sendai																																							

48. Uncertainty, Network 5, Scenario 4

Network 5 Scenario 4 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi				131,710
Tokyo	57,138			
Toyama	110,847			
Aichi	91,208			
KINKI				81,026
CHUGOKU				59,088
SHIKOKU	55,557			
KYUSHU-OKINAWA				20,963

Network 5 Scenario 4 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima	7,550	153,600		153,600							
Yamagata											
Akita											
Iwate	146,050		80,573		153,600						

Network 5 Scenario 4 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho
Tome and Kurihara	46,512		20,858	46,512					2,130					15,841																44							3,552	18,151	
Kesennuma		18,530				133,985												140	84	249	612																		
North Ishinomaki			25,654		16,830		16,762																		15,056	6,271													
South Ishinomaki		27,982						62,771								559	46,564	10,901				140	18					3,012					117	61	84	1391			
South East Ishinomaki					29,682					12,198	744	35978	17,491							110				12,974	9,764	345	150	2,153										32,011	
Taiwa Town																																							
North West Sendai																																							
North East Sendai																																							
Central Sendai																																							
South East Sendai																																							
South Sendai																																							

49. Deterministic, Network 5, Scenario 5

Network 5 Scenario 5 Echelon 1	Fukushima	Yamagata	Akita	Iwate
	Hokkaido87,436			
	Tochigi131,710			
	Tokyo121,174			
	Toyama110,847			
	Aichi91,208			
	KINKI55,90825,118			
	CHUGOKU59,088			
	SHIKOKU55,557			
	KYUSHU-OKINAWA20,058			

Network 5 Scenario 5 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
	Fukushima92,800153,600153,600										
	Yamagata										
	Akita										
	Iwate153,600143,70460,800										

Network 5 Scenario 5 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho			
	50,739	50,739		29,561					2,322						609		11,891	152	90	666	119								47	162	2,348	126	65	90		3,874						
	Kesennuma				1,712		68,476						17,280																						1516		19,800		34,920			
	North Ishinomaki		50,73921,178		50,739		18,285						5444														6,840		375													
	South Ishinomaki										13,306810		3380419,080		50,796				270		152		18		16,4245,004		13,936															
	South East Ishinomaki						144,452																				9,148															
	Taiwa Town																																									
	North West Sendai																																									
	North East Sendai																																									
	Central Sendai																																									
South East Sendai																																										
South Sendai																																										

50. Uncertainty, Network 5, Scenario 5

Network 5 Scenario 5 Echelon 1	Fukushima	Yamagata	Akita	Iwate
Hokkaido				87,436
Tochigi	131,710			
Tokyo	121,174			
Toyama				110,847
Aichi				91,208
KINKI	33,337			
CHUGOKU	58,222			
SHIKOKU	55,557			
KYUSHU-OKINAWA				20,963

Network 5 Scenario 5 Echelon 2	Tome and Kurihara	Kesennuma	North Ishinomaki	South Ishinomaki	South East Ishinomaki	Taiwa Town	North West Sendai	North East Sendai	Central Sendai	South East Sendai	South Sendai
Fukushima		153,600		96,703	149,697						
Yamagata											
Akita											
Iwate	153,600		153,600	50,943							

Network 5 Scenario 5 Echelon 3	Aoba-ku Sendai	Izumi-ku Sendai	Miyagino-ku Sendai	Taihaku-ku Sendai	Wakabayashi-ku Sendai	Ishinomaki	Shiogama	Kesennuma	Shiroishi	Natori	Kakuda	Tagajo	Iwanuma	Tome	Kurihara	Higashimatsushima	Osaki	Zao-machi	Shichikashuku town	Ogawara-machi	Murata town	Shibata town	Kawasaki	Marumori town	Watari-cho	Yamamoto-cho	Matsushima-machi	Shichigahama town	Rifu town	Taiwa-cho	Osato town	Tomiya	Ohira village	Shikama town	Kami-machi	Wakuya town	Misato	Onagawa-cho	Minamisanriku-cho	
Tome and Kurihara						131,212																																		
Kesennuma	50,740					14,953	17,653						19,081			50,797																								
North Ishinomaki				43,821	50,740		633					39,249					11,892	153	271								6,841		376											
South Ishinomaki		50,740	50,740	6,919							811			17,281	610			91	667	120								13,937	48	163		127			1517	3,875				
South East Ishinomaki								68,477	2,323	13,307															16,425	14,153									91				34,921	
Taiwa Town																																								
North West Sendai																																								
North East Sendai																																								
Central Sendai																																								
South East Sendai																																								
South Sendai																																								