A SIMULATION-BASED DATA-DRIVEN ANALYSIS FOR IMPROVING COLLABORATION BETWEEN FOOD BANK FACILITIES BEFORE AND AFTER NATURAL DISASTERS

by

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DEDICATION

To my family, friends, and teachers for their unconditional love, support, patience, and encouragement.

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ABSTRACT

Food banks are non-profit organizations that gather and distribute supplies to agencies serving people in need. Food banks obtain donations (i.e., supplies) from the public and public and private organizations. Catastrophic events like hurricane Harvey leads the way to complexities for serving people in need. Food banks act as food storage and distribution depots for smaller front-line agencies and usually do not give out food directly to people struggling with hunger. The demand for supplies needed by supporting agencies is very dynamic and challenging to predict. The demand for supplies required to collaborating agencies is very dynamic, especially after natural disasters when food banks become significant players in disaster relief efforts. Therefore, planning for the operation of food banks under both normal and disaster relief conditions is a challenging problem. This research aims to develop data-driven models for improving the operation of a network of food bank facilities in charge of providing relief after natural disasters. This research provides a methodology for achieving the defined objective by developing simulation and optimization models for decision-making purposes.

The first part of this thesis is to develop a discrete-event simulation model of a network of food banks to investigate the impact of multiple disaster relief operational policies (i.e., supply prepositioning, distribution center assignment). The model simulates the flow of donations at three food bank facilities and the demand for supplies of 55 demand locations before and after a natural disaster. The simulation model is validated with the real-time data collected at the food bank facility. Discrete-event simulation

model experiments are conducted from the results of the stochastic model developed in the second part of the thesis. The value of the simulation model is demonstrated through the analysis of 21 scenarios, five optimization-based demand distribution policies, and six performance measures: unmet demand, total demand met, daily number of trips, delivery cycle time, demand fulfilment rate and the order fulfilment rate. The results of the simulation model show that there is a 20% increase in the overall demand fulfillment rate if food banks operate as an integrated network with supply prepositioning and demand splitting between operating facilities.

The second part of this thesis is to develop optimization-based decision-making policies for pre-positioning disaster relief supplies considering the transportation limitations of network food bank facilities and the uncertainty in demand. The stochastic programming model determines the best distribution decisions considering supply chain disruptions after hurricane events. The first stage models the pre-positioning of supplies between food banks, while the second stage provides recursive actions for supplies pre-positioning and models supplies distribution to the demand nodes under different scenarios. The developed stochastic model will identify the least-cost strategy associated with pre-positioning existing supplies that will satisfy the demand needs after a natural disaster by considering various parameters like storage cost, transportation cost, truck availability, and docks availability.

1. INTRODUCTION

Catastrophic natural hazards have been on the rise over the past few years causing tremendous loss of life and property [1]. Regarding tropical storms and hurricanes, Houston has become one of the most vulnerable urban areas in the world because of its proximity to the Gulf of Mexico. Even before hurricane Harvey, tropical storm Allison (2001), hurricanes Rita (2005), Katrina (2005), and Ike (2008) all caused widespread flooding. Hurricane Harvey struck Texas on August 25, 2017, and resulted in catastrophic flooding caused by record rainfall that severely affected all counties of Houston [2]. Most flooding receded within a week, but some areas remained flooded for several weeks [3]. More than 156,000 homes were destroyed and at least 70 people died [4, 5]. According to estimates hurricane Harvey caused residential structural damages equal to $77.2 million and residential contents damages equal to $36.9 million in Houston [6]. In the immediate aftermath, about 246,000 where in need of emergency relief supplies and community organizations such as food banks where in charge of mobilizing resources to the affected areas.

Food banks are non-profit organizations that collect and distribute supplies to people in need. Food banks obtain donations (i.e., supplies) from the public, and from public and private organizations. Food banks act as food storage and distribution depots for smaller front-line agencies; and usually do not themselves give out food directly to people struggling with hunger. The demand of supplies needed by supporting agencies is very dynamic and difficult to predict. A variety of factors impact how food banks work, from the size of the facility to the number of staff members. But one thing all food banks have in common is that they rely on donors and volunteers to carry out their day-to-day operations. After natural disasters food banks become major disaster relief hubs. Disaster responses involve planning, coordination, and distribution among a network supplier and distribution centers. Proper planning can lead to serve more people in need. Planning for disaster relief is challenging due to the uncertainty in terms of donation of supplies, the demand from agencies, and the availability of distribution centers. These challenges create a difficult environment to evaluate best operational practices to better meet the demand for supplies. Thus, data-driven models of a network of food banks have been developed to capture some of the most important dynamics and complexities of food bank operations for a region impacted by a natural disaster.

The goal of this thesis is to develop data-driven models for improving the operations of a network of food bank facilities in charge of providing relief after natural disasters. This thesis provides a methodology for achieving the defined goal by developing simulation and optimization models for decision making purposes. This research addresses two specific aims towards achieving the defined goal.

The first objective of this thesis is to develop a discrete-event simulation model to represent the operations and improve the collaboration of a network of food bank facilities located in an area prone to natural disasters. Data from three hunger relief organizations (i.e., food banks) will be used to build the discrete-event simulation model they will represent the dynamic nature of demand and arrivals of donations before and after the hurricanes. The food bank distribution problem is interesting and challenging due to the stochastic nature of the donation arrivals and the uncertainty in terms of the availability of the distribution centers after natural disasters. In this thesis, three food bank facilities are considered: Central Texas food bank (CTFB), the San Antonio food bank (SAFB) and the Houston food bank (HFB). These three facilities serve neighbor areas in central Texas, and all which were affected by Hurricane Harvey. Several published studies examine the challenges faced by food bank facilities and their unpredictable supply [7]. A detailed computational study will be performed to assess performance of different resource allocation policies and their impact in improving the operation of food bank facilities. However, to the best of the authors knowledge, computational studies were performed to assess the food bank operations and their impact when there is demand uncertainty due to natural disasters has not been addressed in literature. The resulting models will enable future research studies to compare different distribution policies based on different performance measures and scenarios. In addition, it will allow for the planning of the allocation of resources at the different facilities based on the risk of being impacted by a natural phenomenon.

The second objective of the thesis is to develop optimization-based decision-making policies for pre-positioning disaster relief supplies considering the transportation limitations of network food bank facilities. The optimization models consider the capacity of the food banks for storage capacity, demand constraints, prepositional capacities, and transportation limitations of the food bank facilities. A stochastic programming model is developed to determine the best distribution decisions during supply chain disruptions after hurricane events. Pre-positioning is an activity performed before the predicted natural disaster event, in which locations are selected to store human or material assets in preparation for disaster relief. The idea is to prepare the supply chain for quick distribution to satisfy the demand post-event. The optimization model developed will identify the least-cost strategy associated with pre-positioning existing supplies that will help the demand needs after a natural disaster by considering different parameters like storage cost, transportation cost, truck availability, and docks availability. The policies developed from the optimization model used to assess the simulation model developed in the first aim.

Current thesis research addresses that the efficiency of food bank operations increase, and food banks will serve more people in need if they partner with nearby facilities to meet the demand requirement of distribution centers before the arrival of natural calamities. Early planning of collaboration with nearby facilities for fulfilling the demand requirement of distribution centers helps the food bank facilities to respond quickly if there is a situation of closing one or more food banks due to natural disasters. To the best of our knowledge, the application of discrete-event simulation combined with optimization models to study and plan food bank facilities' disaster relief operations is new. Existing simulation models in [8] focus on specific problems happening inside the food bank facility without taking into consideration the uncertainty in the supply chain elements in terms of donations received and distribution to demand points. The outcome of this thesis study helps food bank facilities to improve their operational efficiencies in regular and disaster relief scenarios. The study of regular and disaster relief operations of food bank facilities is important as this can help the facilities to plan their operations and serve more population in need.

1.1. Thesis outline

This thesis is structured as follows. Chapter 2 discusses literature strongly related to this topic. The literature review in this thesis is provided in three parts. The first part includes information about the papers related to the simulation methodology; the second part is about applying simulation modeling, and the third is literature on prepositioning policies of the food bank operations. Chapter 3 describes the food bank operations setting, abstraction of the food bank operations as a simulation model, and model's input parameters, including the verification and validation of the simulation model. Chapter 4 discusses the stochastic programming model used to assist in the decision-making process planning and operation of food bank facilities, experimental design, computational results of the stochastic models, and simulation models. Chapter 5 provides a conclusion from the findings in the planning of food bank operations for regular and disaster relief operations and discusses future research directions.

2. LITERATURE REVIEW

The literature review in this thesis is detailed in three parts. Section 2.1 reviews the literature corresponding to the papers related to the methodology of simulation. Section 2.2 discusses the literature about applying simulation modeling to understand the behavior of food bank operations before and after natural disasters. Section 2.3 focuses on the literature review related to the prepositioning policies of the food bank operations during hurricanes.

2.1. Simulation methodology

Simulation modeling is a methodology that models the operation of a system as a sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system. Simulation modeling has been applied to multiple settings including manufacturing [9, 10], healthcare [11-17], and renewable energy[18-21]. McGinnis, et al. [22] described an approach of simulation modelling that exploits recent developments in systems engineering and software engineering to improve discrete-event simulation modelling. Authors in [22] used Sims (Systems modelling language) diagrams like state machine diagrams, sequence diagrams for modelling to be more effective and domain specific. Models in [22] help to simulate the strategic decisions for the business makers with less cost and can help to understand the model transformation from the existing to the new designed system. Authors in [22] have focused with some practical approach for modelling the discrete-event simulation but there is a limit in modelling the transformation of the process. The problem of finding the best decision with less cost is resolved by the simulation tool designed in [22].

Yavari and Roeder [23] discussed about the enrichment levels for simulation models which are quantitative measures for comparing the effectiveness of the alternate models. Captured different factors like bias, speed, variance, and scope for elaborating the enrichment level but still extensive clarifications are needed for estimating the defined factors. Authors in [23] discussed the importance of each factor for a decision maker to finalize the project requirements, limitations and for comparing different alternatives of the project. Models in [23] help to define proper metrics or methodology for ranking different simulation models of the same system.

Barra Montevechi, et al. [24] presented on how to proceed with systematic approach for discrete-event simulation (DES), activity-based simulation (ABC), Design of experiments (DOE), and Net present value (NPV) techniques in the simulation. All these methodologies were integrated to a single methodology for identification of cost-effective process in the manufacturing process which can help for taking strategic decisions that results in the operational performance of the process. Authors in [24] provided the detailed approach of integrating four methodologies in a flow chart and considered the integration of all four approaches DES, DOE, ABC and NPV is indeed important for improved decision making.

2.2. Simulation modeling in disaster-relief scenarios

Peng, et al. [25] introduced dynamic environmental factors into the disaster-relief supply chain to characterize the dynamic relations and provide support to further decision-making in relief operations. A system dynamic model was presented to describe the processes of delivering emergency supply. The research in post-seismic rapid damage assessment of road networks and injured were addressed and the impacts of dynamic road condition and delay in information transfer were simulated and analyzed. Simulation results indicated that the road condition influences the system performance significantly;

the transport time of relief supplies (i.e., transport delay) is a function of the road capacity and the in-transit volume, so the mechanism of considering the feedbacks of these two factors is important to maintain the stability of the relief system. The simulation models developed in paper [25] are the inventory planning strategies which can help in dealing with the information delay effectively.

Zhang, et al. [26] developed an agent-based discrete-event simulation (AB-DES) modelling framework for transportation evacuation by integrating an event scheduling scheme into an agent-based method. To study an evacuation process and to understand its intrinsic phenomena, authors in [26] need to model the behavior of evacuees including their decision making, cognitive capabilities, and complex interactions among evacuees and emergency agencies. Authors in [26] integrated the agent-based simulation and discrete-event simulation approaches using a hybrid simulation space to capture the traffic behaviors and interactions between traveler agents for evacuation process.

Ribino, et al. [27] performed an agent-based simulation to analyze the behavior of automatic logistic warehouses under the influence of specific factors, thereby obtaining indicators to support decision making during warehouse performance improvement. This study focused mainly on automatic warehouses where goods are moved by automatic guided vehicles (AGV). Authors in paper [27] considered logistic warehouses as critical nodes in supply chain. Improving the performance of warehouse basically involves increasing the amount of goods forwarded toward a new destination. This mainly depends on the efficiency of an AGV, which can be influenced by several factors, such as the warehouse's physical configuration and management strategies. The main objective study conducted by authors in [27] was to investigate the behavior of automatic logistic warehouses under the influence of specific factors (i.e., layout configurations, AGV fleet size, and management strategies) to obtain indicators that might support decision making during warehouse performance improvement. Authors in paper [27] proposed the warehouse model simulation combining three different perspectives environmental model, organizational model, and behavioral model.

The study presented in this thesis complements the work of [25], [26] and [27]. Authors in [25] and [26] discussed on the factors effecting the disaster relief operations and process of evacuation respectively. Authors in [27] focused on simulation of warehouse operations for improving the performance. But the simulation models presented in current thesis incorporates the uncertainty associated with the impact of the hurricane at a network of food banks in terms of the number of resources available at the food bank. Donations are categorized as regular donations and disaster-relief donations to understand their impact in the recommended decisions. The simulation models developed in this thesis provides further insights to the improve the distribution center assignments after hurricanes.

2.3. Pre-positioning models of disaster-relief operations

Optimization models are commonly use for the decision making related to resources allocation in multiple settings [28-30]. Johnstone, et al. [31] demonstrated that resource pre-positioning is not a new concept and has been applied in the military for quite some time. Proper prepositioning strategies provide a means to deploy forces rapidly without resorting to an increased overseas presence. The research presented in [31] focuses on defining and developing a mathematical model to aid decision makers with a strategy for positioning and configuring prepositioned assets. Prepositioning is the "stockpiling of equipment and supplies at, or near the point of planned use (or point of debarkation)"[32].

Sheu [33] explained how humanitarian logistics research can be classified based on the nature and timing of the decisions to be made which means preparedness vs. post-event relief. Authors in [33] presented a hybrid fuzzy clustering-optimization approach to the operation of emergency logistics co-distribution responding to the urgent relief demands in the crucial rescue period. Based on a proposed three-layer emergency logistics co-distribution conceptual framework, the proposed methodology of authors in [33] involves two recursive mechanisms: (1) disaster-affected area grouping, and (2) relief co-distribution.

Jia, et al. [34] first survey general facility location problems and identify models used to address common emergency situations, such as house fires and regular health care needs. Authors in [34] then analyze the characteristics of large-scale emergencies and propose a general facility location model that is suited for large-scale emergencies. The second goal presented in paper [34] is to analyze the characteristics of largescale emergencies and propose tailored location models that take into account the unique characteristics of these emergencies. The authors in [34] classify large-scale emergencies as those that have a sizeable and sudden volume of demand and low frequency of occurrence. The Authors in [34] presented two parameters to describe uncertainty and suggested location models to (1) maximize the demand covered a group of facilities, (2) minimize the demand weighted distance between the new facilities and the demand points, and (3) minimize the maximum service distance.

Marthak [35] discussed a stochastic model that considered the uncertainty associated with the impact of the hurricane at each facility in terms of the number of available supplies, donations received at the facility, and the expected demand for their service region. But in current thesis the impact of hurricane is considered by including transportation limitations like transportation cost, truck availability and docks availability.

3. MODELING AND SIMULATION OF FOOD BANK OPERATIONS

3.1 Description of the food bank network and operations

Figure 1 depicts the overview of food bank network operations. Food banks receive donations (i.e., supplies) from retailers, individuals, and from public and private organizations. Once donations are received by the food bank, the supplies are sorted, inspected according to quality standards, scanned to update the product in the Enterprise Resource Planning (ERP) system and are then re-packed for storing in the food bank warehouse. Food banks schedule order pick-ups and/or deliveries to distribution centers (i.e., schools, food pantries or individuals). Deliveries are performed using food bank trucks.

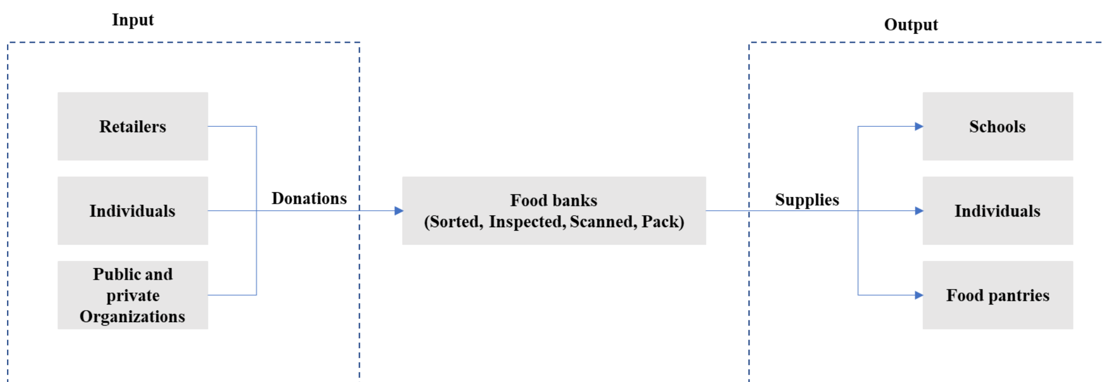


Figure 1: Overview of food bank network operations

Even though most food banks are part of the Feeding America network [36], each facility typically operates as independent supplier which takes care of agencies located within a certain distance radius. In general, collaboration between food banks is very limited. Natural hazards, like hurricane Harvey in 2017, showed that better planning and collaboration are needed between food bank facilities. The demand for relief supplies increases after a natural disaster and a single facility might be unable to cover such demand. In addition, natural hazards could damage roads and buildings which can limit the operation capacity of food banks located close to area impacted by the natural phenomenon.

In this thesis study, the operation of three Texas food bank facilities is studied. The group of facilities includes the Central Texas food bank (CTFB) in Austin, the San Antonio food bank (SAFB) and the Houston food bank (HFB). As shown in Figure 2, these three facilities serve neighbor areas in central Texas, and all were impacted at some degree by hurricane Harvey. HFB, CTFB, and SAFB experienced higher than normal demands after hurricane Harvey. CTFB and SAFB distributed supplies in the Houston area after hurricane Harvey. However, since no plans were developed for collaboration between facilities, the distribution of supplies was inefficient which impacted the number of people that was served. The simulation model presented in this thesis is developed with the goal of helping food bank facilities prepare better for disaster relief operations.

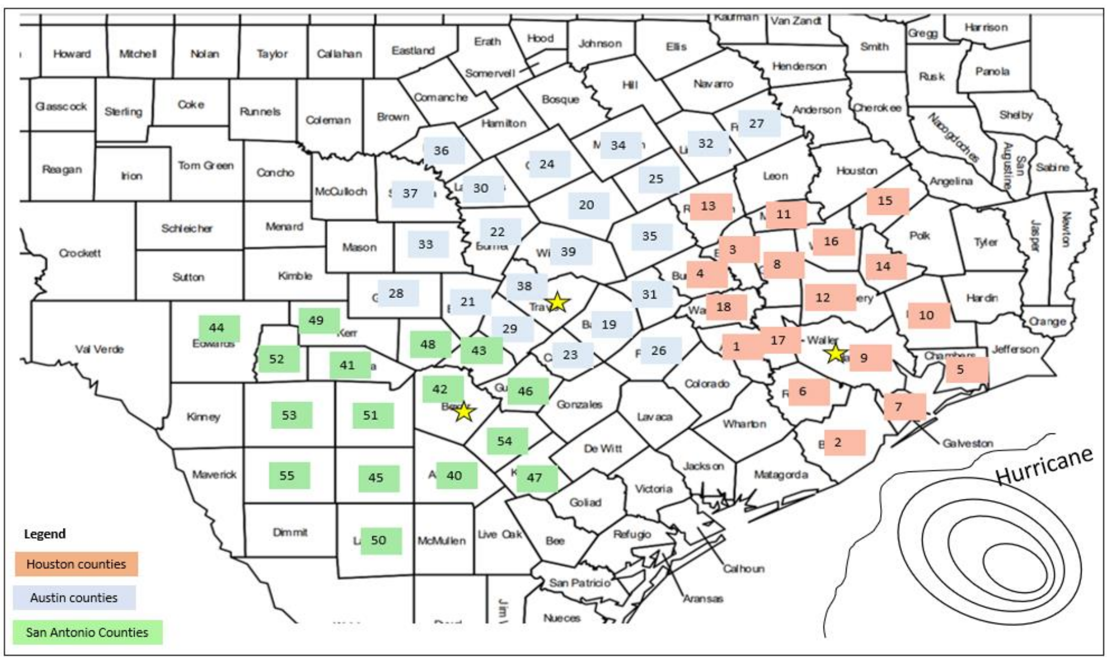


Figure 2: Counties map of Houston, Austin, and San Antonio food banks

3.2 Performance measures

The primary performance measures considered for each food bank facility in this study were: *unmet demand, total demand met, daily number of trips, delivery cycle time, demand fulfilment rate, and the order fulfilment rate*. The *unmet demand* is the number of supplies (in pallets) which the food bank is unable to supply to distribution center. The average weekly unmet demand per food bank is calculated at the end of every week. The *total demand met in pallets* is considered as total demand of the distribution center satisfied by the food bank facility at the end of simulation run. The *number of trips* considers one trip as complete only when truck delivers the supplies to the distribution center and return to the food bank post-delivery at distribution center. The daily average number of trips by trucks are calculated at the end of each day of simulation. The *delivery cycle time* is the time taken by the food bank to deliver the supplies to the distribution center once the order is requested. The *demand fulfilment rate* is the percentage of overall demand (in pallets) met by the food bank facilities at the end of simulation run. The *order fulfilment rate* is the percentage of orders completed by the food bank facilities at the end of simulation run.

3.3 Model abstraction

In this section, the abstraction of the discrete-event simulation model is presented. There are three major processes considered as part of the simulation: arrival of donations, warehouse operations, and distribution of supplies. The following subsections explain the abstraction for these three major processes.

3.3.1 Arrival of donations

Figure 3 explains the arrival process of donations. When the food banks receive these donations from trucks, the volunteers will check if the entry doors and forklifts are available for unloading the supplies. Entry doors is the place in loading and unloading area of the food bank where the donations arrive to the food bank. Forklifts are used for unloading or loading the supplies in the food bank. If the entry door is available, the supplies will be unloaded from the truck and transferred to food bank warehouse using a forklift. If the entry door is not available, then the volunteers must wait for the availability of the entry door by performing other tasks in the food bank. The number of entry doors and forklifts available in each food bank is provided in Table 1.

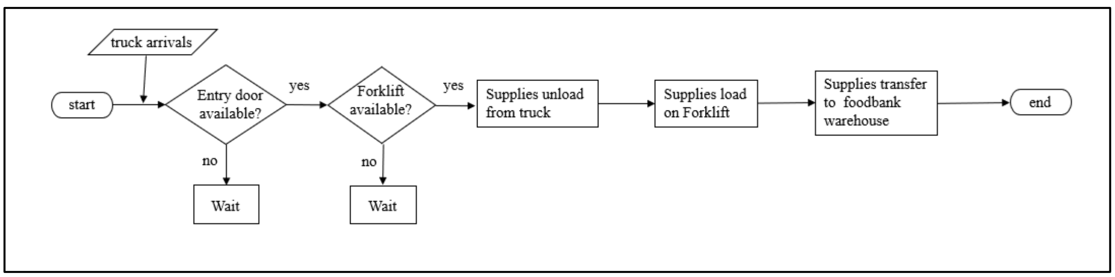


Figure 3: Flowchart of donation arrivals

3.3.2 Warehouse operations

Figure 4 shows the steps involved once the donations reach warehouse of the food bank. Once the supplies arrive the warehouse, they will be unloaded from the forklift, sorted, will be provided with a barcode, and then will be placed in the shelves of the warehouse. The barcoding helps to monitor the inventory level of the supplies in the warehouse. Once the food bank receives order request from distribution center, food bank operations manager will check the current inventory level of the food bank. If the demand can be met by the food bank, then the order will be processed, and supplies will be seized for delivery to the distribution center. If food bank is unable to meet the demand, then the order request is considered as cancelled.

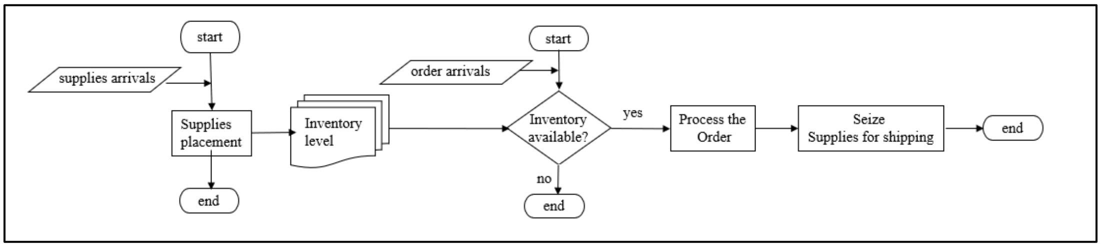


Figure 4: Flowchart of warehouse operations

3.3.3 Distribution of supplies

Figure 5 explains the process of supply distribution to the distribution center (i.e., agencies). Once the supplies are ready for the delivery, the volunteers will check for the availability of exit doors, forklifts, and trucks for loading the supplies into the truck to deliver at distribution center as per order request. Trucks are used for delivering the supplies to the distribution center from the food bank. If the exit doors, forklifts, and/or trucks are not available, then the volunteers must wait for the availability of these resources by performing other tasks in the food bank. Once all three resources (exit doors, forklifts, and trucks) are available the volunteers will load the supplies in the truck and will be shipped to the distribution center. This completes the order request process of the food bank. The availability of trucks in the food bank for shipping depends on the transportation time for delivering the supplies of previous orders. The number of exit doors, forklifts, and trucks available for each food bank is provided in Table 1.

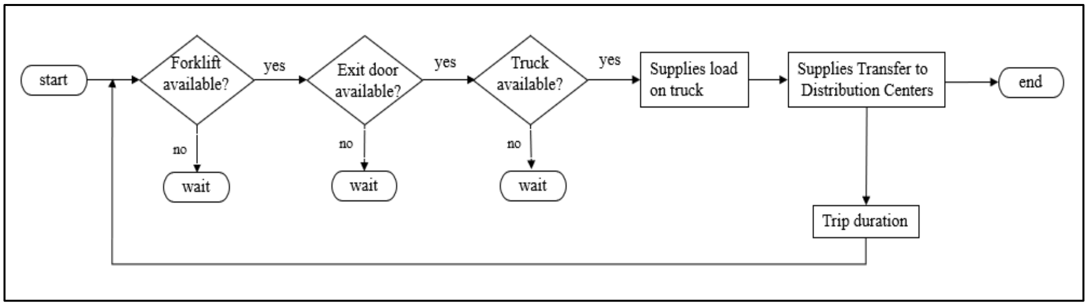


Figure 5: Flowchart of supplies distribution

3.4 Model design

The discrete-event simulation model was designed to simulate food bank operations. The purpose of the simulation model is to investigate the performance of multiple disaster relief operational policies (i.e., supply prepositioning, distribution center assignment). The simulation model was implemented in SIMIO software, Version 12.205.20430 (32 bit) (https://www.simio.com/). The implementation of the food bank simulation model is explained in two stages: 1) Donation generation and warehouse operations and 2) Warehouse operations and supplies distribution.

3.4.1 Donation generation and warehouse operations

In donation generation stage of the model, the arrival of donations is modelled using “source” block at time 0 for HFB, CTFB and SAFB. Entire donation generation process is depicted in figure 6. The donations generated through “source” block, pass through “seize” block for seizing the entry doors and forklifts of food bank as shown in figure 7. The donations are unloaded from the forklift and then transferred to the food bank warehouse area. The resources entry doors and forklifts will be released through “release” block once the transferring is complete as shown in figure 8. After release of food bank entry doors and forklifts, the inventory level of the food bank is stored in a variable using “assign” block. This variable helps to monitor the inventory levels of each food bank facility.

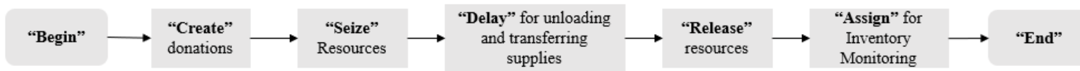


Figure 6: Donation generation and warehouse operations process overview

Figure 7: Resource seizing process

Figure 8: Resource releasing process

3.4.2 Warehouse Operations and supplies distribution

In demand generation stage of the model, the order requests from every distribution center of the food bank are modelled using "source" block at time 0 for HFB, CTFB and SAFB. Once the demand request is created in the "source" block, the quantity of demand orders is checked with the current inventory level variable at the food bank using "decide" block. In the "decide" block, the current inventory level is checked with logical function "*Demand requested <Current Inventory of food bank*". If this condition is *true*, then the food bank can process the order request and the inventory level of the food bank will be subtracted with the demand of the distribution center using an "assign" block. Post inventory update, the supplies will be transferred to the dock area of the food bank for shipping. If the condition "*Demand requested <Current inventory of food bank*" is *false*, then the unmet demand of each distribution center and the total unmet demand by the food bank is counted in a variable using "assign" block. The entire process of this step is shown in figure 9. It is assumed that the processing time of orders, once received at the food bank, follows Uniform distribution. The Uniform distribution has parameters

that specify the minimum and maximum values and is represented as $U(a, b)$; where a is maximum value and b is the minimum value. All values within this range have an equal probability of occurring.

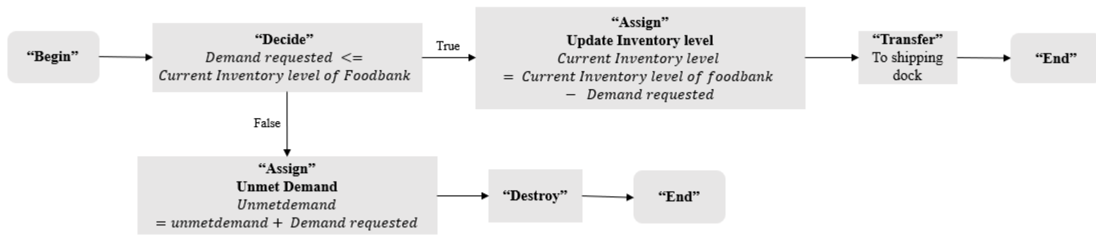


Figure 9: Order processing process

After transferring of supplies to the dock area, the supplies are shipped to the requested distribution center by using food bank delivery trucks. Entire transportation process is depicted in figure 10. Firstly, the resources food bank exit doors and forklifts are seized for transferring supplies to the unloading area and then trucks of food bank also seized using "seize" block for shipping supplies to the distribution center. After seizing all the three resources (exit doors, forklifts, and trucks) the supplies are unloaded from the forklift and loaded to the truck. The loading/unloading time of supplies are modeled using a "delay" block. After loading of supplies into the truck, resources forklifts and food bank exit doors are released using "release" block. Supplies are shipped to the distribution center within the transportation time mentioned in Table 2 for each food bank facility. Transportation time of supplies to each distribution center is modeled using a "delay" block. The resource truck is released using "release" block after unloading of supplies at the distribution center and returning to the food bank facility. This completes the process of fulfilling the demand request of distribution center by the food bank facility.

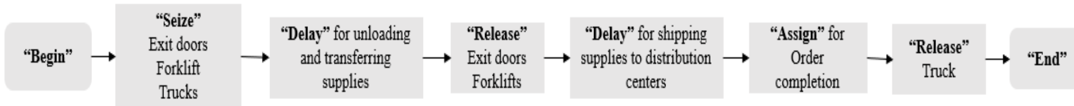


Figure 10: Process of shipping supplies to distribution center

3.5 Data

This section describes model input and parameter values. The parameters used in this research are obtained from 2-year historical data provided by all three food bank facilities for years 2016 and 2017. Food banks provided the data for donations, initial inventory of each food bank and demand requirement of distribution centers for both disaster relief and regular operations. There are total number of 55 counties in the scope of current research study of which counties labelled from 1 to 18 belong to HFB, counties from 19 to 39 belong to CTFB and from 40 to 55 belongs to SAFB.

3.5.1 Model parameters

The simulation model requires several input parameters that define the food bank capacities, including resource capacities and the regular food bank operating hours. Resource capacities of each food bank is labeled as M entry doors, N exit doors, O forklifts and T trucks. It is assumed that maximum load the truck can carry is 3 number of pallets and each pallet is weighed $\sim 4600\ lbs$ of supplies. Trucks are used to ship the supplies from food bank to the distribution center. Table 1 depicts the resources for HFB, CTFB and SAFB food bank facilities. For model validation in Section 3.6, the assumptions of resources are $M = 4$ entry doors $N = 3$ exit doors, $O = 3$ forklifts and $T = 8$ trucks operating for 8 hours in a day.

Table 1: Food bank input parameters

Food bank	Entry Doors ($\boldsymbol{M}$)	Exit Doors ($\boldsymbol{N}$)	Forklifts ($\boldsymbol{O}$)	Trucks ($\boldsymbol{T}$)
HFB	4	5	3	10
CTFB	4	3	3	8
SAFB	3	3	3	8

(HFB- Houston food bank, CTFB-Central Texas food bank, SAFB-San Antonio food bank)

Table 2 indicates the transportation time of supplies in the trucks from each food bank facility to the distribution centers. Travel time to the distribution center is calculated under the following assumptions. 1) Supplies are delivered from supply node to the distribution center using roadways and 2) Transportation time is calculated by assuming that the trucks are travelling on an average speed of 40 miles per hour and there is no damage for roads after hurricane Harvey. Distances from the each food bank facility to each distribution center were obtained from Google maps [1].

Table 2: Transportation Time from food bank to the counties

Demand Node	County #	County Name	HFB (Minutes)	CTFB (Minutes)	SAFB (Minutes)
h1	1	Austin	206.7	306	456
h2	2	Brazoria	144.6	525	651
h3	3	Brazos	309	315	558
h4	4	Burleson	318	255	480
h5	5	Chambers	136.5	624	753
h6	6	Fort Bend	124.8	414	543
h7	7	Galveston	134.1	609	738
h8	8	Grimes	228.6	366	570
h9	9	Harris	7.2	486	615
h10	10	Liberty	141	624	759
h11	11	Madison	324	420	660
h12	12	Montgomery	137.7	507	696
h13	13	Robertson	411	315	561
h14	14	San Jacinto	180	540	738
h15	15	Trinity	333	576	786
h16	16	Walker	240	453	660
h17	17	Waller	174.9	357	525
h18	18	Washington	247.2	279.9	483
h19	1	Bastrop	435	88.8	324
h20	2	Bell	555	252.3	465
h21	3	Blanco	654	163.8	234.3
h22	4	Burnet	639	187.5	321
h23	5	Caldwell	495	73.8	224.1
h24	6	Coryell	663	327	534
h25	7	Falls	495	330	549
h26	8	Fayette	330	187.8	372

Demand Node	**County #**	**County Name**	**HFB (Minutes)**	**CTFB (Minutes)**	**SAFB (Minutes)**
h27	9	Freestone	480	504	759
h28	10	Gillespie	741	251.7	233.1
h29	11	Hays	579	87.9	227.7
h30	12	Lampasas	726	276.9	441
h31	13	Lee	363	163.2	402
h32	14	Limestone	519	405	645
h33	15	Llano	735	245.7	333
h34	16	McLennan	579	321	558
h35	17	Milam	429	223.8	471
h36	18	Mills	825	378	537
h37	19	San Saba	786	351	444
h38	20	Travis	492	5.1	263.1
h39	21	Williamson	567	138.3	378
h40	1	Atascosa	732	360	137.1
h41	2	Bandera	819	375	195.6
h42	3	Bexar	633	256.8	3.9
h43	4	Comal	591	175.8	148.2
h44	5	Edwards	1092	594	492
h45	6	Frio	792	414	177
h46	7	Guadalupe	501	150.6	152.7
h47	8	Karnes	603	284.1	184.2
h48	9	Kendall	705	246	161.4
h49	10	Kerr	873	387	284.4
h50	11	La Salle	879	555	315
h51	12	Medina	720	342	86.4
h52	13	Real	981	498	321
h53	14	Uvalde	903	528	271.5
h54	15	Wilson	591	249.3	113.1
h55	16	Zavala	1005	516	276.3

(HFB- Houston food bank, CTFB-Central Texas food bank, SAFB-San Antonio food bank)

3.5.2 Model probability models

The *interarrival rate of donations* were estimated based on the number of trucks arriving to each facility every day. The *quantity of donated supplies* per truck was estimated in pallets. Each truck delivered on average from 2 to 3 pallets per arrival. Processing times for *unloading trucks*, *placing supplies on the warehouse shelves*, and for *retrieving the supplies from the warehouse's shelves* were also considered random. Finally, the *demand for supplies* from each agency was also considered random. Two different operational scenarios were considered in this work: pre-disaster (i.e., normal conditions) and post-disaster (i.e., after a natural disaster).

The pre-disaster *interarrival rate of donations* was estimated based on the number of trucks that arrived at each facility from January 1st, 2016, until July 31st, 2017. The post-disaster *interarrival rate of donations* was estimated based on the number of trucks that arrived at each facility August 1st, 2017, until December 31st, 2017. Food banks receive different product types as donations every day. But for this thesis study, whole quantity of donations is aggregated for specific day irrespective of the product type. It was assumed that the number of arrivals per unit time is Poisson distributed. Therefore, the *interarrival rate of donations*, of both pre-disaster and post-disaster scenarios, follow the exponential distribution. This exponential distribution has a single parameter that specifies the mean, $expo(\lambda)$. Table 3 shows the interarrival rate of donations for each food bank facility when considering the pre-disaster and post-disaster scenarios. The data provided by SAFB was very limited. However, since CTFB and SAFB are about the same size and serve similar populations, they were modeled using the same probability distributions.

Table 3: Interarrival rate of donations to the Food bank

Food bank	**Distribution of Inter-Arrival Rate of Donations (In minutes)**	
	Pre-disaster	**Post-disaster**
HFB	$expo(30.87)$	$expo(24.49)$
CTFB	$expo(73.188)$	$expo(75.92)$
SAFB	$expo(73.188)$	$expo(75.92)$

(HFB- Houston food bank, CTFB-Central Texas food bank, SAFB-San Antonio food bank)

The *quantity of donated supplies* was modeled using the Normal distribution **(i.e., $\mathbf{N}(\boldsymbol{\mu}, \boldsymbol{\sigma})$), t**he Weibull distribution **(i.e., $\boldsymbol{Weib}(\boldsymbol{\alpha}, \boldsymbol{\beta})$)** and Gamma distribution **(i.e., $\boldsymbol{\Gamma}(\boldsymbol{\alpha}, \boldsymbol{\beta})$).** Table 4 indicates the distribution of the number of donations received at each food bank for pre-disaster and post-disaster scenarios.

Table 4: Amount of donations received by food bank

Food bank	Distribution for Amount of Donations at Food bank	
	Pre-disaster (In Pallets)	**Post-disaster (In Pallets)**
HFB	$N(2.26,1.28)$	$N(3.64,2.36)$
CTFB	$\Gamma(3.52,0.435)$	$Weib(1.63,1.83)$
SAFB	$\Gamma(3.52,0.435)$	$Weib(1.63,1.83)$

(HFB- Houston food bank, CTFB-Central Texas food bank, SAFB-San Antonio food bank)

3.5.3 Demand for supplies

The demand for supplies in the simulation was modeled from the demand-changing factors for each of the 55 county agencies. These values were calculated from the two-year historical data received for all three food banks. The details of these factor values are provided in the Appendix of this thesis report.

Table 5 list the probability models used to represent the demand in pallets for each county agency. A uniform distribution with parameters 0 and 1 was assumed for those counties where the demand was very low. The Beta distribution is represented using two shape parameters α and β; $\mathbf{Beta}\ (\boldsymbol{\alpha}, \boldsymbol{\beta})$. The lognormal distribution using parameters normal mean and normal standard deviation as $\boldsymbol{LOGN}(\boldsymbol{\mu}, \boldsymbol{\sigma})$**.** According to the food banks' historical data of order requests, HFB receives order requests every 1 to 2 days from the distribution centers, whereas CTFB and SAFB receive order requests every week. Hence, the interarrival rate of demand order requests for HFB are $U(1,2)$ days, and for CTFB, SAFB is $U(5,7)$ days.

Table 5: Demand probability models for county agencies

Food bank	County #	Pre-disaster Demand order distribution (In pallets)	Post-disaster Demand order distribution (In pallets)
HFB	1	$U(0,1)$	2.03+.16*$Beta(0.95,0.976)$
HFB	2	1.4+1.21*$Beta(1.1,0.92)$	$U(25,26.7)$
HFB	3	2.02+1.13*$Beta(1.28,1.04)$	35+2.55*$Beta(0.755,0.758)$
HFB	4	$U(0,1)$	1.81+.14* $Beta(0.937,0.892)$
HFB	5	$U(0,1)$	2.4+.18*$Beta(0.827,0.835)$
HFB	6	2.02+ $Weib(1.43,0.816)$	41+3.01* $Beta(0.751,0.751)$
HFB	7	1.53+1.32∗ $Beta(1.09,0.921)$	27.2+1.98* $Beta(0.757,0.751)$

Food bank	County #	Pre-disaster Demand order distribution (In pallets)	Post-disaster Demand order distribution (In pallets)
HFB	8	$U(0,1)$	3.3+0.25* $Beta(0.856,0.858)$
HFB	9	$U(31,49)$	$U(519,551)$
HFB	10	$U(0,1)$	8.68+0.64* $Beta(0.799,0.779)$
HFB	11	$U(0,1)$	$U(1.71,1.85)$
HFB	12	2.11+1.18*$Beta(1.28,1.04)$	36.6+2.66* $Beta(0.754,0.751)$
HFB	13	$U(0,1)$	$U(1.81,1.96)$
HFB	14	$U(0,1)$	3.34+0.25* $Beta(0.799,0.845)$
HFB	15	$U(0,1)$	2.56+0.19* $Beta(0.804,0.805)$
HFB	16	$U(0,1)$	7.67+0.57* $Beta(0.813,0.804)$
HFB	17	$U(0,1)$	4.88+0.36* $Beta(0.791,0.788)$
HFB	18	$U(0,1)$	3.22+0.25* $Beta(0.933,0.914)$
CTFB	19	$U(0,1)$	$U(0,1)$
CTFB	20	2.02+ $LOGN(-2.48,0.94)$	2+0.98* $Beta(0.771,0.593)$
CTFB	21	$U(0,1)$	$U(0,1)$
CTFB	22	$U(0,1)$	$U(0,1)$
CTFB	23	$U(0,1)$	$U(0,1)$
CTFB	24	$U(0,1)$	$U(0,1)$
CTFB	25	$U(0,1)$	$U(0,1)$
CTFB	26	$U(0,1)$	$U(0,1)$
CTFB	27	$U(0,1)$	$U(0,1)$
CTFB	28	$U(0,1)$	$U(0,1)$
CTFB	29	1.28+0.33* $Beta(0.808,0.319)$	1.26+0.64* $Beta(0.832,0.662)$
CTFB	30	$U(0,1)$	$U(0,1)$
CTFB	31	$U(0,1)$	$U(0,1)$
CTFB	32	$U(0,1)$	$U(0,1)$
CTFB	33	$U(0,1)$	$U(0,1)$
CTFB	34	2.1+ $LOGN(-2.40,0.9263)$	2.06+1.04* $Beta(0.804,0.663)$
CTFB	35	$U(0,1)$	$U(0,1)$
CTFB	36	$U(0,1)$	$U(0,1)$
CTFB	37	$U(0,1)$	$U(0,1)$
CTFB	38	6.55+ $LOGN(-1.31,0.95)$	6.42+3.22* $Beta(0.788,0.654)$
CTFB	39	1.53+1.32*$Beta(0.764,0.308)$	1.55+0.79* $Beta(0.824,0.679)$
SAFB	40	$U(0,1)$	$U(0,1)$
SAFB	41	$U(0,1)$	$U(0,1)$
SAFB	42	15+ $LOGN(-0.6609,0.472)$	15+6.98* $Beta(0.685,0.472)$
SAFB	43	$U(0,1)$	$U(0,1)$
SAFB	44	$U(0,1)$	$U(0,1)$
SAFB	45	$U(0,1)$	$U(0,1)$
SAFB	46	$U(0,1)$	$U(0,1)$
SAFB	47	$U(0,1)$	$U(0,1)$
SAFB	48	$U(0,1)$	$U(0,1)$
SAFB	49	$U(0,1)$	$U(0,1)$
SAFB	50	$U(0,1)$	$U(0,1)$
SAFB	51	$U(0,1)$	$U(0,1)$
SAFB	52	$U(0,1)$	$U(0,1)$
SAFB	53	$U(0,1)$	$U(0,1)$
SAFB	54	$U(0,1)$	$U(0,1)$
SAFB	55	$U(0,1)$	$U(0,1)$

3.6 SIMIO model

3.6.1 Modeling of "Donation generation and warehouse operations" in SIMIO

Figure 11 furnishes the SIMIO modeling of "Donation's arrivals and warehouse operations" process mentioned in section 3.4.1 of this thesis study for HFB. The SIMIO model is same for other two food banks as well. The number of entities is generated from the "source" block as per the distribution model in the "creating entities" add-on process triggers as defined in figure 12. The number of entities for regular and disaster relief operations is according to figures 13 and 14.

Figure 11: Overview of donations arrival in SIMIO model

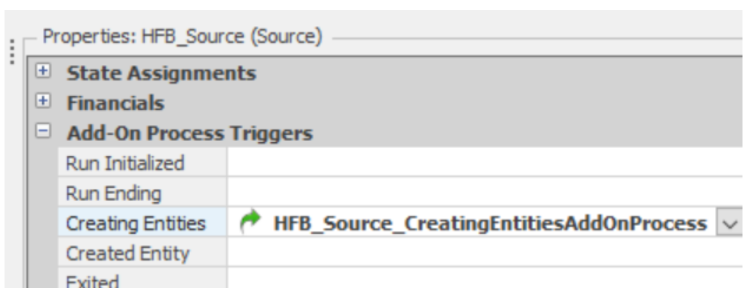


Figure 12: Add-on process trigger for creating entities in "source" block

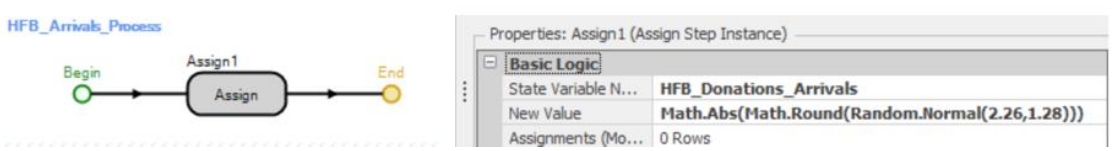


Figure 13: Number of donations arrive during regular operations for HFB

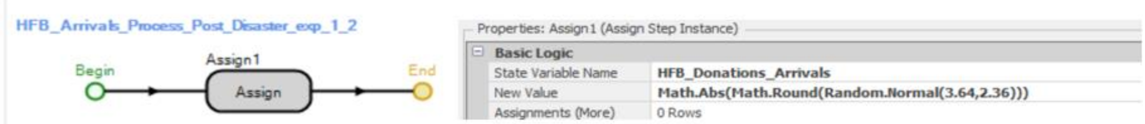


Figure 14: Number of donations arrive during disaster relief operations for HFB

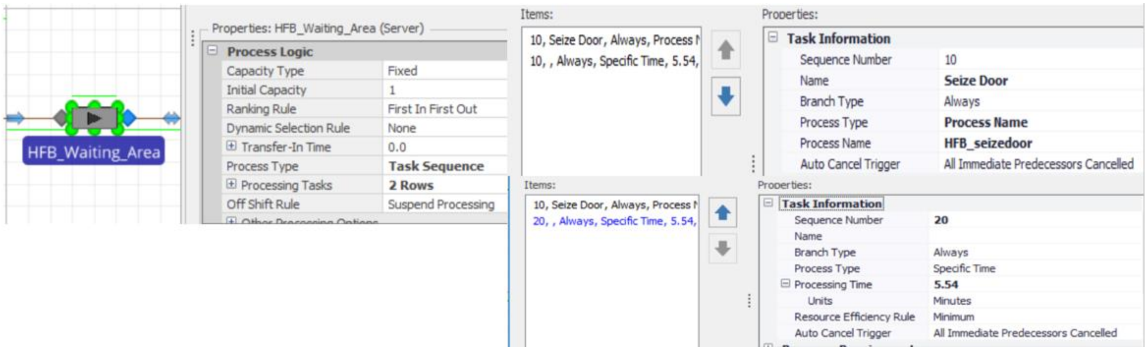


Figure 15: Process of unloading and shipping supplies to food bank warehouse

Figure 15 depicts the process of unloading and shipping of supplies to the food bank warehouse. The “HFB_Waiting_Area” is modeled as a server with two process steps. The first process is to seize two resources food bank entry doors and forklifts; the second process step is processing time to unload the supplies from truck to the forklift. The detailed process of seizing the resources is provided in figure 16.

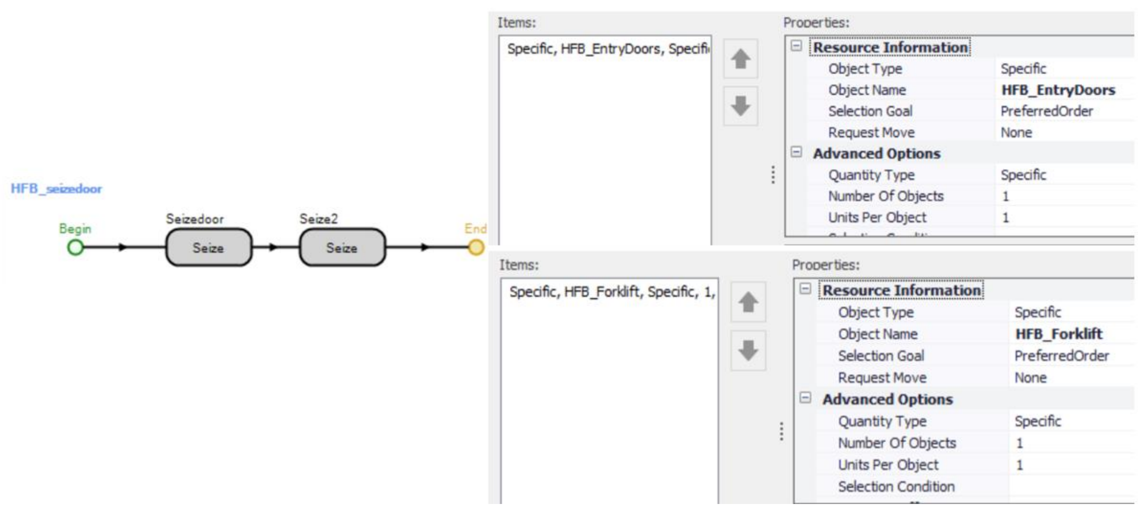


Figure 16: Resource “seize” process

Figure 17 details the process of releasing resources after transferring supplies into the food bank warehouse. In SIMIO, the operations inside the food bank are modeled in the server “HFB_INVENTORY,” as shown in figure 18. The processing time of placing the supplies in the warehouse is five minutes. Once the supplies reach the food bank warehouse, the inventory level of the food bank is updated using the “assign” variable “HFB_Inv,” which helps to monitor the current inventory level of the food bank. Whenever supplies reach the food bank warehouse, the SIMIO model updates the variable “HFB_Inv” will be with a new value “HFB_Inv + HFB_INVENTORY.Processing.Contents”.

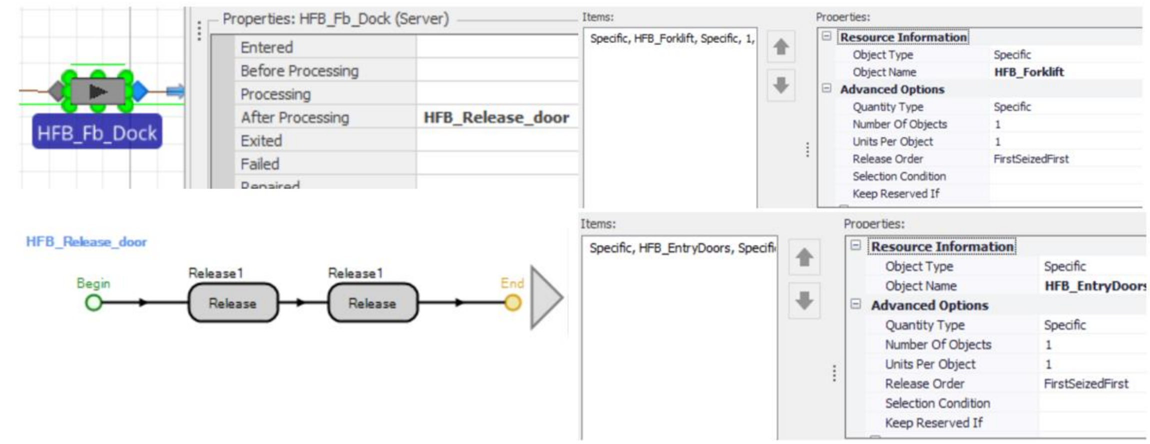


Figure 17: Resource “release” process

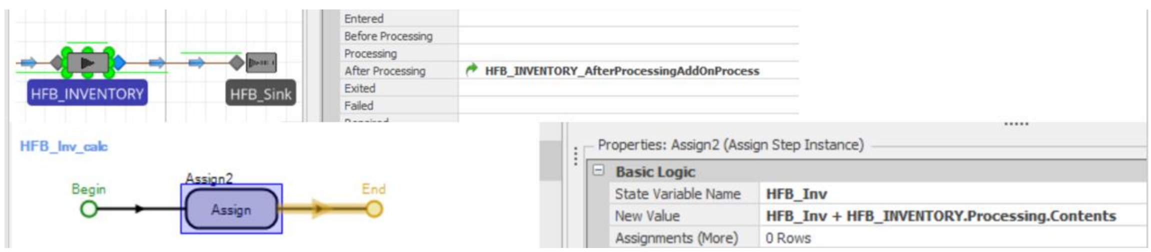


Figure 18: Food bank inventory management

3.6.2 Modeling of “Warehouse operations and supplies distribution” in SIMIO

Figure 19 gives an overview of order requests from the distribution center to the food bank. Whereas figure 19 depicts one distribution center, the same model was implemented for all distribution centers of three food bank facilities in this thesis scope. "HFB_DC1" is the source for generating demand order requests. Entities are generated from the add-on process defined in the "Creating Entities" tab of the "HFB_DC1" source. The detailing of order requests for regular and disaster-relief operations is modeled as shown in figures 20 and 21. Once the entity for order request is generated, the processing of order requests' decision is as per the logic in the add-on process of the "created entity" tab. The demand of supplies for the order request is stored in variable "HFB_DC1_Demand" for both regular and post-disaster operations.

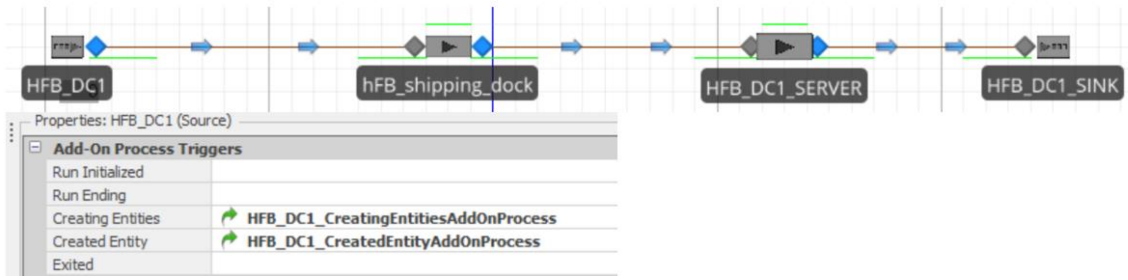


Figure 19: Demand order request modeling in SIMIO

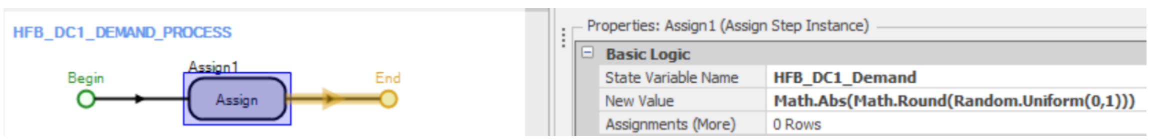


Figure 20: Order request process of distribution center in regular operations

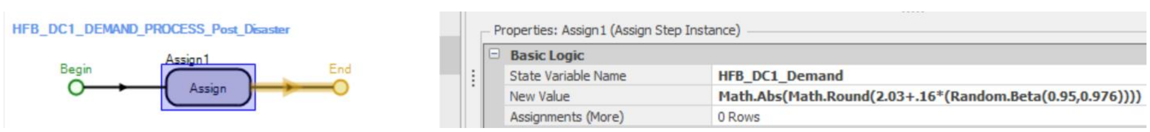


Figure 21: Order request process of distribution center in disaster-relief operations

Figure 22 illustrates the process of processing order requests. In the "decide" block, the current inventory level is checked with the logical function "*HFB_DC1_Demand <HFB_Inv*". If this condition is *true*, then the food bank can process the order request, and the inventory level variable *"HFB_Inv"* of the food bank was updated as *"HFB_Inv-HFB_DC1_Demand"* using an "assign" block as shown in figure 23. Another assignment with the variable name *"HFB_demand_filled"* is used to monitor the demand fulfilled by the food bank for all distribution centers. The variable *"HFB_demand_filled"* is updated with a new value *"HFB_demand_filled+HFB_DC1_Demand"*. Post these updates, the model transfers the supplies to the dock area of the food bank for shipping using *the*

"Transfer" block.

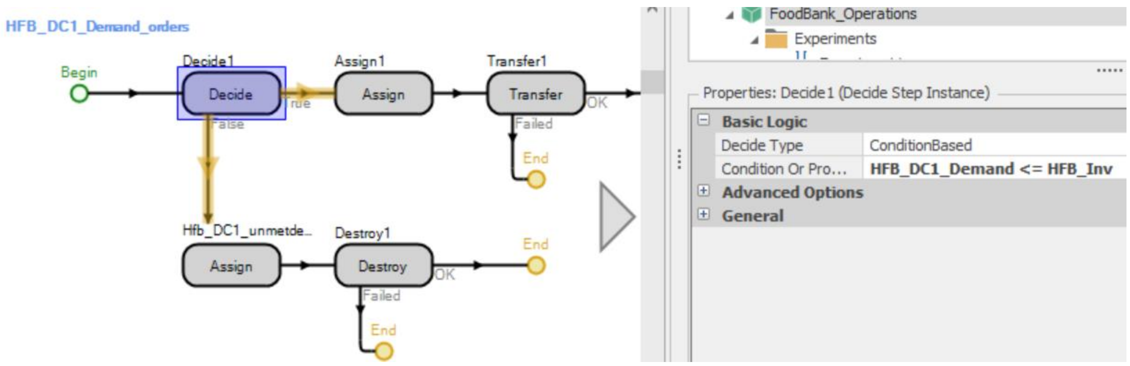


Figure 22: Food bank inventory monitor process

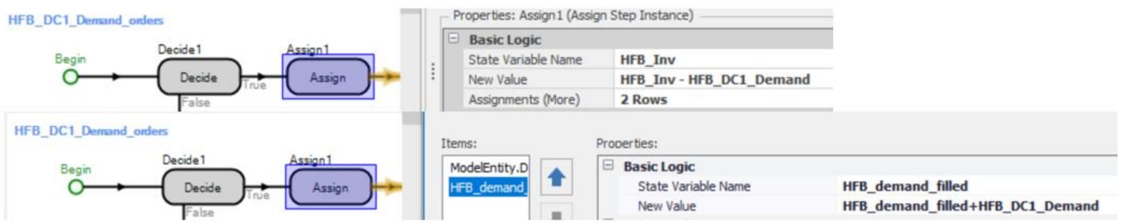


Figure 23: "Assign" variable updates of order request process

If the condition "*HFB_DC1_Demand <HFB_Inv*" is *false,* then the unmet demand of each distribution center and the total unmet demand by the food bank is counted in variables *"HFB_DC1_Unmet_Demand"* and *"HFB_unmetDemand,"* respectively using the "assign" block as shown in figure 24. The number of order requests not fulfilled is also counted in the variable *"counthfb_unmet"* using the "assign" block.

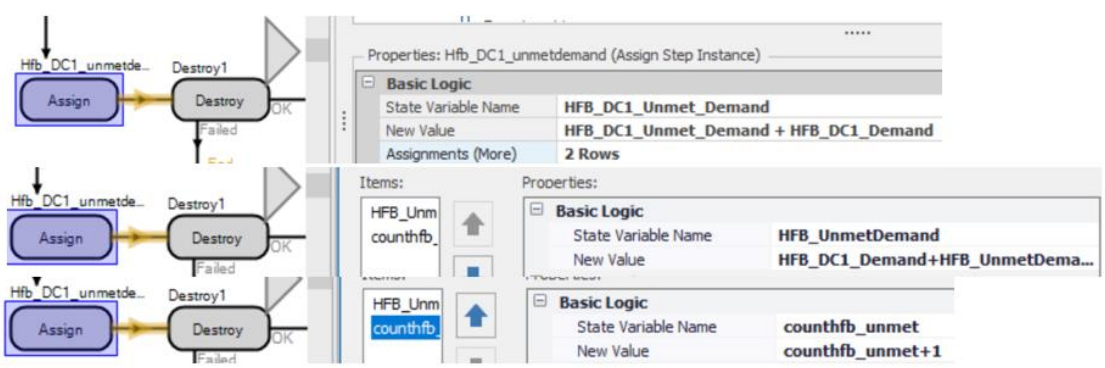


Figure 24: "Assign" variable updates for unmet order requests

After transferring of supplies to the dock area, the supplies are shipped to the distribution center. Entire SIMIO modeling of the shipping process is depicted in figure 25. Firstly, the resources *"HFB_exitdoors"* and "*HFB_forklifts"* are seized for transferring supplies to the unloading area and then resource *"HFB_Trucks"* also seized using "seize" block for shipping supplies to the distribution center. After seizing all the three resources ("*HFB_exitdoors"*, "*HFB_forklifts*", and "*HFB_Trucks"*) the supplies are unloaded from the forklift and loaded to the truck. The loading/unloading time of supplies for 5.54 minutes are modeled using a "delay" block. After loading of supplies into the truck, resources *"HFB_exitdoors"* and "*HFB_forklifts"* are released using "release" block as shown in figure 26. Supplies are shipped to the DC1 distribution center within the transportation time mentioned in Table 2 from HFB. Transportation time of supplies to each distribution center is modeled using a "delay" block. The resource "HFB_Trucks" is released using "release" block after unloading of supplies at the distribution center and returning to the food bank facility as shown in figure 27. This completes the process of fulfilling the demand request of distribution center by the food bank facility.

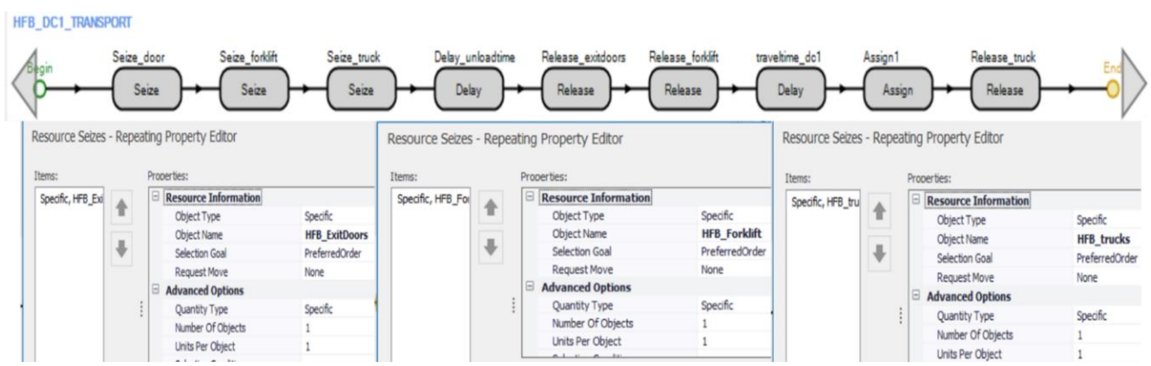


Figure 25: SIMIO Model of order shipping process

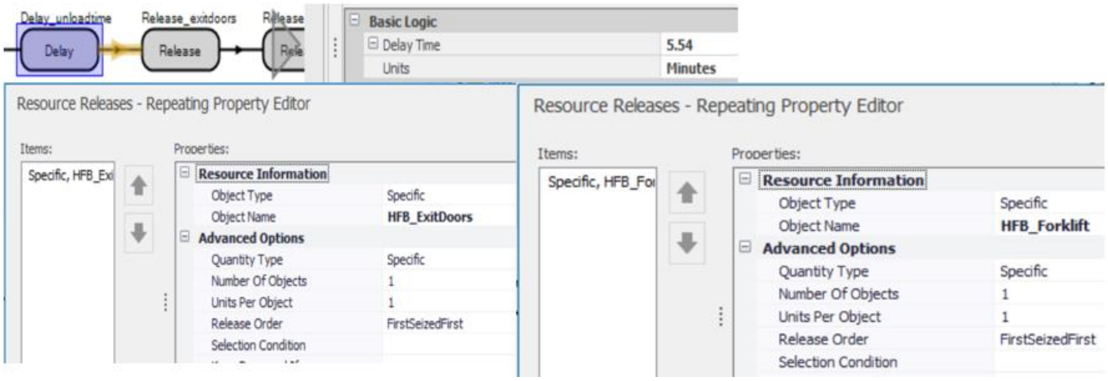


Figure 26: Loading of shipments into truck and “Release” of resources

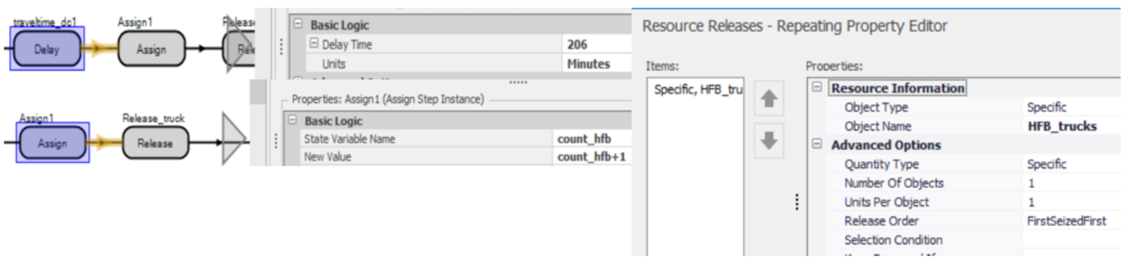


Figure 27: Transporting of shipments to distribution center and release of “Truck”

3.6.3 SIMIO set up

The simulation setup is defined as indicated in figure 28. The simulation model of all five experiments defined in Table 7 is run for 8 weeks of which first 4 weeks is for post-disaster scenario and next 4 weeks is for regular operations for 10 replications. The initial inventory values of each experiment are modeled from the results of the stochastic model in chapter 4 of this thesis study. Initial values of resources and inventories of all five experiments is modeled as shown in figure 29.

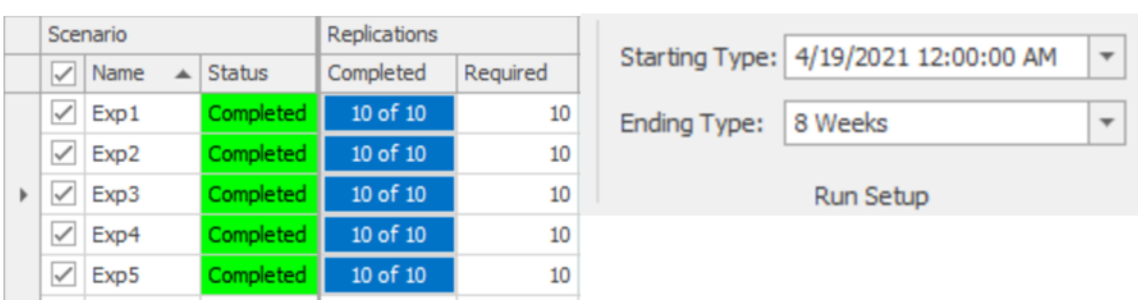
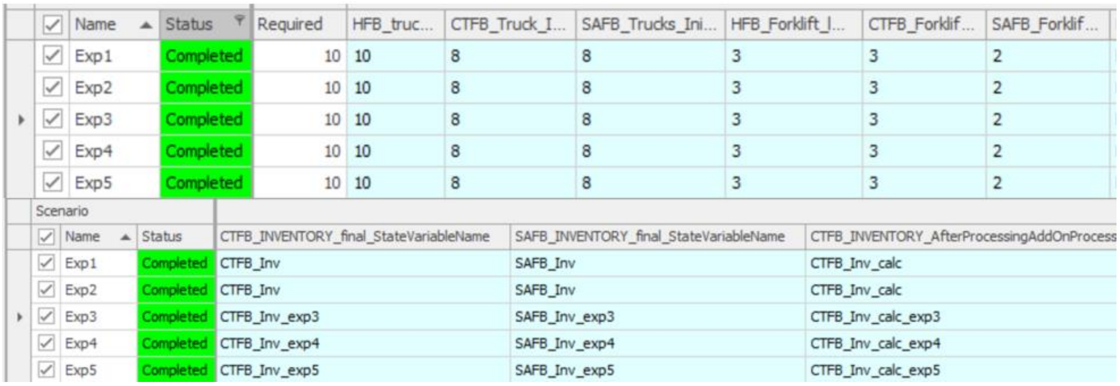


Figure 28: Run set up of simulation model



	Name	Status	Required	HFB_truc...	CTFB_Truck_I...	SAFB_Trucks_Ini...	HFB_Forklift_I...	CTFB_Forklif...	SAFB_Forklif...
☑	Exp1	Completed	10	10	8	8	3	3	2
☑	Exp2	Completed	10	10	8	8	3	3	2
☑	Exp3	Completed	10	10	8	8	3	3	2
☑	Exp4	Completed	10	10	8	8	3	3	2
☑	Exp5	Completed	10	10	8	8	3	3	2

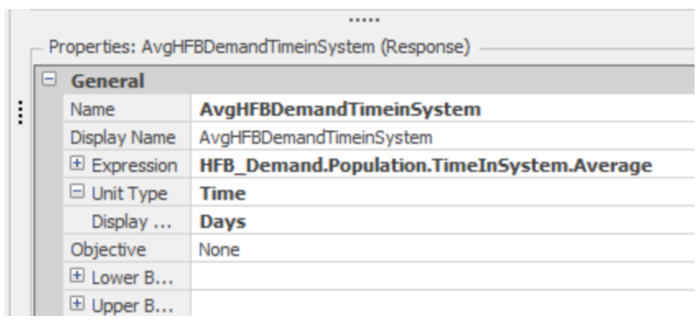
Scenario

	Name	Status	CTFB_INVENTORY_final_StateVariableName	SAFB_INVENTORY_final_StateVariableName	CTFB_INVENTORY_AfterProcessingAddOnProcess
☑	Exp1	Completed	CTFB_Inv	SAFB_Inv	CTFB_Inv_calc
☑	Exp2	Completed	CTFB_Inv	SAFB_Inv	CTFB_Inv_calc
☑	Exp3	Completed	CTFB_Inv_exp3	SAFB_Inv_exp3	CTFB_Inv_calc_exp3
☑	Exp4	Completed	CTFB_Inv_exp4	SAFB_Inv_exp4	CTFB_Inv_calc_exp4
☑	Exp5	Completed	CTFB_Inv_exp5	SAFB_Inv_exp5	CTFB_Inv_calc_exp5

Figure 29: Initial inventory values and resource variable values

3.6.4 Performance Measures set up in SIMIO

The performance measure "*delivery cycle time*" is calculated with expression "*HFB_Demand.Population.TimeinSystem.Average"* for HFB food bank as shown in figure 30.



Properties: AvgHFBDemandTimeinSystem (Response)

General	
Name	AvgHFBDemandTimeinSystem
Display Name	AvgHFBDemandTimeinSystem
Expression	HFB_Demand.Population.TimeInSystem.Average
Unit Type	Time
Display ...	Days
Objective	None
Lower B...	
Upper B...	

Figure 30: *"Delivery cycle"* Performance measure expression

Performance measure *"daily average number of trips"* for HFB is calculated using expression defined in Tally static variable *"DailyAvgTrips_HFB"* as indicated in figure 31 and *"weekly unmet demand"* is calculated using expression in tally static variable *"WeeklyAvgUnmetDemand_HFB"* as indicated in figure 32.

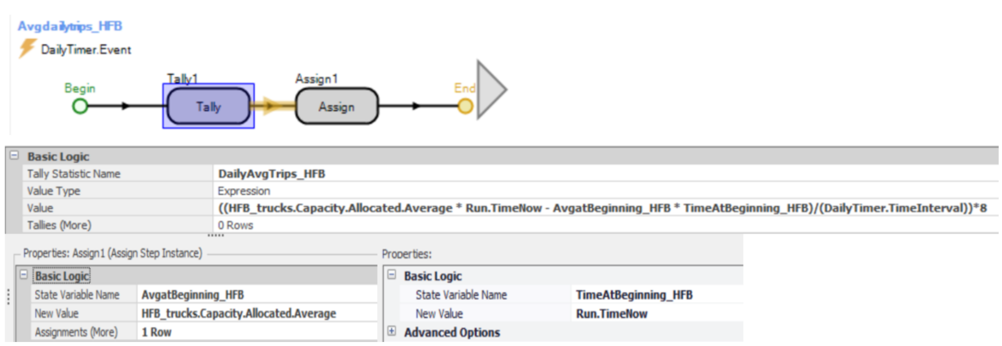


Figure 31: "Daily average number of trips" performance metric expression

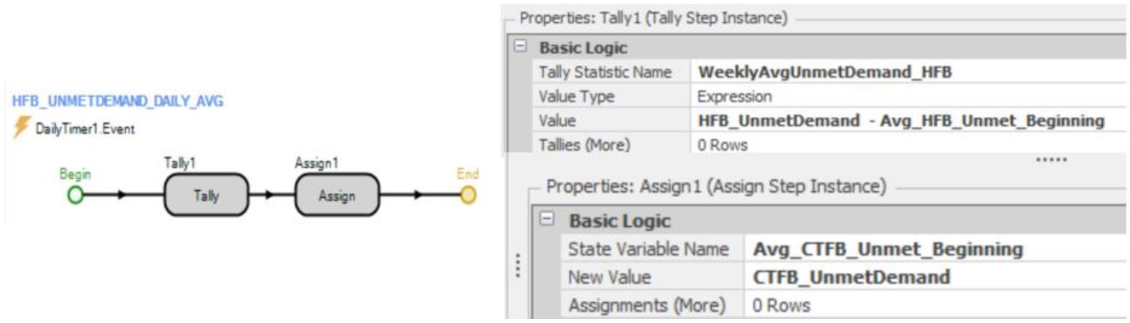


Figure 32: “Weekly unmet demand” performance measure expression

3.7 Model verification and validation

The simulation model was verified using the SIMIO software trace option. The step-by-step verification process included following multiple entities through the entire process until they leave the system. The simulation results are validated with the real-time experiment data at the food bank site. The approach examines the outputs by comparing direct model outputs between the simulated food bank operations and the real-time food bank operations to ensure the systems were stable. Unmet demand, delivery cycle time, and the daily average number of trips are the performance measures used for the simulation model's verification and validation.

Table 6 indicates the percentage difference in the average of real-time food bank operations data and the simulation model output for ten replications. If the simulation output is x, and the real-time data report is y, then the percentage difference between both outputs is computed as $((x - y)/y) * 100$ [37]. As the percentage difference is less than 15% for all performance measures, the model operates as intended. There is a percentage difference because the detailing of few processes inside the food bank is not modeled. The simulation model may require more data, which leads to increasing the complexity of the model in all aspects of inside operations like sorting, unpacking, quality check, again repacking.

Table 6: Model verification and validation results

Performance Measure	Real time Data	Simulation Output	Percentage Difference (%)
Unmet Demand	0	0	0
Delivery cycle time	1.75 days	1.68 days	4
Daily number of trips	5.3	4.6	13

3.8 Experimentation

3.8.1 Design of experiments

The experimental design considers five scenarios that represent the different ways a hurricane can affect the operation of a network of food banks in central Texas. Table 7 describes the five experimental scenarios considered in this research. Experiment 1 assumes that all food banks can operate after the hurricane and that they work independently during the disaster relief period. Experiment 2 assumes that all food banks can operate after the hurricane, but they can collaborate (i.e., distribute supplies for agencies outside their region) during the disaster relief period. Experiments 3, 4, and 5 assume that one or more food banks are closed during the disaster relief period and these three experiments also allow collaboration between food banks during the disaster relief period. The purpose of all five experiments of SIMIO model is to understand the operational efficiency of the food bank network when all food banks are open and when one or two facilities in the network become non-operational after the impact of a hurricane category 4 or 5. The simulation considers operations for 8 weeks, of which the first 4 weeks simulate the disaster relief operations for hurricane Harvey and then transition to 4 weeks of normal operations. The initial inventory of each food bank is a parameter which is considered from the results of the stochastic model provided in chapter 4 of this thesis study.

Table 7: List of Experiments for Simulation

Experiment No.	Description	HFB open ?	CTFB open?	SAFB open?
1	All food banks can operate after the hurricane, and they work independently during the disaster relief period.	Yes	Yes	Yes
2	All food banks can operate after the hurricane and they collaborate (i.e., distribute supplies for agencies outside their region) during the disaster relief period.	Yes	Yes	Yes
3	HFB closed during the disaster relief period and CTFB and SAFB collaborate (i.e., distribute supplies for agencies outside their region) during the disaster relief period.	No	Yes	Yes
4	HFB and CTFB are closed during the disaster relief period and SAFB distribute supplies for all agencies in central Texas during the disaster relief period.	No	No	Yes
5	HFB and SAFB are closed during the disaster relief period and CTFB distribute supplies for all agencies in central Texas during the disaster relief period.	No	Yes	No

3.8.2 Assignment of county agencies

As stated earlier, in experiment 1 all food banks are working independently, and they only serve their county agencies. However, in experiments 2-5 collaboration is allowed and food banks can serve county agencies outside their region during the disaster relief period. A two-stage stochastic programming model was used to decide the assignment of county agencies within the network of operating food banks per experiments in chapter 4 of this thesis. The stochastic programming model is discussed in chapter 4 of this thesis.

4. STOCHASTIC PROGRAMMING MODEL

4.1 Methodology and problem statement

4.1.1 Problem statement

The goal of this chapter of thesis is to develop optimization-based decision-making policies for the prepositioning of disaster relief supplies considering the transportation limitations of a network food bank facilities and the uncertainty in the demand. The problem is formulated as a two-stage stochastic programming model that considers the uncertainty in terms of available supplies, donations received at the facility, and the expected demand for their service region. The first phase of the model will determine if the system requires pre-positioning of the expected inventory considering the expected donations. The second phase of the model will determine the activities to be undertaken during the response phase.

In the stochastic model presented in this thesis, the three major food bank facilities (HFB, CTFB, and SAFB) affected due to Hurricane Harvey are supply nodes. Whereas demand nodes are the counties served by food bank facilities. The distance between supply nodes and demand nodes is according to the distance through road transportation. Supplies are allowed to be pre-positioned between the supply nodes. They are also entitled to transfer from supply nodes (food bank facilities) to the demand nodes (counties or distribution centers) before and after natural disasters.

4.1.2 Assumptions

In this thesis study, the effect of hurricane Harvey is considered, which affected Texas and Louisiana in 2017. The counties served by Houston food bank (HFB), Central Texas food bank (CTFB), and San Antonio food bank (SAFB) are analyzed for determining the supply and demand nodes. The historical data provided by the food banks gave information about the inventory and capacity for each food bank facility. From the data, it is noticed that there is a surge in demand after a natural disaster that needs to be satisfied with the available inventory. The following are the assumptions while defining the problem.

- Consider a supply and demand network with N supply nodes, and H demand nodes.
- Each supply node consists of $n \in N$, corresponds to a food bank facility which can store and distribute supplies.
- The set of demand nodes, $h \in H$, represents locations that shows the requirement of population. In this research, the counties are considered the demand nodes.
- Demand nodes that are nearer to the event path experience greater change in demand.
- The disaster donations, in addition to regular donations, is determined using the historical data obtained from food bank facilities.
- The interconnections between supply nodes and demand nodes illustrated are the transportation routes. It is assumed that movement of food takes place using the roadways.
- The size and volume of storage of the CTFB and the SAFB is similar. Hence, the values for inventory and donations are same.
- The additional transportation capacities are considered for post disaster events.

Pre-positioning supplies is shipping the supplies between the food bank facilities to serve the counties when one or more food bank facilities are disrupted due to natural disasters. The stochastic programming model considers the current inventory level at the food bank facilities while initiating the process of pre-positioning.

4.2 Supply and demand nodes

4.2.1 Supply network

Texas is the major area affected due to hurricane Harvey and has the major contribution of serving the population in need during the hurricane. HFB, CTFB and SAFB are three major supply nodes considered in this thesis study. Storage capacity and initial inventory levels for each food bank facility (supply nodes) is pre-defined. In this thesis study, supply node is defined as $n \epsilon N$ and i, j are the indices used for defining inbound and outbound flows of supplies from each supply node which means $i, j, n \epsilon N$. Distances between each supply node are indicated in Table 8. From the historical data provided by food bank facilities, there is an increase in the number of donations received after natural disasters. The data shows that there is lower demand uncertainty for category 1,2 and 3 hurricanes, whereas high demand uncertainty is expected for categories 4 and 5 hurricanes.

Table 8: Distance matrix in miles between food bank facilities

Food bank facility	HFB	CTFB	SAFB
HFB	-	165	208
CTFB	165	-	86
SAFB	208	86	-

4.2.2 Demand nodes and forecasted demand

Demand nodes are counties (distribution centers) served by each food bank in its proximity. Food banks use delivery trucks for delivering supplies to the distribution centers before and after hurricanes. Historical data provided by the food bank facilities have the details of the number of supplies demanded by the distribution centers before and after hurricanes.

The demand of supplies for the food banks under normal operation was estimated considering the counties and their corresponding population in poverty [38]. This thesis study estimates the demand for a county using Equation (1) in paper [1] which consider the poverty population (p_c) for each county and the product need factor (H_f) which considers the people that are not classified as in poverty level but that will need help from the food bank for other reasons such as unemployment.

Table 9: Estimated weekly demand per county

County Number	County Name	Poverty %	Poverty Population	Demand (lb)
1	Austin	10.20%	3,058.88	629
2	Brazoria	10.10%	37,390.20	7,683
3	Brazos	23.20%	52,607.86	10,810
4	Burleson	14.80%	2,721.57	559
5	Chambers	8.50%	3,608.59	741
6	Fort Bend	7.90%	62,240.78	12,789
7	Galveston	12.10%	40,884.69	8,401
8	Grimes	17.50%	4,963.00	1,020
9	Harris	16.50%	775,272.14	159,302
10	Liberty	15.10%	13,034.77	2,678
11	Madison	17.90%	2,581.54	530
12	Montgomery	9.30%	54,956.03	11,292
13	Robertson	15.80%	2,730.87	561
14	San Jacinto	17.50%	5,025.83	1,033
15	Trinity	26.10%	3,847.14	791
16	Walker	15.90%	11,524.32	2,368
17	Waller	13.80%	7,331.39	1,506
18	Washington	13.80%	4,844.90	996
19	Bastrop	12.60%	10,958.98	2,252
20	Bell	13.00%	46,233.46	9,500
21	Blanco	10.10%	1,181.90	243
22	Burnet	11%	5,229.62	1,075
23	Caldwell	14.10%	6,097.83	1,253
24	Coryell	15%	11,221.20	2,306
25	Falls	21.70%	3,761.70	773
26	Fayette	13.30%	3,371.42	693
27	Freestone	13.70%	2,713.70	558
28	Gillespie	9.60%	2,573.18	529
29	Hays	13.20%	29,387.29	6,038
30	Lampasas	12.90%	2,738.54	563
31	Lee	12.30%	2,108.71	433
32	Limestone	22.20%	5,221.22	1,073

County Number	County Name	Poverty %	Poverty Population	Demand (lb)
33	Llano	12.30%	2,662.46	547
34	McLennan	18.90%	48,120.72	9,888
35	Milam	15.60%	3,920.44	806
36	Mills	14.60%	718.47	148
37	San Saba	16.80%	1,017.07	209
38	Travis	12.00%	149,849.16	30,791
39	Williamson	6.40%	36,270.02	7,453
40	Atascosa	15.70%	7,898.67	1,623
41	Bandera	13.40%	3,058.42	628
42	Bexar	17.20%	341,600.43	70,192
43	Comal	7.10%	10,534.48	2,165
44	Edwards	22.10%	426.09	88
45	Frio	27.50%	5,449.40	1,120
46	Guadalupe	8.50%	13,913.99	2,859
47	Karnes	21.80%	3,411.70	701
48	Kendall	7.50%	3,423.08	703
49	Kerr	13.90%	7,284.30	1,497
50	La Salle	29.60%	2,229.18	458
51	Medina	12.30%	6,263.28	1,287
52	Real	18.10%	629.52	129
53	Uvalde	22.90%	6,147.73	1,263
54	Wilson	10.90%	5,474.42	1,125
55	Zavala	32.00%	3,834.56	788

The estimated demand mentioned in Table 8 is the quantity of supplies requested by the distribution centers. The demand varies depending on the scenarios which is mentioned in next section of this thesis.

4.3 Distribution centers Modeling

The cost calculated in the stochastic model depends on the distance between the distribution centers and food bank facilities. Table 10 indicates the distances between the food bank facilities and distribution centers (counties). Distances mentioned are the minimum distances estimated from [39], which includes state and interstate highways.

Table 10: Distance of demand nodes from supply nodes

County #	County Name	HFB	CTFB	SAFB
1	Austin	68.9	102	152
2	Brazoria	48.2	175	217
3	Brazos	103	105	186
4	Burleson	106	85	160
5	Chambers	45.5	208	251
6	Fort Bend	41.6	138	181

County #	County Name	HFB	CTFB	SAFB
7	Galveston	44.7	203	246
8	Grimes	76.2	122	190
9	Harris	2.4	162	205
10	Liberty	47	208	253
11	Madison	108	140	220
12	Montgomery	45.9	169	232
13	Robertson	137	105	187
14	San Jacinto	60	180	246
15	Trinity	111	192	262
16	Walker	80	151	220
17	Waller	58.3	119	175
18	Washington	82.4	93.3	161
19	Bastrop	145	29.6	108
20	Bell	185	84.1	155
21	Blanco	218	54.6	78.1
22	Burnet	213	62.5	107
23	Caldwell	165	24.6	74.7
24	Coryell	221	109	178
25	Falls	165	110	183
26	Fayette	110	62.6	124
27	Freestone	160	168	253
28	Gillespie	247	83.9	77.7
29	Hays	193	29.3	75.9
30	Lampasas	242	92.3	147
31	Lee	121	54.4	134
32	Limestone	173	135	215
33	Llano	245	81.9	111
34	McLennan	193	107	186
35	Milam	143	74.6	157
36	Mills	275	126	179
37	San Saba	262	117	148
38	Travis	164	1.7	87.7
39	Williamson	189	46.1	126
40	Atascosa	244	120	45.7
41	Bandera	273	125	65.2
42	Bexar	211	85.6	1.3
43	Comal	197	58.6	49.4
44	Edwards	364	198	164
45	Frio	264	138	59
46	Guadalupe	167	50.2	50.9
47	Karnes	201	94.7	61.4
48	Kendall	235	82	53.8
49	Kerr	291	129	94.8
50	La Salle	293	185	105
51	Medina	240	114	28.8
52	Real	327	166	107
53	Uvalde	301	176	90.5
54	Wilson	197	83.1	37.7
55	Zavala	335	172	92.1

4.4 Stochastic modeling

The decision-making model has been formulated as a two-stage stochastic programming model [40]. The first stage models the pre-positioning of supplies between food banks while the second stage provides recursive actions for supplies prepositioning and also models supplies distribution to the demand nodes under different scenarios. Using the notation described in Table 11, the two-stage stochastic linear programing model is formulated using Equations (1) to (3).

Table 11: Decision variables and parameters of stochastic model

First-Stage Decision Variables	
S_n	Stored (pre-positioned) quantity of supplies at supply node n
x_{nj}	Quantity of supply units shipped from supply node n to supply node j, $n, j \in N$.
x_{in}	Inbound Quantity of supply units shipped from supply node i to supply node n, $i, n \in N$.
x_{jn}	Quantity of supply units shipped from supply node j to supply node n, $n, j \in N$.
Second-Stage Decision Variables	
$u_{h,\omega}$	Unmet demand quantity at node h, per scenario ω.
$f_{in,\omega}$	Inbound Quantity of supplies shipped from supplier i to supplier n, per scenario ω.
$w_{nj,\omega}$	Quantity of supplies shipped from supplier n to supplier j, per scenario ω.
$y_{nh,\omega}$	Quantity of supplies shipped from supplier node n to demand node h, per scenario ω.
$A_{n,\omega}$	Additional capacity of trucks supplier node n, per scenario ω.
$B_{n,\omega}$	Total capacity of trucks supplier node n, per scenario ω.
Supply Node Parameters	
I_n	Initial inventory stored at supply node n.
C_n	Storage capacity at supply node n.
D_n	Regular (Normal) donations at supplier node n prior to the event.
R_n	Disaster relief donations at supplier node n after the event.
d_{nj}	Unit transportation cost from supply node n to supply node j.
p_ω	Probability for the scenario ω
b_n	Number of vehicles at supply node n
a_n	Truck capacity of vehicles at supply node n
g_n	Number of trips at supply node n
Demand Node Parameters	
F_h	Forecasted demand at demand node h prior to the event.
v_h	Unit cost for unmet demand at demand node h.
d_{nj}	Unit transportation cost from supply node n to demand node h.
t_{nh}	Unit transportation cost from supply node n to demand node h.
K_n	Number of additional trucks at supply node n for scenario
e_n	Penalty cost of additional trucks for supply node n
Supply and Demand Changing Factors	
$\gamma_{n,\omega}$	Demand changing factor at demand node h per scenario ω.
$\delta_{n,\omega}$	Donation changing factor at supply node n per scenario ω.
$\propto_{n,\omega}$	Inventory changing factor at supply node n per scenario ω.

The first stage pre-positioning model involves the movement of food between supply nodes only. The flow is represented by decision variable x_{ij} to indicate the flow between supply node i to supply node j. The transportation cost between suppliers is represented as d_{nj}. The response phase uses a similar decision variable $w_{nj,\omega}$ which correspond to flow between supplier to supplier under scenario ω. Additionally, the flow from a supplier to a demand node needs to be specified using variable $y_{nh,\omega}$ from supply node n to demand node h with a transportation cost t_{nh}.

"The donation changing factor represents the change in donations per scenario ω. It is understood that donation quantity varies according to the severity of event. The inventory changing factor represents the functionality of food bank" [1]. For categories 4 and 5 hurricane, food bank facilities face difficulties for operations and there are high chances of closing the facilities because of damage for a period till recovery. When the facility is closed, they cannot deliver supplies to the distribution centers. "Similarly, the after-event demand changing factor ($F_h * \gamma_{n,\omega}$) involves the adjustments in demand following the hurricane. Sometimes, the severity of hurricane is more or less than predicted, then the forecasted demand may increase or decrease accordingly. It may happen that people, where the event took place, may have not moved out after being served evacuation notice. Hence the demand may have increased for food. The unmet demand $u_{h,\omega}$ represents the potential loss of life and property due to insufficient supplies. In practicality, it illustrates the cost required to acquire goods from another source at a higher cost" [1].

$$Min \sum_{n}\sum_{j} x_{nj} * \ d_{nj} + \sum_{\omega\in\Omega} p_{\omega} * \left\{\sum_{n}\sum_{h} y_{nh,\omega} * t_{nh} + \sum_{n}\sum_{j} w_{nj,\omega} * \ d_{nj} + \sum_{h} u_{h,\omega} * \ v_{h} + \sum_{n} A_{n,\omega} * e_{n}\right\} \qquad (1)$$

Subject to

Pre-Positioning Constraints

Modified Flow Balance

$$S_n = \sum_j x_{jn} + \ I_n - \sum_j x_{nj} + D_n, \qquad \forall n \in N \qquad (2a)$$

Pre-Positioned Storage Capacity

$$S_n \leq \ C_n, \qquad \forall n \in N \qquad (2b)$$

Transportation capacity

$$\sum_{j} x_{jn} \leq b_n * a_n * g_n, \qquad \forall n \in N \qquad (2c)$$

Response Stage Constraints

Flow Constraint (original) f

$$S_n * \propto_{n,\omega} + R_n * \ \delta_{n,\omega} + \sum_i f_{in,\omega} \ \geq \ \sum_j w_{nj,\omega} \ + \ \sum_h y_{nh,\omega} \quad \forall n \in N, \omega \in \qquad (3a)$$

Inbound = Outbound Flow constraint

$$\sum_i f_{in,\omega} = \ \sum_j w_{nj,\omega} \qquad i \neq n, n \neq j \quad \forall n \in N, \omega \in \Omega \qquad (3b)$$

Response Stage Storage Capacity

$$S_n * \propto_{n,\omega} + R_n * \ \delta_{n,\omega} \leq \ C_n, \qquad \forall n \in N \ , \omega \in \Omega \qquad (3c)$$

Transportation Limitation constraint

$\sum_j w_{nj,\omega} + \sum_h y_{nh,\omega} \leq B_{n,\omega}$, $\forall n \in N, \omega \in \Omega$ $(3d)$

Additional trucks requirement constraint

$A_{n,\omega} \leq b_n * a_n * g_n * K_n$, $\forall n \in N, \omega \in \Omega$ $(3e)$

Total Trucks constraints

$B_{n,\omega} = b_n * a_n * g_n + A_{n,\omega}$ $\forall n \in N, \omega \in \Omega$ $(3f)$

Demand Requirement

$\sum_j y_{nh,\omega} + u_{h,\omega} = F_h * \gamma_{h,\omega}$ $\forall h \in H, \omega \in$

Ω $(3g)$

Non-Negativity Constraints

$x_{nj}, x_{in}, x_{jn}, f_{in,\omega}, A_{n,\omega}, B_{n,\omega}, w_{in,\omega}, y_{nh,\omega}, u_{h,\omega}, S_n, D_n, R_n \geq 0$

$\forall n, j \in N, \forall h \in H, \omega \in \Omega$ $(3h)$

The objective function minimizes the cost associated to the prepositioning of supplies and the expected unmet demand. Constraint $(2a)$ ensures the total of outbound flows and pre-positioned supply quantity equals the total of inflows and initial inventory. Constraint $(2b)$ ensures the stored quantity is always less than or at the most equal to the capacity of warehouse. Constraint $(2c)$ ensures that the quantity to be shipped between the supply nodes to be always less than or at most equal to the transportation quantity of the supply node. Constraint $(3a)$ and $(3b)$ deals with the movement of supplies after the hurricane, ensuring flow balance between supplier to supplier and supplier to demands. Constraint $(3c)$ ensures that the regular donations and disaster relief donations received to be always less than or at most equal to the capacity of the warehouse. Constraints $(3d)$, $(3e)$, $(3f)$ ensures that the quantity to be shipped between the supply nodes to the demand nodes to be always less than or at most equal to the total transportation quantity which includes original and additional transportation limitations of the supply node. Constraint ($3g$) confirms the supply and demand requirement. Constraint ($3h$) binds all decision variables to be non-negative.

4.5 Experimental design of stochastic modeling

The aim of the experimental design is to gather insights for the prepositioning and distribution of supplies when considering the impact of a natural disaster. In this paper, hurricane Harvey served as the case study and the parameters used in the model were estimated using data collected by the food banks before and after the natural disaster. The experiments consider five different scenarios as discussed in Table 12.

Table 12: List of experiments for stochastic Model

Experiment No.	Description	HFB open?	CTFB open?	SAFB open?
1	*Benchmark:* No prepositioning and HFB is closed after hurricane Harvey	No	Yes	Yes
2	*Ideal:* Prepositioning is allowed and all food banks operating independently of the hurricane category.	Yes	Yes	Yes
3	*HFB closed:* Prepositioning is allowed, and HFB will close due to hurricane category 4 or 5	No	Yes	Yes
4	*HFB and CTFB closed:* Prepositioning is allowed, and HFB and CTFB will close due to hurricane category 4 or 5	No	No	Yes
5	*HFB and SAFB closed:* Prepositioning is allowed, and HFB and SAFB will close due to hurricane category 4 or 5	No	Yes	No

(HFB- Houston food bank, CTFB-Central Texas food bank, SAFB-San Antonio food bank)

The five experiments discussed in Table 12 seek to understand the robustness of the food bank network in terms of operational capacity when one or two facilities in the network become nonoperational after the impact of a hurricane category 4 or 5. The situations defined in the experiments try to determine the applicability of pre-positioning and explore the system capability of meeting the demands for supplies. The data used in this research is obtained from the historical data provided by HFB, CTFB, and SAFB. The food banks provided the data for donations, inventory, distribution, disaster relief donations, and disaster relief distribution. A total of 21 scenarios are considered in the two-stage stochastic programming model. The probabilities for each scenario are computed using the product of two factors probability of the strength of the natural disaster and probability of citizens reaction to a forecasted event as presented in Chapman, et al. [41]. There are 55 counties in the scope of which counties from 1 to 18 belong to HFB, counties from 19 to 39 belong to CTFB and from 40 to 55 belongs to SAFB.

4.6 Stochastic model parameters

The data used in this thesis is obtained from the historical data provided by HFB, CTFB and SAFB. The food banks provided the data for donations, inventory, demand during regular operations, disaster relief donations, and demand during disaster relief operations.

Donations are forecasted from the calculations performed in chapter 3 of thesis study by Marthak [35]. Table 13 indicates the parameters of food bank facilities and Table 14 indicates the transportation capacities of all three facilities.

Table 13: Parameters of food bank facilities

Parameters		HFB	CTFB	SAFB
I_n	Initial inventory stored at supply node n in lbs	7,995,435.16	5,484,931.36	5,484,931.36
C_n	Storage capacity at supply node n	17,500,000.00	9,000,000.00	9,000,000.00
D_n	Regular forecasted donations at supply node n in lbs	261,445.20	44,989.85	44,989.85
R_n	Disaster relief forecasted donations at supplier node n in lbs	610,363.92	57,367.28	57,367.28

Table 14: Parameters of Transportation capacities for food bank facilities

Parameters		HFB	CTFB	SAFB
b_n	Number of vehicles at supply node n	10	8	8
a_n	Truck capacity of vehicles at supply node n in lbs	40,000	36,000	36,000
g_n	Number of trips at supply node n	3	3	3
K_n	Number of additional trucks at supply node n for scenario	4	4	4

e_n	Penalty cost of additional trucks for supply node n in dollars	500	500	500

The probabilities of 21 scenarios considered in this thesis is calculated same as the methodology mentioned in section 4.5.1 of the study done by Marthak [35]. Probabilities of each scenario is mentioned in Table 15 indicated below. Hurricanes are categorized from least damaging hurricane to most damaging on a scale of 1 to 5. Category 1 is the least damaging and is considered not to affect the supply and demand to a large extent. Category 5 hurricanes are the most damaging hurricanes affecting a larger population.

Table 15: Probabilities of hurricane categories for all scenarios

Event	**Scenario (Ω)**	**Probability P (ω)**
No Hurricane	ω1	0.493671
Category 1	ω2	0.040506
	ω3	0.040506
	ω4	0.005063
	ω5	0.040506
Category 2	ω6	0.010127
	ω7	0.060759
	ω8	0.010127
	ω9	0.020253
Category 3	ω10	0.018987
	ω11	0.025316
	ω12	0.006329
	ω13	0.012658
Category 4	ω14	0.006329
	ω15	0.094937
	ω16	0.018987
	ω17	0.006329
Category 5	ω18	0.008861
	ω19	0.06557
	ω20	0.013291
	ω21	0.000886

The donation changing factor ($\delta_{n,\omega}$) and the inventory changing factor ($\alpha_{n,\omega}$) are used to model the open and closure of food bank facilities due to a hurricane category 4 or 5. Tables 16 and 17 indicates inventory changing and donation changing factors for experiments 2 to 5. These values are calculated from the two-year historical data received for all three food banks. The values of demand changing factors are provided in the Appendix of this thesis report.

Table 16: Donation changing factor of food bank facilities for all experiments

Exp #	Experiment 2			Experiment 3			Experiment 4			Experiment 5		
Food bank	HFB	CTFB	SAFB	HFB	CTFB	SAFB	HFB	CTFB	SAFB	HFB	CTFB	SAFB
ω1	1	1	1	1	1	1	1	1	1	1	1	1
ω2	1	1	1	1	1	1	1	1	1	1	1	1
ω3	1	1	1	1	1	1	1	1	1	1	1	1
ω4	1	1	1	1	1	1	1	1	1	1	1	1
ω5	1	1	1	1	1	1	1	1	1	1	1	1
ω6	1	1	1	1	1	1	1	1	1	1	1	1
ω7	1	1	1	1	1	1	1	1	1	1	1	1
ω8	1	1	1	1	1	1	1	1	1	1	1	1
ω9	1	1	1	1	1	1	1	1	1	1	1	1
ω10	1	1	1	1	1	1	1	1	1	1	1	1
ω11	1	1	1	2	1	1	2	1	1	2	1	1
ω12	1	1	1	2	1	1	2	1	1	2	1	1
ω13	1	1	1	2	1	1	2	1	1	2	1	1
ω14	1	1	1	0	1	1	0	1	1	1	1	1
ω15	1	1	1	0	1.3	1.3	0	1.3	1.3	2.3	1.3	1.3
ω16	1	1	1	0	1	1	0	1	1	1	1	1
ω17	1	1	1	0	1.3	1.3	0	1.3	1.3	2.3	1.3	1.3
ω18	1	1	1	0	1	1	0	1	1	1	1	1
ω19	1	1	1	0	1.5	1.5	0	1.5	1.5	2.7	1.5	1.5
ω20	1	1	1	0	1	1	0	1	1	1	1	1
ω21	1	1	1	0	1.5	1.5	0	1.5	1.5	2.7	1.5	1.5

Table 17: Inventory Changing Factor of food bank facilities for all experiments

Exp #	**Experiment 2**			**Experiment 3**			**Experiment 4**			**Experiment 5**		
Food bank	**HFB**	**CTFB**	**SAFB**	**HFB**	**CTFB**	**SAFB**	**HFB**	**CTFB**	**SAFB**	**HFB**	**CTFB**	**SAFB**
ω1	1	1	1	1	1	1	1	1	1	1	1	1
ω2	1	1	1	1	1	1	1	1	1	1	1	1
ω3	1	1	1	1	1	1	1	1	1	1	1	1
ω4	1	1	1	1	1	1	1	1	1	1	1	1
ω5	1	1	1	1	1	1	1	1	1	1	1	1
ω6	1	1	1	1	1	1	1	1	1	1	1	1
ω7	1	1	1	1	1	1	1	1	1	1	1	1
ω8	1	1	1	1	1	1	1	1	1	1	1	1

Exp #	Experiment 2			Experiment 3			Experiment 4			Experiment 5		
Food bank	**HFB**	**CTFB**	**SAFB**	**HFB**	**CTFB**	**SAFB**	**HFB**	**CTFB**	**SAFB**	**HFB**	**CTFB**	**SAFB**
ω9	1	1	1	1	1	1	1	1	1	1	1	1
ω10	1	1	1	1	1	1	1	1	1	1	1	1
ω11	2	1	1	1	1	1	1	1	1	1	1	1
ω12	2	1	1	1	1	1	1	1	1	1	1	1
ω13	2	1	1	1	1	1	1	1	1	1	1	1
ω14	1	1	1	0	1	1	0	0	1	0	1	0
ω15	2.3	1.3	1.3	0	1	1	0	0	1	0	1	0
ω16	1	1	1	0	1	1	0	0	1	0	1	0
ω17	2.3	1.3	1.3	0	1	1	0	0	1	0	1	0
ω18	1	1	1	0	1	1	0	0	1	0	1	0
ω19	2.7	1.5	1.5	0	1	1	0	0	1	0	1	0
ω20	1	1	1	0	1	1	0	0	1	0	1	0
ω21	2.7	1.5	1.5	0	1	1	0	0	1	0	1	0

4.7 Results and discussions

4.7.1 Results and discussions of stochastic model

The five experimental results performed in this chapter of the thesis are summarized in Table 18. The five experiments were performed to understand the movement of supplies from food bank facilities to the distribution centers for regular and disaster relief operations when all food banks are operating and if one or more food bank facilities are not working due to disaster. Experiment 1 is named the *benchmark experiment* and it is based on hurricane Harvey. HFB was unable to provide service for almost a week after Harvey [42]. The *benchmark experiment* (i.e., Experiment 1) assumes no prepositioning between food bank facilities and that the HFB will not open for service after the hurricane. Experiment 2 is named the *ideal experiment*, which allows prepositioning before the natural disaster and where it is assumed that all food bank facilities will be open after a hurricane event independently of the category of the hurricane experienced. Experiments 3, 4, and 5 also allow for prepositioning before the event and consider that one or two food bank facilities will not open if the Texas region is impacted by a hurricane category 4 or higher. The results from Table 18 indicates that there is no preposition of supplies for experiments 1 and 2, whereas there is preposition of supplies for experiments 3, 4 and 5. Experiment 2 has the smallest cost and not prepositioning cost associated to it. In experiment 2 the network of food banks is capable of supplying to all counties. Experiment 1 is associated with high cost compared to all other experiments because prepositioning is not allowed in this experiment and there are 9 counties experiencing unmet demand due to insufficient supplies. County 9 of HFB is experiencing high demand after hurricane which is major reason for high cost. Figure 33 depicts the distribution coverage of each food bank of experiment 1 for categories 4 and 5 hurricanes.

Table 18: Prepositioning decisions from stochastic model

Exp #	**Description**	**HFB Open?**	**CTFB Open?**	**SAFB Open?**	**Minimum cost ($)**	**Preposition of supplies**
1	Benchmark	No	Yes	Yes	2,776,538,594	--
2	Ideal	Yes	Yes	Yes	49,796,490	--
3	HFB Closed	No	Yes	Yes	522,485,560	HFB to CTFB
4	HFB and CTFB closed	No	No	Yes	896,653,063	HFB to SAFB CTFB to SAFB
5	HFB and SAFB closed	No	Yes	No	817,796,434	HFB to CTFB SAFB to CTFB

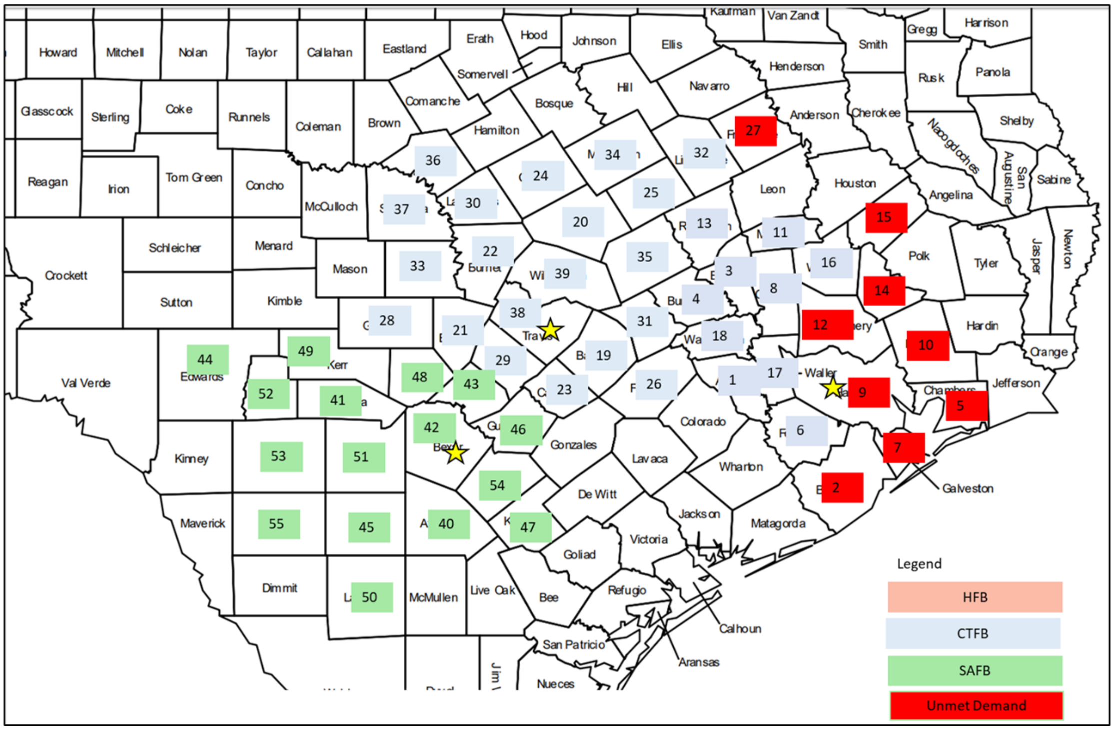


Figure 33: Counties served by each food bank for Experiment 1

Figure 34 depicts the distribution coverage of each food bank for experiment 2. From Table 18, the pre-position cost of this experiment is least compared to all experiments. Computational results of the stochastic model indicate that there is no requirement of pre-positioning the supplies. There is no unmet demand in experiment 2, which means the number of supplies is sufficient to serve the distribution centers by food banks. From figure 34, it can be observed that HFB is serving few counties as distribution centers under HFB experiencing high demand due to hurricanes compared to other two food banks due to proximity towards Gulf Coast. CTFB and SAFB are also supporting HFB counties to meet the demand requirement of supplies.

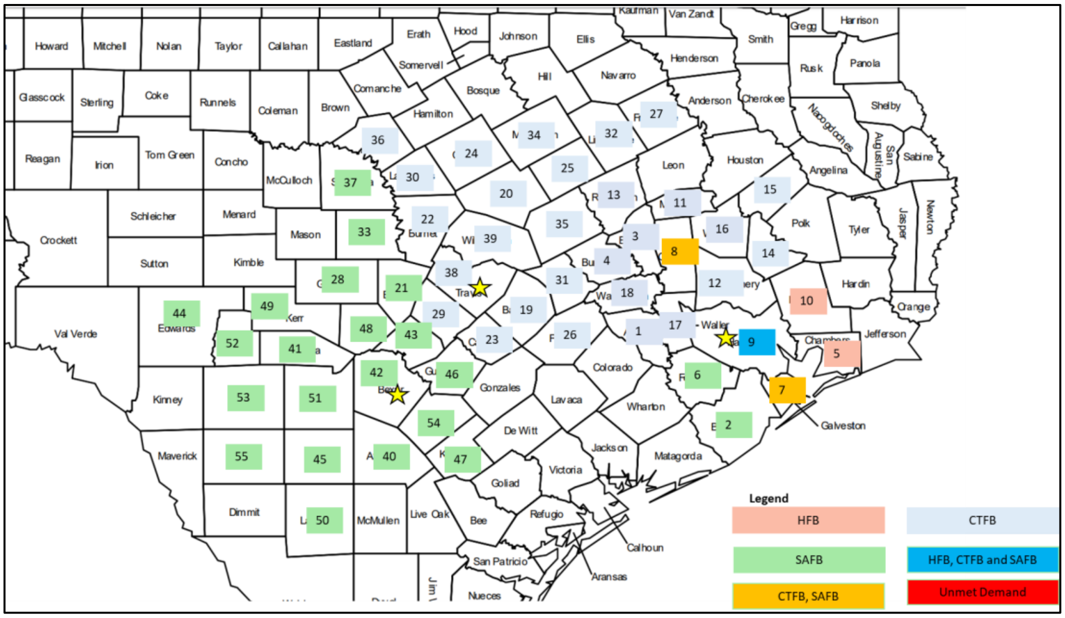


Figure 34: Counties served by food bank for experiment 2

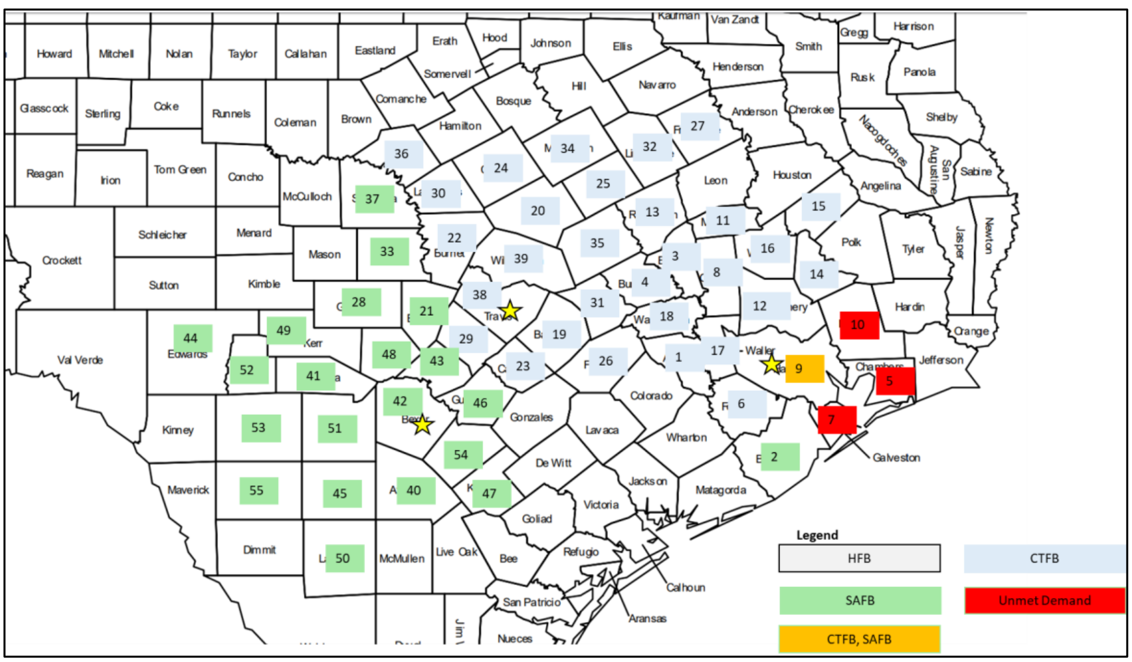


Figure 35: Counties served by food bank for experiment 3

In experiment 3, HFB is closed due to hurricane category 4 or higher. The cost of experiment 3 is ~81% less compared with experiment 1. Figure 35 depicts that even though pre-position is allowed there is unmet demand for few counties. Majority of counties under HFB are served by CTFB. County 9 of HFB is served by both CTFB and SAFB due its high demand when impacted by category 4 and 5 hurricanes.

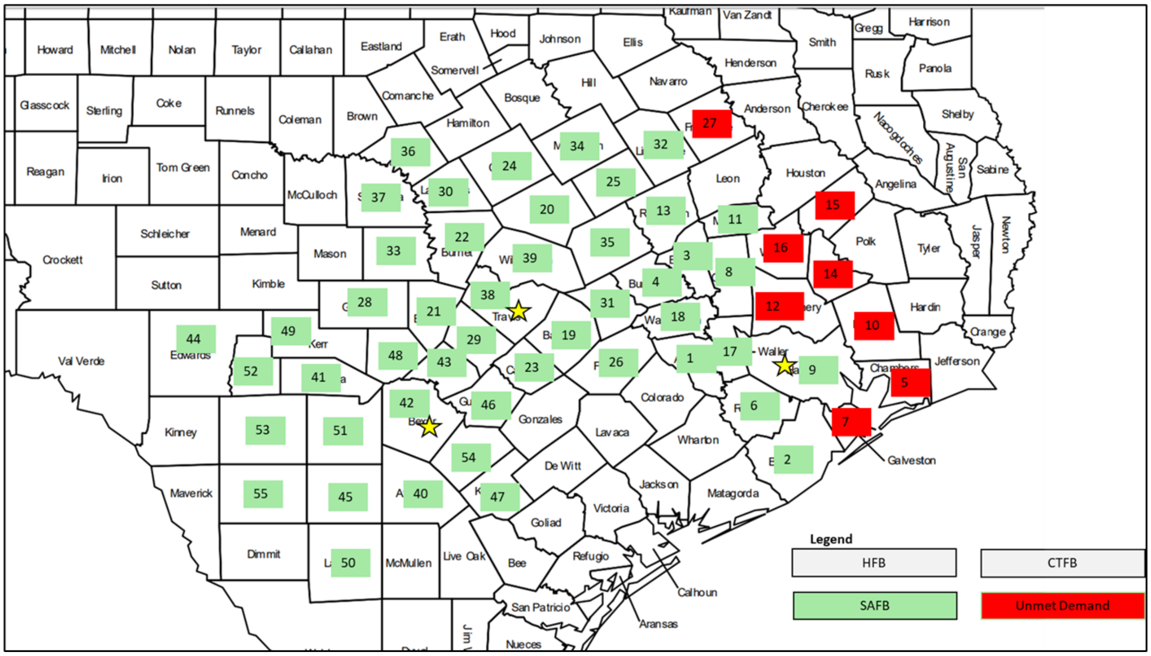


Figure 36: Counties served by food bank for experiment 4

Figure 36 gives an overview of experiment 4 results when HFB and the CTFB are closed after a hurricane category 4 or higher. Figure 36 shows that SAFB is serving more counties due to the unavailability of the other two food bank facilities. Table 18 indicates that SAFB receives supplies from HFB and CTFB before the hurricane to support their counties for categories 4 and 5 hurricanes. There is unmet demand for 7 HFB counties and one county# 27 of CTFB. The SAFB tries to meet the demand requirement of each demand node keeping the transportation cost minimum.

Figure 37 gives an overview of experiment 5 results when HFB and the SAFB are closed after a hurricane category 4 or higher. Figure 15 shows that CTFB is serving more counties due to the unavailability of the other two food bank facilities. Table 18 indicates that CTFB receives supplies from HFB and SAFB before the hurricane to support their counties for categories 4 and 5 hurricanes. There is unmet demand for 7 HFB counties and four SAFB counties. The CTFB tries to meet the demand requirement of each demand node keeping the transportation cost minimum.

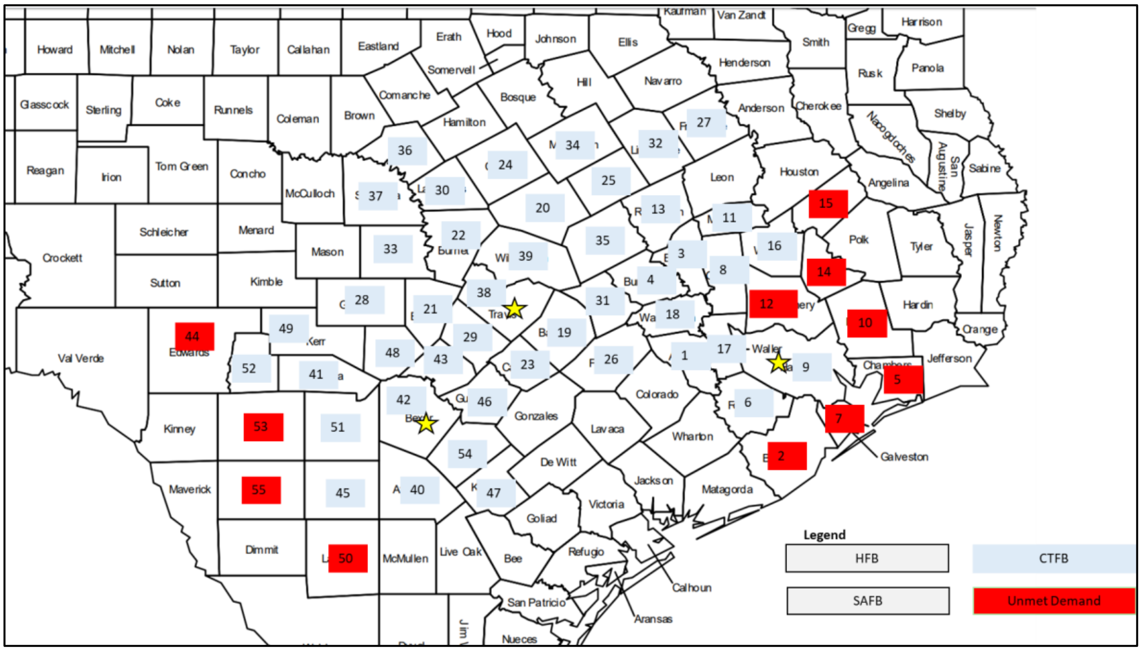


Figure 37: County served by food bank for experiment 5

Table 19 summarizes the unmet demand of all experiments for all categories of hurricanes. Table 20 below indicates the distribution coverage of each food bank for categories 1,2 and 3 categories and Table 21 for categories 4 and 5 hurricanes.

Table 19: Counties of unmet demand for all experiments

Exp #	Description	HFB Open ?	CTFB Open?	SAFB Open?	Unmet Demand counties	
					Cat. – 1,2,3	Cat. -4 &5
1	Benchmark	No	Yes	Yes	None	2,5,7,9,10,12,14,15,27
2	Ideal	Yes	Yes	Yes	None	None
3	HFB Closed	No	Yes	Yes	None	5,7,10
4	HFB and CTFB closed	No	No	Yes	None	2,5,7,10,11,12,14,15,16,27,
5	HFB and SAFB closed	No	Yes	No	None	2,5,7,10,12,14,15,44,50,53,55

Table 20: Distribution coverage of each food bank for categories 1,2 and 3 hurricanes

Exp #	**Counties covered**		
	HFB	**CTFB**	**SAFB**
2,3,4 and 5	1,2,3,5,6,7,8,9,1011,12, 14,15,16,17,18	4,13,19,20,21,22,23,24,25,26,2 7,29,30,31,32,33,34,35,36,37,3 8,39,46	28,40,41,42,43,44,45,47,48,4 9, 50,51,52,53,54,55

Table 21: Distribution coverage of each food bank for categories 4 and 5 hurricanes

Exp #	**Counties covered**		
	HFB	**CTFB**	**SAFB**
1	Close	1,3,4,6,8,9,11,13,16,17,18,19,20,22,2 3,24,25,26,29,30,31,32,34,35,36,38,3 9	9,21,28,33,37,40,41,42,43,44,45,46,47,4 8,49,50,51,52,53,54,55
2	5,9,10	1,3,4,7,8,9,11,12,13,14,15,16,17,18,1 9,20,22,23,24,25,26,27,29,30,31,32,3 4,35,36,38,39	2,6,7,9,21,28,33,37,40,41,42,43,44,45,46 ,47,48,49,50,51,52,53,54,55
3	Close	1,3,4,5,6,7,8,9,10,11,12,13,14,15,16,1 7,18,19,20,22,23,24,25,26,27,29,30,3 1,32,34,35,36,38,39	25,7,9,21,28,33,37,40,41,42,43,44,45,46, 47,48,49,50,51,52,53,54,55
4	Close	Close	1,2,3,4,6,8,9,11,12,13,16,17,18,19,20,21, 22,23,24,25,26,28,29,30,31,32,33,34,35, 36,37,38,39,40,41,42,43,44,45,46,47,48, 49,50,51,52,53,54,55
5	Close	1,2,3,4,6,8,9,11,12,13,16,17,18,19,20, 21,22,23,24,25,26,27,28,29,30,31,32, 33,34,35,36,37,38,39,40,41,42,43,45, 46,47,48,49,51,52,54,55	Close

4.7.2 Results and discussions of simulation model in chapter 3 of this thesis

Table 21 shows the assignment of county agencies for each food bank per experiment according to the results of the stochastic model defined in section 4.2. The simulation model connectors between supply nodes and demand nodes in chapter 3 of this thesis are modeled according to the results in Table 21 for experiments 2 to 5. The simulation is set up for 10 replications for all 5 experiments with a warmup period of 1 week. The simulation model results are presented in Tables 22 and 23. The tables show the results for the performance measurements discussed in Section 3.2 per experiment as described in Table 7. The results mentioned are the average values of simulation results with 95% confidence intervals. Table 22 lists the results for experiments 1 and 2 in where all food banks are assumed to be in operation during the disaster relief period. The only difference between these two experiments is that in experiment 2 collaboration is allowed between the food banks. It is observed that the total demand met (in pallets) for the HFB is less than the total demand unmet (in pallets) on both experiments. The reasoning behind this result is that the demand for supplies is very high during the disaster relief period and the inventory available is not enough to cover the demand for all Houston agencies. Specifically, county numbers 2,3,6,9, and 12 of HFB experience high demand for disaster relief operations, of which county 9 demand is very high as it is prone to disaster affected regions. However, the results for experiment 2 demonstrate that the collaboration among the food banks is effective since it produces a 16% increase in the demand fulfillment rate. This increase is demand fulfillment rate is possible because the CTFB is distributing supplies to multiple HFB agencies during the disaster relief period. Table 22 shows that the average number of trips per day increases from 5.1 to 17.36 for the HFB when collaboration is allowed within the food bank network (i.e., experiment 2). Experiment 2 also shows that the number of trips per day for the HFB decreases from 13.54 in experiment 1 to 5.2 is experiment 2. The reasoning behind this result is that HFB is supplying only to those agencies that are located close to the facility which are the ones with the highest demand in the Houston area. In terms of orders' fulfillment rates, the results show that in experiment 2(i.e., collaboration between food banks) all food bank facilities have a rate higher than 90%.

Table 22: Simulation model experimental results for experiments 1 and 2

Exp# (E#)	Food bank	Total demand met (in pallets)	Total demand unmet (In pallets)	Demand fulfillment rate (%)	Orders' fulfillment rate (%)	Avg. number of trips per day	Delivery cycle time (In days)
E1: All food banks in operation and no collaboration	HFB	3,995 ± 133	7,775 ± 142	36.58	86.4	13.54 ± 0.14	1.69 ± 0.07
	CTFB	239 ± 3	0		100	5.1 ± 0.06	1.72 ± 0.02
	SAFB	250 ± 6.1	0		100	3.43 ± 0.03	1.67 ± 0.01
E2: All food banks in operation and collaborating	HFB	4,422 ± 56	6,653 ± 310	42.36	93.5	5.2 ± 0.06	1.63 ± 0.01
	CTFB	239 ± 6.1	2 ± 3		99.7	17.36 ± 0.15	1.80 ± 0.03
	SAFB	236 ± 11	10 ± 6		98.9	5.25 ± 0.1	1.71 ± 0.03

Table 23 lists the results for experiments 3, 4, and 5 where not all food banks are in operation during the first four weeks of the disaster relief period. The results for experiment 3, 4, and 5 show that only around 22-25% of the demand can be covered during the disaster relief period if at least one food bank facility is not operating. However, the collaboration between food bank facilities allows to have at least 73% of the orders from the agencies assigned to HFB fulfilled. The average number of trips per day per experiment shows which facility is impacted the most when one or two of the facilities is not in operation. For instance, experiment 3 shows that when HFB is down, the CTFB performs most of the distribution with average number of trips of 19.32. Similarly, SAFB and CTFB are impacted the most in experiments 4 and 5, respectively.

Table 23: Simulation model experimental results for experiments 3, 4, and 5

Exp (E#)	**Food bank**	**Total demand met (in pallets)**	**Total demand unmet (In pallets)**	**Demand fulfillment rate (%)**	**Orders' fulfillment rate (%)**	**Avg. number of trips per day**	**Delivery cycle time (in days)**
E3: HFB closed and CTFB and SAFB collaborating	HFB	2,632 ± 40	8,533 ± 148	25.92	77.0	2.7 ± 0.03	1.40 ± 0.01
	CTFB	161 ± 7.7	85 ± 8		85.9	19.32 ± 0.3	1.55 ± 0.04
	SAFB	230 ± 10.6	25.2 ± 12.5		97.9	5.7 ± 0.2	1.62 ± 0.03
E4: HFB and CTFB closed and SAFB in charge of distribution	HFB	2,195 ± 30.6	8,641 ± 188	22.47	73.3	3.6 ± 0.04	2.17 ± 0.14
	CTFB	198 ± 6.39	47 ± 6.02		94.0	9.87 ± 0.1	3.00 ± 0.25
	SAFB	153 ± 4.7	98 ± 5.45		92.8	19.43 ± 0.5	3.20 ± 0.25
E5: HFB and SAFB closed and CTFB in charge of distribution	HFB	2,200 ± 39	8,732 ± 213	22.38	73.7	3.24 ± 0.34	1.39 ± 0.03
	CTFB	179 ± 7.86	66 ± 4.43		88.7	21.5 ± 0.04	1.66 ± 0.03
	SAFB	185 ± 10.7	80 ± 5.65		95.8	3.36 ± 0.07	1.78 ± 0.03

(HFB-Houston food bank, CTFB- Central Texas food bank, SAFB-San Antonio food bank)

5. CONCLUSION

The goal of this thesis is to develop data-driven models for improving the operations of a network of food bank facilities in charge of providing relief after natural disasters. This research is based on data received from three major food bank facilities in Texas region HFB, CTFB and SAFB, before and after the impact of a natural disaster. Food bank simulation models were developed to understand the behavior of food bank operations during "regular" and "disaster relief" operational periods. The simulation model input parameters are interpreted using two years of historical data at each food bank.

These results of our case study provide valuable information to increase the supply chain resilience for the food banks facilities affected by natural hazards. For instance, the simulation model results showed that proper planning in terms of supply prepositioning provides an increase of almost 20% in demand fulfillment after a hurricane category 4. The simulation model developed in this work also showed to be valuable to study and plan for scenarios in which one of the distribution centers become inactive after a hurricane.

One of the most challenging aspects of planning for disaster relief is to decide which distribution center should serve the different areas affected by the natural hazard. If proper planning is not developed multiple things can go wrong. For instance, an area could end up being under served because no distribution center was assigned to cover its demand. To address this challenge, we presented a two-stage stochastic programming that aims to serve as a decision-making model for the prepositioning of supplies within a network of food banks when planning for natural hazards. The stochastic model considers the uncertainty associated with the impact of the hurricane on a network of food banks in terms of the number of available supplies, donations received per facility, transportation limitations and the expected demand for their service region after the natural disaster. The stochastic model identifies the least-cost strategy associated with pre-positioning existing supplies that will satisfy the demand needs after a natural disaster. The results show that the pre-positioning of supplies provided cost savings in terms of distance traveled and unmet demand. The results from stochastic model are considered for modeling the connectors between supply nodes and demand nodes in the simulation model.

To the best of our knowledge, the application of discrete-event simulation combined with optimization models to study and plan food bank facilities' disaster relief operations is a new and showed to be an effective tool that can minimize the unmet demand of food bank facilities and serve more people in need. The presented simulation model framework is capable to simulate the operations of any food bank facility by modifying the values of donations arrivals and distribution center demand distributions which can help to strategize and plan the disaster relief operations.

Future research can focus on developing more new scheduling models in discrete-event simulation, which can help the food bank operations. There is a scope of improvement in measuring more key performances. The inclusion of partial fulfillment of orders to be processed by food bank facilities can help the management improve food bank operations in disaster relief operations. There is a possibility of including the sensitivity analysis of food bank resources in the simulation model, which can help the food banks to plan the resources during disaster relief operations. Future research could also extend the presented stochastic model to consider other natural disasters like earthquakes and a pandemic. There is also additional scope to consider integrating different food banks located at a greater distance and their impact on the pre-positioning and overall cost. In the future, there is a possibility of building an iterative process of combining the results from the stochastic model to the discrete event simulation model and again checking the behavior of the stochastic model with the results of the discrete event simulation model to identify the optimal assignment allocation of distribution centers for disaster relief operations.

APPENDIX SECTION

APPENDIX A

DEMAND CHANGING FACTOR OF HOUSTON FOOD BANK

Counties	Food Bank	Scenarios																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	Houston	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
2		1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
3		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
4		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
5		1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
6		1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
7		1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
8		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
9		1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
10		1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
11		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
12		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
13		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
14		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
15		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
16		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
17		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
18		1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5

APPENDIX B

DEMAND CHANGING FACTOR OF CENTRAL TEXAS FOOD BANK

Counties	Food Bank	Scenarios																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
19	CTFB	1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
20		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
21		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
22		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
23		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
24		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
25		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
26		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
27		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
28		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
29		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
30		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
31		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
32		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
33		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
34		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
35		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
36		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
37		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
38		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
39		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4

APPENDIX C

DEMAND CHANGING FACTOR OF SAN ANTONIO FOOD BANK

Counties	Food Bank	Scenarios																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
40	San Antonio	1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
41		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
42		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
43		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
44		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
45		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
46		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
47		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
48		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
49		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
50		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
51		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
52		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
53		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
54		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4
55		1	1	1	1	1	1	1.1	1	1.1	1	1.2	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4

APPENDIX D

MODEL FILE OF STOCHASTIC MODELING (Experiments 2,3,4 and 5)

set SUPPLIER_NODE1;
set SUPPLIER_NODE2;
set DEMAND_NODE;
set SCENARIO;

Parameters

param N >0; # supplier node 1
param J >0; # supplier node 2
param I >0; # Inbound Supplier node1
param H >0; # No. of distribution centers
param S >0; #No. of scenarios

param Initial_Inventory_supplynode{SUPPLIER_NODE1} >=0;
param Storage_Capacity_supplynode {SUPPLIER_NODE1} >=0;
param Regular_Donations_supplynode{SUPPLIER_NODE1} >=0;
param Disaster_Donations_supplynode{SUPPLIER_NODE1} >=0;
param Transportation_cost_ss {SUPPLIER_NODE1,SUPPLIER_NODE2} >=0; #dnj Unit transportation cost from supply node to demand node
param Transportation_trips_supplier {SUPPLIER_NODE1} >=0;
param Forecasted_demand_DC {DEMAND_NODE} >=0;
param Transportation_cost_sd {SUPPLIER_NODE1,DEMAND_NODE} >=0;
param prob {SCENARIO} >=0;
param demand_change_factor{DEMAND_NODE,SCENARIO}; # Demand changing factor at demand node per scenario
param donation_change_factor{SUPPLIER_NODE1,SCENARIO}; #delta,omega- Donation changing factor at supply node per scenario
param Inventory_change_factor{SUPPLIER_NODE1,SCENARIO};#Inventory changing factor at supply node per scenario
param Unmet_demand_unit_cost >=0; # Unit cost for unmet demand at demand node
param remain_penality_unit_cost >=0;
param Trucks_trucktype1_avail_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_trucktype2_avail_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_trucktype1_capacity_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_trucktype2_capacity_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_Limit_supplynode{SUPPLIER_NODE1} >=0;

Decision Variables

var Pre_Positioned_quantity {1..N} >= 0; #Sn prepositioned quantiy to be stored
var Quantity_SS {1..N,1..J} >=0; # quantity of supplies to be shipped
var Quantity_IB_SS {1..I,1..N} >=0;
var Unmet_demand{DEMAND_NODE, SCENARIO} >= 0;#Unmet demand quantity at node

per scenario
var Quantity_SS_Scenario{SUPPLIER_NODE1,SUPPLIER_NODE2, SCENARIO} >= 0;# , Quantity of supplies shipped from supplier to supplier per scenario
var Quantity_IB_SS_Scenario {1..I,1..N,1..S} >=0;
var Quantity_SD{SUPPLIER_NODE1,DEMAND_NODE, SCENARIO} >= 0;# Quatity of supplies shipped from supplier node to demand node per scenario
#var Donation_SS{SUPPLIER_NODE1,SCENARIO} >=0;
var Additional_truck{SUPPLIER_NODE1, SCENARIO} >=0;
var Truck_total_available{SUPPLIER_NODE1, SCENARIO} >=0;

Objective Function

minimize preposition_cost:

sum {n in SUPPLIER_NODE1, j in SUPPLIER_NODE2}
Quantity_SS[n,j]*Transportation_cost_ss[n,j]+
sum {s in SCENARIO}prob[s]*((sum {n in SUPPLIER_NODE1,h in DEMAND_NODE}Quantity_SD[n,h,s]* Transportation_cost_sd[n,h]) +
(sum {n in SUPPLIER_NODE1,j in SUPPLIER_NODE2}Quantity_SS_Scenario[n,j,s]* Transportation_cost_ss[n,j])+
(sum {h in DEMAND_NODE}Unmet_demand_unit_cost* Unmet_demand[h,s])+
(sum {n in SUPPLIER_NODE1}remain_penality_unit_cost* Additional_truck[n,s]));

Constraints

Pre-positioning constraints - First stage:

subject to
Flow Balance constraints:

Total_sent1_quant{n in 1..1}:
Pre_Positioned_quantity[1]=sum{i in 2..3}Quantity_SS[i,n]+Initial_Inventory_supplynode[1]-sum{j in 2..3}Quantity_SS[n,j]+Regular_Donations_supplynode[n];

subject to
Total_sent2_quant{n in 2..2}:
Pre_Positioned_quantity[2]=sum{i in 1..1}Quantity_SS[i,n]+sum{i in 3..3}Quantity_SS[i,n]+Initial_Inventory_supplynode[2]-(sum{j in 1..1}Quantity_SS[n,j]+sum{j in 3..3}Quantity_SS[n,j])+Regular_Donations_supplynode[2];

subject to
Total_sent4_quant{n in 3..3}:
Pre_Positioned_quantity[3]=sum{i in 1..1}Quantity_SS[i,n]+sum{i in 2..2}Quantity_SS[i,n]+Initial_Inventory_supplynode[3]-(sum{j in 1..1}Quantity_SS[n,j]+sum{j in 2..2}Quantity_SS[n,j])+Regular_Donations_supplynode[3];

subject to
Pre-positioned storage capacity constraints:

```
Pre_positioned_storage_capacity{n in 1..N}:
Pre_Positioned_quantity[n] <= Storage_Capacity_supplynode[n];

subject to
## Truck-capacity constraint:
Truck_capacity{n in 1..3}:
sum{j in 1..3}Quantity_SS[n,j] <=
((Trucks_trucktype1_capacity_supplynode[n]*Trucks_trucktype1_avail_supplynode[n])+
(Trucks_trucktype2_capacity_supplynode[n]*Trucks_trucktype2_avail_supplynode[n]))*Transpo
rtation_trips_supplier[n];


# Response-stage constraints:
#subject to
## Damage:
#Donation_Constraint{n in 1..N,s in 1..S}:

#Donation_SS[n,s] = Pre_Positioned_quantity[n] + (Disaster_Donations_supplynode[n] *
donation_change_factor[n,s]);

## Flow constraint:
#subject to
#Total_send_const{n in SUPPLIER_NODE1, s in SCENARIO}:
#(sum{j in SUPPLIER_NODE2}
Quantity_SS_Scenario[n,j,s]*Inventory_change_factor[n,s])+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <=
#(Donation_SS[n,s] * Inventory_change_factor[n,s])+ (sum{i in
SUPPLIER_NODE1}Quantity_IB_SS_Scenario[i,n,s]*Inventory_change_factor[n,s]);

#subject to
#Total_send_const{n in SUPPLIER_NODE1, s in SCENARIO}:
#(sum{j in SUPPLIER_NODE2} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <=
#(Donation_SS[n,s] * Inventory_change_factor[n,s])+ (sum{i in
SUPPLIER_NODE1}Quantity_IB_SS_Scenario[i,n,s]);
subject to
#Total_send_const{n in SUPPLIER_NODE1, s in SCENARIO}:
#(sum{j in SUPPLIER_NODE2} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <=
#(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ (sum{i in
SUPPLIER_NODE1}Quantity_IB_SS_Scenario[i,n,s])+
#(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);


Total_send1_const{n in 1..1, s in SCENARIO}:
(sum{j in 2..3} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE} Quantity_SD[n,h,s]
<=
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ (sum{i in
2..3}Quantity_IB_SS_Scenario[i,n,s])+
(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);
```

```
Total_send2_const{n in 2..2, s in SCENARIO}:
((sum{j in 1..1} Quantity_SS_Scenario[n,j,s])+(sum{j in 3..3}
Quantity_SS_Scenario[n,j,s]))+sum{h in DEMAND_NODE} Quantity_SD[n,h,s] <=
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ ((sum{i in
1..1}Quantity_IB_SS_Scenario[i,n,s])+(sum{i in 3..3}Quantity_IB_SS_Scenario[i,n,s]))+
(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);

Total_send3_const{n in 3..3, s in SCENARIO}:
(sum{j in 1..2} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE} Quantity_SD[n,h,s]
<=
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ (sum{i in
1..2}Quantity_IB_SS_Scenario[i,n,s])+
(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);
Total_send4_const{n in 2..2, s in SCENARIO}:
((sum{j in 1..1} Quantity_SS_Scenario[n,j,s])+(sum{j in 3..3} Quantity_SS_Scenario[n,j,s]))=
((sum{i in 1..1}Quantity_IB_SS_Scenario[i,n,s])+(sum{i in
3..3}Quantity_IB_SS_Scenario[i,n,s]));
Total_send5_const{n in 1..1, s in SCENARIO}:
(sum{j in 2..3} Quantity_SS_Scenario[n,j,s])=
(sum{i in 2..3}Quantity_IB_SS_Scenario[i,n,s]);
Total_send6_const{n in 3..3, s in SCENARIO}:
(sum{j in 1..2} Quantity_SS_Scenario[n,j,s])=
(sum{i in 1..2}Quantity_IB_SS_Scenario[i,n,s]);
subject to
## Demand Constraint:
Demand_Constraint{h in DEMAND_NODE, s in SCENARIO}:
sum{n in SUPPLIER_NODE1} Quantity_SD[n,h,s] + Unmet_demand[h,s] =
(Forecasted_demand_DC[h] * demand_change_factor[h,s]);
subject to
# Response stage Storage capacity constraint
Pre_positioned_storage_capacity_response_stage{n in 1..N,s in 1..S}:
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+(Pre_Positioned_quantity[n]
* Inventory_change_factor[n,s]) <= Storage_Capacity_supplynode[n];
subject to
# Truck-capacity constraintsS_D
Truck_capacity_sd{n in          SUPPLIER_NODE1, s in SCENARIO}:
sum{j in SUPPLIER_NODE2} Quantity_SS_Scenario[n,j,s]+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <= Truck_total_available[n,s];

subject to
Truck_available_total{n in SUPPLIER_NODE1, s in SCENARIO}:
Truck_total_available[n,s]=
(((Trucks_trucktype1_capacity_supplynode[n]*Trucks_trucktype1_avail_supplynode[n])+
(Trucks_trucktype2_capacity_supplynode[n]*Trucks_trucktype2_avail_supplynode[n]))*Transpo
rtation_trips_supplier[n])+
Additional_truck[n,s];
subject to
Truck_Limit{n in SUPPLIER_NODE1,s in SCENARIO}:
Additional_truck[n,s]<=Trucks_Limit_supplynode[n]*Transportation_trips_supplier[n];
```

APPENDIX E

MODEL FILE OF STOCHASTIC MODELING (Experiment 1)

```
set SUPPLIER_NODE1;
set SUPPLIER_NODE2;
set DEMAND_NODE;
set SCENARIO;

# Parameters

param N >0; # supplier node 1
param J >0; # supplier node 2
param I >0; # Inbound Supplier node1
param H >0; # No. of distribution centers
param S >0; #No. of scenarios


param Initial_Inventory_supplynode{SUPPLIER_NODE1} >=0;
param Storage_Capacity_supplynode {SUPPLIER_NODE1} >=0;
param Regular_Donations_supplynode{SUPPLIER_NODE1} >=0;
param Disaster_Donations_supplynode{SUPPLIER_NODE1} >=0;
param Transportation_cost_ss {SUPPLIER_NODE1,SUPPLIER_NODE2} >=0; #dnj Unit
transportation cost from supply node to demand node
param Transportation_trips_supplier {SUPPLIER_NODE1} >=0;
param Forecasted_demand_DC {DEMAND_NODE} >=0;
param Transportation_cost_sd {SUPPLIER_NODE1,DEMAND_NODE} >=0;
param prob {SCENARIO} >=0;
param demand_change_factor{DEMAND_NODE,SCENARIO}; # Demand changing factor at
demand node per scenario
param donation_change_factor{SUPPLIER_NODE1,SCENARIO}; #delta,omega- Donation
changing factor at supply node per scenario
param Inventory_change_factor{SUPPLIER_NODE1,SCENARIO};#Inventory changing factor
at supply node per scenario
param Unmet_demand_unit_cost >=0; #  Unit cost for unmet demand at demand node
param remain_penality_unit_cost >=0;
param Trucks_trucktype1_avail_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_trucktype2_avail_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_trucktype1_capacity_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_trucktype2_capacity_supplynode{SUPPLIER_NODE1} >=0;
param Trucks_Limit_supplynode{SUPPLIER_NODE1} >=0;


# Decision Variables

var Pre_Positioned_quantity {1..N} >= 0; #Sn prepositioned quantiy to be stored
var Quantity_SS {1..N,1..J} >=0; # quantity of supplies to be shipped
var Quantity_IB_SS {1..I,1..N} >=0;
var Unmet_demand{DEMAND_NODE, SCENARIO} >= 0;#Unmet demand quantity at node
per scenario
var Quantity_SS_Scenario{SUPPLIER_NODE1,SUPPLIER_NODE2, SCENARIO} >= 0;# ,
```

Quantity of supplies shipped from supplier to supplier per scenario
var Quantity_IB_SS_Scenario {1..I,1..N,1..S} >=0;
var Quantity_SD{SUPPLIER_NODE1,DEMAND_NODE, SCENARIO} >= 0;# Quatity of supplies shipped from supplier node to demand node per scenario
#var Donation_SS{SUPPLIER_NODE1,SCENARIO} >=0;
var Additional_truck{SUPPLIER_NODE1, SCENARIO} >=0;
var Truck_total_available{SUPPLIER_NODE1, SCENARIO} >=0;

Objective Function

minimize preposition_cost:

sum {n in SUPPLIER_NODE1, j in SUPPLIER_NODE2}
Quantity_SS[n,j]*Transportation_cost_ss[n,j]+
sum {s in SCENARIO}prob[s]*((sum {n in SUPPLIER_NODE1,h in DEMAND_NODE}Quantity_SD[n,h,s]* Transportation_cost_sd[n,h]) +
(sum {n in SUPPLIER_NODE1,j in SUPPLIER_NODE2}Quantity_SS_Scenario[n,j,s]* Transportation_cost_ss[n,j])+
(sum {h in DEMAND_NODE}Unmet_demand_unit_cost* Unmet_demand[h,s])+
(sum {n in SUPPLIER_NODE1}remain_penality_unit_cost* Additional_truck[n,s]));

Constraints

Pre-positioning constraints - First stage:

subject to
Flow Balance constraints:

Total_sent1_quant{n in 1..1}:
Pre_Positioned_quantity[1]=sum{i in 2..3}Quantity_SS[i,n]+Initial_Inventory_supplynode[1]-sum{j in 2..3}Quantity_SS[n,j]+Regular_Donations_supplynode[n];

subject to
Total_sent2_quant{n in 2..2}:
Pre_Positioned_quantity[2]=sum{i in 1..1}Quantity_SS[i,n]+sum{i in 3..3}Quantity_SS[i,n]+Initial_Inventory_supplynode[2]-(sum{j in 1..1}Quantity_SS[n,j]+sum{j in 3..3}Quantity_SS[n,j])+Regular_Donations_supplynode[2];

subject to
Total_sent4_quant{n in 3..3}:
Pre_Positioned_quantity[3]=sum{i in 1..1}Quantity_SS[i,n]+sum{i in 2..2}Quantity_SS[i,n]+Initial_Inventory_supplynode[3]-(sum{j in 1..1}Quantity_SS[n,j]+sum{j in 2..2}Quantity_SS[n,j])+Regular_Donations_supplynode[3];

subject to
Pre-positioned storage capacity constraints:
Pre_positioned_storage_capacity{n in 1..N}:

```
Pre_Positioned_quantity[n] <= Storage_Capacity_supplynode[n];

subject to
## Truck-capacity constraint:
Truck_capacity{n in 1..3}:
sum{j in 1..3}Quantity_SS[n,j] <=
((Trucks_trucktype1_capacity_supplynode[n]*Trucks_trucktype1_avail_supplynode[n])+
(Trucks_trucktype2_capacity_supplynode[n]*Trucks_trucktype2_avail_supplynode[n]))*Transpo
rtation_trips_supplier[n];


# Response-stage constraints:
#subject to
## Damage:
#Donation_Constraint{n in 1..N,s in 1..S}:

#Donation_SS[n,s] = Pre_Positioned_quantity[n] + (Disaster_Donations_supplynode[n] *
donation_change_factor[n,s]);

## Flow constraint:
#subject to
#Total_send_const{n in SUPPLIER_NODE1, s in SCENARIO}:
#(sum{j in SUPPLIER_NODE2}
Quantity_SS_Scenario[n,j,s]*Inventory_change_factor[n,s])+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <=
#(Donation_SS[n,s] * Inventory_change_factor[n,s])+ (sum{i in
SUPPLIER_NODE1}Quantity_IB_SS_Scenario[i,n,s]*Inventory_change_factor[n,s]);

#subject to
#Total_send_const{n in SUPPLIER_NODE1, s in SCENARIO}:
#(sum{j in SUPPLIER_NODE2} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <=
#(Donation_SS[n,s] * Inventory_change_factor[n,s])+ (sum{i in
SUPPLIER_NODE1}Quantity_IB_SS_Scenario[i,n,s]);
subject to
#Total_send_const{n in SUPPLIER_NODE1, s in SCENARIO}:
#(sum{j in SUPPLIER_NODE2} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <=
#(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ (sum{i in
SUPPLIER_NODE1}Quantity_IB_SS_Scenario[i,n,s])+
#(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);


Total_send1_const{n in 1..1, s in SCENARIO}:
(sum{j in 2..3} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE} Quantity_SD[n,h,s]
<=
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ (sum{i in
2..3}Quantity_IB_SS_Scenario[i,n,s])+
(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);

Total_send2_const{n in 2..2, s in SCENARIO}:
```

```
((sum{j in 1..1} Quantity_SS_Scenario[n,j,s])+(sum{j in 3..3}
Quantity_SS_Scenario[n,j,s]))+sum{h in DEMAND_NODE} Quantity_SD[n,h,s] <=
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ ((sum{i in
1..1}Quantity_IB_SS_Scenario[i,n,s])+(sum{i in 3..3}Quantity_IB_SS_Scenario[i,n,s]))+
(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);

Total_send3_const{n in 3..3, s in SCENARIO}:
(sum{j in 1..2} Quantity_SS_Scenario[n,j,s])+sum{h in DEMAND_NODE} Quantity_SD[n,h,s]
<=
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+ (sum{i in
1..2}Quantity_IB_SS_Scenario[i,n,s])+
(Pre_Positioned_quantity[n]*Inventory_change_factor[n,s]);
Total_send4_const{n in 2..2, s in SCENARIO}:
((sum{j in 1..1} Quantity_SS_Scenario[n,j,s])+(sum{j in 3..3} Quantity_SS_Scenario[n,j,s]))=
((sum{i in 1..1}Quantity_IB_SS_Scenario[i,n,s])+(sum{i in
3..3}Quantity_IB_SS_Scenario[i,n,s]));
Total_send5_const{n in 1..1, s in SCENARIO}:
(sum{j in 2..3} Quantity_SS_Scenario[n,j,s])=
(sum{i in 2..3}Quantity_IB_SS_Scenario[i,n,s]);

Total_send6_const{n in 3..3, s in SCENARIO}:
(sum{j in 1..2} Quantity_SS_Scenario[n,j,s])=
(sum{i in 1..2}Quantity_IB_SS_Scenario[i,n,s]);
subject to
## Demand Constraint:
Demand_Constraint{h in DEMAND_NODE, s in SCENARIO}:
sum{n in SUPPLIER_NODE1} Quantity_SD[n,h,s] + Unmet_demand[h,s] =
(Forecasted_demand_DC[h] * demand_change_factor[h,s]);

subject to
# Response stage Storage capacity constraint
Pre_positioned_storage_capacity_response_stage{n in 1..N,s in 1..S}:
(Disaster_Donations_supplynode[n] * donation_change_factor[n,s])+(Pre_Positioned_quantity[n]
* Inventory_change_factor[n,s]) <= Storage_Capacity_supplynode[n];
subject to
# Truck-capacity constraintsS_D
Truck_capacity_sd{n in          SUPPLIER_NODE1, s in SCENARIO}:
sum{j in SUPPLIER_NODE2} Quantity_SS_Scenario[n,j,s]+sum{h in DEMAND_NODE}
Quantity_SD[n,h,s] <= Truck_total_available[n,s];

subject to
Truck_available_total{n in SUPPLIER_NODE1, s in SCENARIO}:
Truck_total_available[n,s]=
(((Trucks_trucktype1_capacity_supplynode[n]*Trucks_trucktype1_avail_supplynode[n])+
(Trucks_trucktype2_capacity_supplynode[n]*Trucks_trucktype2_avail_supplynode[n]))*Transpo
rtation_trips_supplier[n])+
Additional_truck[n,s];

subject to
Truck_Limit{n in SUPPLIER_NODE1,s in SCENARIO}:
Additional_truck[n,s]<=Trucks_Limit_supplynode[n]*Transportation_trips_supplier[n];
```

APPENDIX F

DATA FILE OF STOCHASTIC MODELING (Experiment 1)

```
set SUPPLIER_NODE1 := 1 2 3;
set SUPPLIER_NODE2 := 1 2 3;
#set SUPPLIER_NODE1_IB := 1 2 3;
set DEMAND_NODE := 1 2 3 4 5 6 7 8 9 10
                11 12 13 14 15 16 17 18 19 20
                21 22 23 24 25 26 27 28 29 30
                31 32 33 34 35 36 37 38 39 40
                41 42 43 44 45 46 47 48 49 50
                51 52 53 54 55;
set SCENARIO := 1 2 ;
#param n =3; # supplier node 1
#param j =3; # supplier node 2
#param h =55; # No. of distribution centers
#param S =21; #No. of scenarios

param N =3; # supplier node 1
param I =3; # supplier node 1 Inbound
param J =3; # supplier node 2
param H =55; # No. of distribution centers
param S =2; #No. of scenarios

param Initial_Inventory_supplynode:=

1       1998858.79
2       1371232.84
3       1371232.84;

param Storage_Capacity_supplynode:=

1       17500000
2       9000000
3       9000000;

param Regular_Donations_supplynode:=

1       65361.30
2       11247.46
3       11247.46;

param Disaster_Donations_supplynode:=

1       610363.92
2       57367.28
3       57367.28;

param Trucks_trucktype1_avail_supplynode:=
```

```
1           10
2           5
3           5;

param Trucks_trucktype2_avail_supplynode:=

1           10
2           3
3           3;

param Trucks_trucktype1_capacity_supplynode:=

1           40000
2           36000
3           36000;

param Trucks_trucktype2_capacity_supplynode:=

1           40000
2           12200
3           12200;


param Transportation_cost_ss:

            1 2 3:=
1           1000 165 208
2           165     1000 86
3           208     86 1000;

param Transportation_trips_supplier:=
1           3
2           3
3           3;

param Transportation_cost_sd:
            1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55:=

1 68.9 48.2 103 106 45.5 41.6 44.7 76.2 2.4 47 108 45.9 137 60 111 80 58.3 82.4 1000 1000 1000
1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
2 102 175 105 85 208 138 203 122 162 208 140 169 105 180 192 151 119 93.3 29.6 84.1 54.6
62.5 24.6 109 110 62.6 168 83.9 29.3 92.3 54.4 135 81.9 107 74.6 126 117 1.7 46.1 120 125 85.6
58.6 198 138 50.2 94.7 82 129 185 114 166 176 83.1 172
3 152 217 186 160 251 181 246 190 205 253 220 232 187 246 262 220 175 161 108 155 78.1 107
74.7 178 183 124 253 77.7 75.9 147 134 215 111 186 157 179     148 87.7 126 45.7 65.2  1.3 49.4
164 59  50.9 61.4 53.8 94.8 105 28.8 107 90.5 37.7 92.1;


param Forecasted_demand_DC:=
```

1	628.54
2	7682.92
3	10809.83
4	559.23
5	741.49
6	12789.2
7	8400.96
8	1019.79
9	159302.49
10	2678.38
11	530.45
12	11292.33
13	561.14
14	1032.7
15	790.51
16	2368.01
17	1506.45
18	995.53
19	2251.84
20	9500.03
21	242.86
22	1074.58
23	1252.98
24	2305.73
25	772.95
26	692.76
27	557.61
28	528.74
29	6038.48
30	562.71
31	433.3
32	1072.85
33	547.08
34	9887.82
35	805.57
36	147.63
37	208.99
38	30790.92
39	7452.74
40	1623.01
41	628.44
42	70191.87
43	2164.62
44	87.55
45	1119.74
46	2859.04
47	701.03
48	703.37
49	1496.77
50	458.05
51	1286.98

```
52	129.35
53	1263.23
54	1124.88
55	787.92;
param prob:=
#1	0.494
#2	0.041
#3	0.041
#4	0.005
#5	0.041
#6	0.01
#7	0.061
#8	0.01
#9	0.02
#10	0.019
#11	0.025
#12	0.006
#13	0.013
#14	0.006
#15	0.095
#16	0.019
#17	0.006
#18	0.009
#19	0.066
#20	0.013
#21	0.001;
1	0.50
2	0.50;
param demand_change_factor: 1	2	:=
1	15.4	15.4
2	15.4	15.4
3	15.4	15.4
4	15.4	15.4
5	15.4	15.4
6	15.4	15.4
7	15.4	15.4
8	15.4	15.4
9	15.4	15.4
10	15.4	15.4
11	15.4	15.4
12	15.4	15.4
13	15.4	15.4
14	15.4	15.4
15	15.4	15.4
16	15.4	15.4
17	15.4	15.4
18	15.4	15.4
19	1.3	1.3
20	1.3	1.3
21	1.3	1.3
22	1.3	1.3
```

```
23	1.3	1.3
24	1.3	1.3
25	1.3	1.3
26	1.3	1.3
27	1.3	1.3
28	1.3	1.3
29	1.3	1.3
30	1.3	1.3
31	1.3	1.3
32	1.3	1.3
33	1.3	1.3
34	1.3	1.3
35	1.3	1.3
36	1.3	1.3
37	1.3	1.3
38	1.3	1.3
39	1.3	1.3
40	1.3	1.3
41	1.3	1.3
42	1.3	1.3
43	1.3	1.3
44	1.3	1.3
45	1.3	1.3
46	1.3	1.3
47	1.3	1.3
48	1.3	1.3
49	1.3	1.3
50	1.3	1.3
51	1.3	1.3
52	1.3	1.3
53	1.3	1.3
54	1.3	1.3
55	1.3	1.3
;
param donation_change_factor:
  1	2:=
1 0	0
2 1.3 1.3
3 1.3 1.3;
param Inventory_change_factor:
			1	2	:=
1			0	0
2			1	1
3			1	1;
param Unmet_demand_unit_cost = 2000;
param remain_penality_unit_cost = 500;
param Trucks_Limit_supplynode:=

1	6400000
2	866400
3	866400;
```

APPENDIX G

DATA FILE OF STOCHASTIC MODELING (Experiment 2)

```
set SUPPLIER_NODE1 := 1 2 3;
set SUPPLIER_NODE2 := 1 2 3;
#set SUPPLIER_NODE1_IB := 1 2 3;
set DEMAND_NODE := 1 2 3 4 5 6 7 8 9 10
            11 12 13 14 15 16 17 18 19 20
            21 22 23 24 25 26 27 28 29 30
            31 32 33 34 35 36 37 38 39 40
            41 42 43 44 45 46 47 48 49 50
            51 52 53 54 55;
set SCENARIO := 1 2 3 4 5 6 7 8 9 10
          11 12 13 14 15 16 17 18 19 20
          21;
#param n =3; # supplier node 1
#param j =3; # supplier node 2
#param h =55; # No. of distribution centers
#param S =21; #No. of scenarios

param N =3; # supplier node 1
param I =3; # supplier node 1 Inbound
param J =3; # supplier node 2
param H =55; # No. of distribution centers
param S =21; #No. of scenarios

param Initial_Inventory_supplynode:=

1       1998858.79
2       1371232.84
3       1371232.84;

param Storage_Capacity_supplynode:=

1       17500000
2       9000000
3       9000000;

param Regular_Donations_supplynode:=

1       65361.30
2       11247.46
3       11247.46;

param Disaster_Donations_supplynode:=

1       610363.92
2       57367.28
3       57367.28;
```

```
param Trucks_trucktype1_avail_supplynode:=

1	10
2	5
3	5;

param Trucks_trucktype2_avail_supplynode:=

1	10
2	3
3	3;

param Trucks_trucktype1_capacity_supplynode:=

1	40000
2	36000
3	36000;

param Trucks_trucktype2_capacity_supplynode:=

1	40000
2	12200
3	12200;


param Transportation_cost_ss:

	1 2 3:=
1	1000 165 208
2	165	1000 86
3	208	86 1000;

param Transportation_trips_supplier:=
1	3
2	3
3	3;

param Transportation_cost_sd:
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55:=

1 68.9 48.2 103 106 45.5 41.6 44.7 76.2 2.4 47 108 45.9 137 60 111 80 58.3 82.4 1000 1000 1000
1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
2 102 175 105 85 208 138 203 122 162 208 140 169 105 180 192 151 119 93.3 29.6 84.1 54.6
62.5 24.6 109 110 62.6 168 83.9 29.3 92.3 54.4 135 81.9 107 74.6 126 117 1.7 46.1 120 125 85.6
58.6 198 138 50.2 94.7 82 129 185 114 166 176 83.1 172
3 152 217 186 160 251 181 246 190 205 253 220 232 187 246 262 220 175 161 108 155 78.1 107
74.7 178 183 124 253 77.7 75.9 147 134 215 111 186 157 179	148 87.7 126 45.7 65.2	1.3 49.4
164 59	50.9 61.4 53.8 94.8 105 28.8 107 90.5 37.7 92.1;
```

param Forecasted_demand_DC:=

1	628.54
2	7682.92
3	10809.83
4	559.23
5	741.49
6	12789.2
7	8400.96
8	1019.79
9	159302.49
10	2678.38
11	530.45
12	11292.33
13	561.14
14	1032.7
15	790.51
16	2368.01
17	1506.45
18	995.53
19	2251.84
20	9500.03
21	242.86
22	1074.58
23	1252.98
24	2305.73
25	772.95
26	692.76
27	557.61
28	528.74
29	6038.48
30	562.71
31	433.3
32	1072.85
33	547.08
34	9887.82
35	805.57
36	147.63
37	208.99
38	30790.92
39	7452.74
40	1623.01
41	628.44
42	70191.87
43	2164.62
44	87.55
45	1119.74
46	2859.04
47	701.03
48	703.37
49	1496.77

```
50	458.05
51	1286.98
52	129.35
53	1263.23
54	1124.88
55	787.92;

param prob:=

1	0.494
2	0.041
3	0.041
4	0.005
5	0.041
6	0.01
7	0.061
8	0.01
9	0.02
10	0.019
11	0.025
12	0.006
13	0.013
14	0.006
15	0.095
16	0.019
17	0.006
18	0.009
19	0.066
20	0.013
21	0.001;


param demand_change_factor: 1	2	3	4	5	6	7	8
	9	10	11	12	13	14	15	16	17	18	19
	20	21:=
1	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
2	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
3	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
4	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
5	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
6	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
7	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
8	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
```

9	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
10	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
11	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
12	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
13	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
14	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
15	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
16	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
17	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
18	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
19	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
20	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
21	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
22	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
23	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
24	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
25	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
26	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
27	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
28	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
29	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
30	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
31	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
32	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
33	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
34	1	1	1	1	1	1	1.1	1	1.1	1	1.2

```
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
35      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
36      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
37      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
38      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
39      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
40      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
41      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
42      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
43      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
44      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
45      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
46      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
47      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
48      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
49      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
50      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
51      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
52      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
53      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
54      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
55      1     1     1     1     1     1     1.1   1     1.1   1     1.2
        1     1.2   1     1.3   1     1.3   1     1.4   1     1.4
;

param donation_change_factor:

              1     2     3     4     5     6     7     8     9     10
        11    12    13    14    15    16    17    18    19    20    21:=
1             1     1     1     1     1     1     1     1     1     1
```

```
        2       2       2       1       2.3     1       2.3     1       2.7     1       2.7
2               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1.3     1       1.3     1       1.5     1       1.5
3               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1.3     1       1.3     1       1.5     1       1.5;


param Inventory_change_factor:
                1       2       3       4       5       6       7       8       9       10
        11      12      13      14      15      16      17      18      19      20      21:=
1               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1
2               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1
3               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1       1;
;

param Unmet_demand_unit_cost = 2000;


param remain_penality_unit_cost = 500;

param Trucks_Limit_supplynode:=

1       6400000
2       866400
3       866400;
```

APPENDIX H

DATA FILE OF STOCHASTIC MODELING (Experiment 3)

```
set SUPPLIER_NODE1 := 1 2 3;
set SUPPLIER_NODE2 := 1 2 3;
#set SUPPLIER_NODE1_IB := 1 2 3;
set DEMAND_NODE := 1 2 3 4 5 6 7 8 9 10
        11 12 13 14 15 16 17 18 19 20
        21 22 23 24 25 26 27 28 29 30
        31 32 33 34 35 36 37 38 39 40
        41 42 43 44 45 46 47 48 49 50
        51 52 53 54 55;
set SCENARIO := 1 2 3 4 5 6 7 8 9 10
       11 12 13 14 15 16 17 18 19 20
       21;
#param n =3; # supplier node 1
#param j =3; # supplier node 2
#param h =55; # No. of distribution centers
#param S =21; #No. of scenarios

param N =3; # supplier node 1
param I =3; # supplier node 1 Inbound
param J =3; # supplier node 2
param H =55; # No. of distribution centers
param S =21; #No. of scenarios

param Initial_Inventory_supplynode:=

1     1998858.79
2     1371232.84
3     1371232.84;

param Storage_Capacity_supplynode:=

1     17500000
2     9000000
3     9000000;

param Regular_Donations_supplynode:=

1     65361.30
2     11247.46
3     11247.46;

param Disaster_Donations_supplynode:=

1     610363.92
2     57367.28
3     57367.28;
```

param Trucks_trucktype1_avail_supplynode:=

1 10
2 5
3 5;

param Trucks_trucktype2_avail_supplynode:=

1 10
2 3
3 3;

param Trucks_trucktype1_capacity_supplynode:=

1 40000
2 36000
3 36000;

param Trucks_trucktype2_capacity_supplynode:=

1 40000
2 12200
3 12200;

param Transportation_cost_ss:

1 2 3:=
1 1000 165 208
2 165 1000 86
3 208 86 1000;

param Transportation_trips_supplier:=
1 3
2 3
3 3;

param Transportation_cost_sd:
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55:=

1 68.9 48.2 103 106 45.5 41.6 44.7 76.2 2.4 47 108 45.9 137 60 111 80 58.3 82.4 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
2 102 175 105 85 208 138 203 122 162 208 140 169 105 180 192 151 119 93.3 29.6 84.1 54.6 62.5 24.6 109 110 62.6 168 83.9 29.3 92.3 54.4 135 81.9 107 74.6 126 117 1.7 46.1 120 125 85.6 58.6 198 138 50.2 94.7 82 129 185 114 166 176 83.1 172
3 152 217 186 160 251 181 246 190 205 253 220 232 187 246 262 220 175 161 108 155 78.1 107 74.7 178 183 124 253 77.7 75.9 147 134 215 111 186 157 179 148 87.7 126 45.7 65.2 1.3 49.4 164 59 50.9 61.4 53.8 94.8 105 28.8 107 90.5 37.7 92.1;

param Forecasted_demand_DC:=

1	628.54
2	7682.92
3	10809.83
4	559.23
5	741.49
6	12789.2
7	8400.96
8	1019.79
9	159302.49
10	2678.38
11	530.45
12	11292.33
13	561.14
14	1032.7
15	790.51
16	2368.01
17	1506.45
18	995.53
19	2251.84
20	9500.03
21	242.86
22	1074.58
23	1252.98
24	2305.73
25	772.95
26	692.76
27	557.61
28	528.74
29	6038.48
30	562.71
31	433.3
32	1072.85
33	547.08
34	9887.82
35	805.57
36	147.63
37	208.99
38	30790.92
39	7452.74
40	1623.01
41	628.44
42	70191.87
43	2164.62
44	87.55
45	1119.74
46	2859.04
47	701.03
48	703.37
49	1496.77

```
50	458.05
51	1286.98
52	129.35
53	1263.23
54	1124.88
55	787.92;

param prob:=

1	0.494
2	0.041
3	0.041
4	0.005
5	0.041
6	0.01
7	0.061
8	0.01
9	0.02
10	0.019
11	0.025
12	0.006
13	0.013
14	0.006
15	0.095
16	0.019
17	0.006
18	0.009
19	0.066
20	0.013
21	0.001;


param demand_change_factor: 1	2	3	4	5	6	7	8
	9	10	11	12	13	14	15	16	17	18	19
	20	21:=
1	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
2	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
3	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
4	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
5	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
6	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
7	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
8	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
```

9	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
10	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
11	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
12	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
13	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
14	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
15	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
16	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
17	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
18	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
19	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
20	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
21	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
22	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
23	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
24	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
25	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
26	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
27	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
28	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
29	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
30	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
31	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
32	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
33	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
34	1	1	1	1	1	1	1.1	1	1.1	1	1.2

	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
35	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
36	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
37	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
38	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
39	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
40	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
41	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
42	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
43	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
44	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
45	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
46	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
47	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
48	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
49	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
50	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
51	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
52	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
53	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
54	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
55	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	

;

param donation_change_factor:

		1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20	21:=
1		1	1	1	1	1	1	1	1	1	1

```
        2       2       2       0       0       0       0       0       0       0       0
2               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1.3     1       1.3     1       1.5     1       1.5
3               1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1.3     1       1.3     1       1.5     1       1.5
;


param Inventory_change_factor:
                1       2       3       4       5       6       7       8       9       10
        11      12      13      14      15      16      17      18      19      20      21:=
1       1       1       1       1       1       1       1       1       1       1       1
        1       1       0       0       0       0       0       0       0       0
2       1       1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1
3       1       1       1       1       1       1       1       1       1       1       1
        1       1       1       1       1       1       1       1       1       1
;

param Unmet_demand_unit_cost = 2000;


param remain_penality_unit_cost = 500;

param Trucks_Limit_supplynode:=

1       6400000
2       866400
3       866400;
```

APPENDIX I

DATA FILE OF STOCHASTIC MODELING (Experiment 4)

```
set SUPPLIER_NODE1 := 1 2 3;
set SUPPLIER_NODE2 := 1 2 3;
#set SUPPLIER_NODE1_IB := 1 2 3;
set DEMAND_NODE := 1 2 3 4 5 6 7 8 9 10
            11 12 13 14 15 16 17 18 19 20
            21 22 23 24 25 26 27 28 29 30
            31 32 33 34 35 36 37 38 39 40
            41 42 43 44 45 46 47 48 49 50
            51 52 53 54 55;
set SCENARIO := 1 2 3 4 5 6 7 8 9 10
          11 12 13 14 15 16 17 18 19 20
          21;
#param n =3; # supplier node 1
#param j =3; # supplier node 2
#param h =55; # No. of distribution centers
#param S =21; #No. of scenarios

param N =3; # supplier node 1
param I =3; # supplier node 1 Inbound
param J =3; # supplier node 2
param H =55; # No. of distribution centers
param S =21; #No. of scenarios

param Initial_Inventory_supplynode:=

1        1998858.79
2        1371232.84
3        1371232.84;

param Storage_Capacity_supplynode:=

1        17500000
2        9000000
3        9000000;

param Regular_Donations_supplynode:=

1        65361.30
2        11247.46
3        11247.46;

param Disaster_Donations_supplynode:=

1        610363.92
2        57367.28
3        57367.28;
```

```
param Trucks_trucktype1_avail_supplynode:=

1	10
2	5
3	5;

param Trucks_trucktype2_avail_supplynode:=

1	10
2	3
3	3;

param Trucks_trucktype1_capacity_supplynode:=

1	40000
2	36000
3	36000;

param Trucks_trucktype2_capacity_supplynode:=

1	40000
2	12200
3	12200;


param Transportation_cost_ss:

	1 2 3:=
1	1000 165 208
2	165	1000 86
3	208	86 1000;

param Transportation_trips_supplier:=
1	3
2	3
3	3;

param Transportation_cost_sd:
	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55:=

1 68.9 48.2 103 106 45.5 41.6 44.7 76.2 2.4 47 108 45.9 137 60 111 80 58.3 82.4 1000 1000 1000
1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
2 102 175 105 85 208 138 203 122 162 208 140 169 105 180 192 151 119 93.3 29.6 84.1 54.6
62.5 24.6 109 110 62.6 168 83.9 29.3 92.3 54.4 135 81.9 107 74.6 126 117 1.7 46.1 120 125 85.6
58.6 198 138 50.2 94.7 82 129 185 114 166 176 83.1 172
3 152 217 186 160 251 181 246 190 205 253 220 232 187 246 262 220 175 161 108 155 78.1 107
74.7 178 183 124 253 77.7 75.9 147 134 215 111 186 157 179	148 87.7 126 45.7 65.2	1.3 49.4
164 59	50.9 61.4 53.8 94.8 105 28.8 107 90.5 37.7 92.1;
```

param Forecasted_demand_DC:=

1	628.54
2	7682.92
3	10809.83
4	559.23
5	741.49
6	12789.2
7	8400.96
8	1019.79
9	159302.49
10	2678.38
11	530.45
12	11292.33
13	561.14
14	1032.7
15	790.51
16	2368.01
17	1506.45
18	995.53
19	2251.84
20	9500.03
21	242.86
22	1074.58
23	1252.98
24	2305.73
25	772.95
26	692.76
27	557.61
28	528.74
29	6038.48
30	562.71
31	433.3
32	1072.85
33	547.08
34	9887.82
35	805.57
36	147.63
37	208.99
38	30790.92
39	7452.74
40	1623.01
41	628.44
42	70191.87
43	2164.62
44	87.55
45	1119.74
46	2859.04
47	701.03
48	703.37
49	1496.77

```
50	458.05
51	1286.98
52	129.35
53	1263.23
54	1124.88
55	787.92;

param prob:=

1	0.494
2	0.041
3	0.041
4	0.005
5	0.041
6	0.01
7	0.061
8	0.01
9	0.02
10	0.019
11	0.025
12	0.006
13	0.013
14	0.006
15	0.095
16	0.019
17	0.006
18	0.009
19	0.066
20	0.013
21	0.001;


param demand_change_factor: 1	2	3	4	5	6	7	8
	9	10	11	12	13	14	15	16	17	18	19
	20	21:=
1	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
2	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
3	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
4	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
5	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
6	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
7	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
8	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
```

9	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
10	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
11	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
12	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
13	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
14	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
15	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
16	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
17	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
18	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5	
19	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
20	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
21	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
22	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
23	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
24	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
25	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
26	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
27	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
28	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
29	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
30	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
31	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
32	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
33	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
34	1	1	1	1	1	1	1.1	1	1.1	1	1.2

```
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
35      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
36      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
37      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
38      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
39      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
40      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
41      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
42      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
43      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
44      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
45      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
46      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
47      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
48      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
49      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
50      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
51      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
52      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
53      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
54      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
55      1    1    1    1    1    1    1.1  1    1.1  1    1.2
        1    1.2  1    1.3  1    1.3  1    1.4  1    1.4
;

param donation_change_factor:

             1    2    3    4    5    6    7    8    9    10
        11   12   13   14   15   16   17   18   19   20   21:=
1  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  2.0  2.0  2.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
```

```
2  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  0  0  0  0  0  0  0  0
3  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.3  1.0  1.3  1.0  1.5  1.0  1.5
;


param Inventory_change_factor:
                    1         2         3         4         5         6         7         8         9         10
          11        12        13        14        15        16        17        18        19        20        21:=
1  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
2  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
3  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
;

param Unmet_demand_unit_cost = 2000;


param remain_penality_unit_cost = 500;

param Trucks_Limit_supplynode:=

1         6400000
2         866400
3         866400;
```

APPENDIX J

DATA FILE OF STOCHASTIC MODELING (Experiment 5)

```
set SUPPLIER_NODE1 := 1 2 3;
set SUPPLIER_NODE2 := 1 2 3;
#set SUPPLIER_NODE1_IB := 1 2 3;
set DEMAND_NODE := 1 2 3 4 5 6 7 8 9 10
                11 12 13 14 15 16 17 18 19 20
                21 22 23 24 25 26 27 28 29 30
                31 32 33 34 35 36 37 38 39 40
                41 42 43 44 45 46 47 48 49 50
                51 52 53 54 55;
set SCENARIO := 1 2 3 4 5 6 7 8 9 10
             11 12 13 14 15 16 17 18 19 20
             21;
#param n =3; # supplier node 1
#param j =3; # supplier node 2
#param h =55; # No. of distribution centers
#param S =21; #No. of scenarios

param N =3; # supplier node 1
param I =3; # supplier node 1 Inbound
param J =3; # supplier node 2
param H =55; # No. of distribution centers
param S =21; #No. of scenarios

param Initial_Inventory_supplynode:=

1       1998858.79
2       1371232.84
3       1371232.84;

param Storage_Capacity_supplynode:=

1       17500000
2       9000000
3       9000000;

param Regular_Donations_supplynode:=

1       65361.30
2       11247.46
3       11247.46;

param Disaster_Donations_supplynode:=

1       610363.92
2       57367.28
3       57367.28;

param Trucks_trucktype1_avail_supplynode:=

1       10
2       5
3       5;
```

param Trucks_trucktype2_avail_supplynode:=

1 10
2 3
3 3;

param Trucks_trucktype1_capacity_supplynode:=

1 40000
2 36000
3 36000;

param Trucks_trucktype2_capacity_supplynode:=

1 40000
2 12200
3 12200;

param Transportation_cost_ss:

1 2 3:=
1 1000 165 208
2 165 1000 86
3 208 86 1000;

param Transportation_trips_supplier:=
1 3
2 3
3 3;

param Transportation_cost_sd:
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55:=

1 68.9 48.2 103 106 45.5 41.6 44.7 76.2 2.4 47 108 45.9 137 60 111 80 58.3 82.4 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
2 102 175 105 85 208 138 203 122 162 208 140 169 105 180 192 151 119 93.3 29.6 84.1 54.6 62.5 24.6 109 110 62.6 168 83.9 29.3 92.3 54.4 135 81.9 107 74.6 126 117 1.7 46.1 120 125 85.6 58.6 198 138 50.2 94.7 82 129 185 114 166 176 83.1 172
3 152 217 186 160 251 181 246 190 205 253 220 232 187 246 262 220 175 161 108 155 78.1 107 74.7 178 183 124 253 77.7 75.9 147 134 215 111 186 157 179 148 87.7 126 45.7 65.2 1.3 49.4 164 59 50.9 61.4 53.8 94.8 105 28.8 107 90.5 37.7 92.1;

param Forecasted_demand_DC:=

1 628.54
2 7682.92
3 10809.83
4 559.23
5 741.49
6 12789.2
7 8400.96
8 1019.79

9	159302.49
10	2678.38
11	530.45
12	11292.33
13	561.14
14	1032.7
15	790.51
16	2368.01
17	1506.45
18	995.53
19	2251.84
20	9500.03
21	242.86
22	1074.58
23	1252.98
24	2305.73
25	772.95
26	692.76
27	557.61
28	528.74
29	6038.48
30	562.71
31	433.3
32	1072.85
33	547.08
34	9887.82
35	805.57
36	147.63
37	208.99
38	30790.92
39	7452.74
40	1623.01
41	628.44
42	70191.87
43	2164.62
44	87.55
45	1119.74
46	2859.04
47	701.03
48	703.37
49	1496.77
50	458.05
51	1286.98
52	129.35
53	1263.23
54	1124.88
55	787.92;

param prob:=

1	0.494
2	0.041
3	0.041
4	0.005
5	0.041
6	0.01

```
7	0.061
8	0.01
9	0.02
10	0.019
11	0.025
12	0.006
13	0.013
14	0.006
15	0.095
16	0.019
17	0.006
18	0.009
19	0.066
20	0.013
21	0.001;


param demand_change_factor: 1	2	3	4	5	6	7	8	9
	10	11	12	13	14	15	16	17	18	19	20
	21:=
1	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
2	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
3	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
4	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
5	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
6	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
7	1	1	1.3	0.9	1.3	1	1.4	0.9	1.4	1	1.5
	0.9	1.5	15	15.4	15.9	15.4	15	15.5	15.9	15.5
8	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
9	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
10	1	1	1.2	0.9	1.2	1	1.3	0.9	1.3	1	1.4
	0.9	1.4	15	15.4	15.9	15.4	15	15.5	15.9	15.5
11	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
12	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
13	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
14	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
15	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
16	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
17	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
18	1	1	1.1	0.9	1.1	1	1.2	0.9	1.2	1	1.3
	0.9	1.3	15	15.4	15.9	15.4	15	15.5	15.9	15.5
```

19	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
20	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
21	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
22	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
23	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
24	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
25	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
26	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
27	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
28	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
29	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
30	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
31	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
32	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
33	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
34	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
35	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
36	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
37	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
38	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
39	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
40	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
41	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
42	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
43	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
44	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
45	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	
46	1	1	1	1	1	1	1.1	1	1.1	1	1.2
	1	1.2	1	1.3	1	1.3	1	1.4	1	1.4	

```
47      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
48      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
49      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
50      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
51      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
52      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
53      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
54      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
55      1       1       1       1       1       1       1.1     1       1.1     1       1.2
        1       1.2     1       1.3     1       1.3     1       1.4     1       1.4
;


param donation_change_factor:

                1       2       3       4       5       6       7       8       9       10
        11      12      13      14      15      16      17      18      19      20      21:=
1  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  2.0  2.0  2.0  0  0  0  0  0  0  0  0
2  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.3  1.0  1.3  1.0  1.5  1.0  1.5
3  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  0  0  0  0  0  0  0  0
;


param Inventory_change_factor:
                1       2       3       4       5       6       7       8       9       10
        11      12      13      14      15      16      17      18      19      20      21:=
1  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
2  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0
3  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
;

param Unmet_demand_unit_cost = 2000;


param remain_penality_unit_cost = 500;

param Trucks_Limit_supplynode:=

1       6400000
2       866400
3       866400;
```

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