Development of an agent-based model for the analysis of the effect of consumer panic buying on supply chain disruption due to a disaster

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Abstract. The present paper is an effort to introduce the modeling architecture of analyzing the response of a supply chain of bottled water due to consumer panic buying triggered by a large-scale natural disaster. An agent-based system is used to model a simplistic consumer purchase model and a supply chain model. Disaster prompts panic buying among the consumers, which disturbs the supply chain. The strategies used to control the excess demand such as limiting sales per person is considered to understand the effect on the supply chain. A preliminary study of the response of the supply chain due to the disaster and its consequences are presented in this paper.

Keywords: Agent-based simulation, Consumer panic buying, Supply chain disruption, Disaster

1. Introduction

Large scale natural disasters cause extensive damage, disrupting people’s lives and economic activities, even in places away from the disaster-hit areas. There has been a drastic increase in the number of intense natural disasters in the past few decades. The occurrence of these events has shown the importance of mitigation measures in order to alleviate the resulting human and economic loss. The emerging global economy is proving it difficult to restrict the loss to the affected country itself rather, the impact is also been felt by all the associated global organizations, businesses and even other countries, too. People have been tirelessly trying to reduce the impact and damage or consequences by developing mitigation measures
Disasters have a widespread psychological and emotional impact on human behavior. Research shows that disasters bring in the emotion of fear and anxiety, as an immediate natural response. This ‘fear of unknown’ leads people in taking precautionary actions of stockpiling on essentials to mitigate the risk of a possible stockout, which is often termed as ‘panic buying’. Panic buying is a human behavior indicated by a rapid increase in purchase volume before or after a disaster or perceived disaster, or in view of a large price increase or shortage [Wikipedia]. Panic buying reduces supply and creates higher demand, leading to higher price inflation. This increase in demand leads to a shortage of the product. Such a situation increases the number of vulnerable people in need of the product in a post-disaster scenario, especially if the product is a basic essential like food or water.

The Great East Japan Earthquake was one of the most destructive disasters in recent times. The tsunami which followed had led to the failure of the Fukushima Daichi nuclear plant, which had intensified the already heightened crisis manifold. The aftermath included both a humanitarian crisis and massive economic impacts. A huge consequence was the shortages of food, water, medicine and fuel for survivors and also in the neighbouring areas. Panic buying was prevalent in all sectors from food and beverage industry to the auto component market[1]. Fuel, bottled water, bread, instant meals were among the top-sellers [2]. On 23rd March 2011, the Tokyo city officials released a notice that the tap water must not be fed for infants due to increased radioactive iodine levels. Radioactive Iodine to an amount of 210 becquerels per liter was found in the city tap water, where the limit for infants was 100 becquerels per liter and adults was 300 becquerels per liter. While the amount of radioactive iodine was less than the limit for adults, the risk aversive human characteristic instigated people to panic buy on bottled water in unprecedented quantities. The media articles, during the times, have reported the stockout of food and drinking water in stores across the capital city. This situation has hampered the circulation of bottled water within the metroplex and in the affected areas[2].

Panic buying has the potential to disrupt the supply chain with increased demand. This disruption leads to more panic buying forming a vicious circle. Research on understanding consumer panic buying has been conducted by sociologists or psychologists but is mostly limited to statistical analysis. Kurihara and Maruyama[2] had attempted to investigate the causes and factors of consumer behavior from an analysis of a survey conducted after the Great East Japan Earthquake and found that unpreparedness of disaster and excessive media coverage had caused excessive buying of essential goods. Forbes[3] conducted a study to understand the post-disaster consumption trends after the Christ Church earthquake from scanner data of purchases and found consumers purchase increased levels of utilitarian products necessary for survival. Liren et al.[4] have put forward the evolution mechanism and development tendency of panic purchase and suggested that the government involvement con-
controls panic purchase. Cavallo et al. [5] reported that the disaster impacted product availability directly using online data collected from retailers. All the studies used available data or questionnaire survey for understanding the causes of panic buying and gave suggestions based on the results as methods for mitigation. The lack of predictive or simulation models is evident.

A supply chain is an integration of suppliers, manufacturers, distributors, retailers, customers, etc. The inclusion of various elements increases the complexity of the supply chain and a slight variation of a single element, exposes the chain to disturbances. These undesirable events affect supply chain performance and its long term sustainability. As the performance of the supply chain is becoming vital to any business, supply chain disturbances could have a significant effect. With a focus on the causes, effects, and mitigation of the disruptions, a substantial amount of literature is available on supply chain disturbances by the specialists, mostly ignoring the effect of consumer behavior. Natural disasters and supply chain disruptions have been studied together extensively, where an impact on the economy or the direct and indirect losses caused have been discussed. Inoue and Todo [6] have simulated nationwide supply chains of Japan and have calculated the indirect damage and its propagation during the 2011 triple disaster and have used the model to predict the increase in damage during the possible Nankai Trough earthquake. Ivanov and Wendler [7] discussed the difficulties in managing the emergency logistics in disaster situations by analyzing existing quantitative methods and have made suggestions for best practices during disruptions. Supply chain risk management has also been studied and modeled rigorously. Giannakis and Louis [8] have proposed an agent-based model to deal with supply chain risks arising at various stages of the supply chain of manufacturing industries. Consumer panic buying due to supply disturbances have also been studied together. Yoon et al. [1], studied the retailer’s sourcing strategy under consumer stockpiling caused due to supply disruptions and compared single and multiple sourcing from a retailer’s perspective. Shou et al. [9] have studied consumer panic buying with supply disturbances and found that consumers stockpile when the price or holding cost is low or when they carry risk-averse behavior. The above are a few works which are in line with this paper’s research interests. The available literature is limited to panic buying due to supply disturbances and has not included the human behavior in the analysis, but disaster scenario holds a different angle altogether as it is essential to curb panic buying by providing to all the consumers. Hence, bringing together all the elements under one roof and studying them together is of utmost importance in the times of an increasing number of disasters. The lack of research in this area increases the importance and necessity to address this issue.

The objective of the research is to develop a model to study consumer behavior and the response of the supply chain in disaster aftermath together using an agent-based model. Precisely, to analyze the panic buying of bottled water and identify the reasons leading to the disruption of the supply chain and examine strategies to avoid the shortage such as limiting sales per person, increasing communication among agents, etc. The performance of the sup-
ply chain is studied under disaster circumstances and also the measures to control the increased demand; the control measure currently adopted is the quota policy, employed by the retail stores.

The rest of the paper is divided into three parts, where the second part deals with the explanation of the methodology used to develop the supply chain model and the consumer purchase model. The results would be explained in the third section, along with its analysis and discussion. Finally, the last part would deal with the conclusion and future work.

2. Model

The simulation proposes a combination of consumer behavior and supply chain performance to understand the real effects on each other. The methodology to model such scenarios is aptly an agent-based approach, as it allows an autonomous design of the characteristics and actions of the agents involved. Agent-based modeling is an important computational tool in solving and modeling complex systems and is quite popular in various fields, such as traffic simulations, stock market, understanding epidemic spread, etc. Agents have attributes, resources, abilities, which are utilized in achieving goals, often interacting with other agents and the environment. The usefulness of this approach arises from the ability to assign heterogeneous properties to individual agent and each agent being programmed to take relevant actions according to their respective circumstances. The model largely comprises of two parts. The supply chain model and the consumer model. The supply chain model deals with the various activities, the members or the organizations, involved need to undertake on a regular basis to sustain their businesses. While the consumer model comprises the decision making process of the consumer leading to the purchase of the product with the available resources and the human emotions, attitudes and behaviors as factors influencing the purchase decision.

2.1. Supply chain model

The supply chain is a system of all the elements such as people, organizations, activities, resources, information, involved in the manufacture, distribution, sale and consumption of a product. It includes the downward flow of the product and an upward flow of the information and finance. The model is built on the assumption that the price of the product, profits, costs do not play a role in a disaster situation, as price gouging during emergencies is a violation in many places. Moreover, it is considered unethical to increase the price and obtain profits in crisis times. The model uses a supply chain design of continuous replenishment, where buyers are continuously provided with their orders, daily or at regular intervals, by their sellers. Hence, supplier or seller reliability plays a crucial role in such a design. The product in the current model is bottled drinking water. It is assumed that the raw materials required for the
manufacture of bottled water, are available or produced, at the facility itself. Hence, in the current model, the suppliers of materials to the manufacturer are ignored.

The model identifies five key stakeholders involved in the supply of bottled water as supply chain agents (SCA), which are manufacturers, distributors, individual retailers, chain heads, and their chain stores. A three-tiered hierarchical supply chain (Fig. 1) has been considered for the current model to make it simple. The interactions and the information flow among the SCAs are restricted to its immediate upper or lower tiers or precisely, the buyer and seller of each transaction. Currently, communication among the SCAs is restricted to the exchange of information related to buying and selling of the product.

The activities of all the SCAs are currently similar. The prime activity is the obtaining of the product and selling it to their customers except for the manufacturers, on the top of the hierarchy, who produce the product. Distributors are the customers to the manufacturers. The manufacturers sell the product to the distributors, who in turn sell to the chain heads and retail stores, who are the customers of the distributors. The chain head distributes the product among its chain stores. The retail stores (chain and individual), are the SCAs who sell directly to the consumers. The point of contact of the consumers and supply chain are the retail stores or the chain stores only. Hence, these are the SCAs, who are primarily affected when excess demand occurs. An SCA decides its seller based on the distance to the seller's location, preferring the nearest one. Every agent can have only a single seller. Hence, the model is based on single sourcing.

The functions of a supply chain include product development, inventory management, distribution, finance, operations, among which inventory management plays a crucial role. The objective of inventory management is to understand how much inventory to hold, how much to order and when to order, which are obtained by minimizing all the costs viz., holding,
ordering, stockout. A very popular conventional approach[10] is the economic order quantity model, based on which the order quantity, safety inventory etc., are obtained. In this model, the demand during each interval of lead time is assumed to be uncertain, independent, and can be described by a normal distribution.

The quantities required in the calculations of placing an order are explained as follows. The service level probability is the probability that inventory available with the SCA will be sufficient to meet its customer demands, in other words, the probability that a stockout will not occur. Lead time is the time taken to receive an order after it is placed. Lead time inventory is the inventory held by the SCA for sale during lead time, which is the sum of the average demand of the number of intervals in lead time.

\[ \text{Lead Time Inventory} = d \times L \]  \hspace{1cm} (1)

Safety stock is the inventory held in order to reduce the risk that the item will be out of stock and is used above regular sales which is the obtained from the variance of the normal distribution. The variance is the sum of the daily variances for the number of intervals in the lead time. \( \sigma_d \sqrt{L} \) is the square root of the sum of the daily variances during the lead time.

\[ \text{Safety stock} = z \times \sigma_d \times \sqrt{L} \]  \hspace{1cm} (2)

Reorder point is the inventory level at which an order must be placed such that the product is replenished before the product becomes out of stock. Reorder point, with a safety stock which is set to meet a specific service level, is obtained by the sum of lead time inventory and safety stock.

\[ \text{Reorder point} = d \times L + z \times \sigma_d \times \sqrt{L} \]  \hspace{1cm} (3)

Economic order quantity (EOQ) is the optimum quantity of an item to be purchased at one time in order to minimize the combined annual costs of ordering and carrying the item in inventory. The order size is determined by the average demand during the time between orders and the lead time added by the safety stock for a given service level, similar to the calculations of reorder point, of which the current inventory is subtracted to avoid excess inventory-on-hand.

\[ \text{EOQ} = d \times (t_b + L) + z \times \sigma_d \times \sqrt{(t_b + L)} - I \]  \hspace{1cm} (4)

Where,  
- \( L \) – Lead time  
- \( d \) – Avg. Sales  
- \( z \) – Number of standard deviations based on the service level probability  
- \( \sigma_d \) – Standard deviation of avg. sales  
- \( t_b \) – Time between placing two orders  
- \( I \) – Current inventory
All the SCAs use the above methods to manage their inventories, except the manufacturer. Manufacturers decide the production quantity of the next interval based on the average sale and the current inventory available. The average production capacity of the manufacturing facility is assumed to be 60% of the maximum production capacity. The values for lead time, average sales and its standard deviation in the above methods have been assumed based on the information obtained from the reports [11,12] of convenience stores and manufacturers. The average sale and its standard deviation are calculated in regular intervals based on the sales of the SCA in the preceding interval. Here, a 95% service level is considered for all SCAs, for which the value of z from the standard normal distribution table is 1.65. The current inventory is a variable which indicates the quantity of the product held by an SCA at a given time; hence, the value changes with every transaction. The lead time to receive the stock is dependent on its tier and is same for all the agents belonging to the same SCA tier. Currently, the lead time for the distributor and chain head tiers is considered as two intervals, while the chain stores and individual retail stores have a lead time of one interval as retail tier agents have an everyday delivery. The SCA action algorithm is shown in Fig. 2, with the SCA actions indicated in blue (dotted symbols).

### 2.2. Consumer model

The consumer model is the decision making process of the purchase of a product depending on the available resources, influenced by the emotional, behavioral factors of the consumer. The consumer agent in the current model is a household, presuming a purchase made by a member of a household is meant for the entire household. Every household in the model is assumed a size of 1-4 members, as an average household size is 2.5[13]. The age of a member is considered to be between 0-80 years. A member above 18 years is considered as an adult, while 6-18 years members are considered children and 0-6 years are considered infants or toddlers. The household is modeled such that every household has a minimum of two adults if it is not a single household. The decision-maker and the buyer of the household is the ‘head’, while the other members are considered to be the influencers. The household has a knowledge of the environment to a certain radius from its location, defined as the vicinity of the consumer. The consumer knowledge is limited to the stores and other consumers (neighbours) in this area.

The water consumption per day is dependent on the age of the member, viz., adult and child. The consumption is randomly generated with minimum consumption of 0.25 liter and maximum consumption of 1.5 liter for a child and of 3 liters for an adult. The above values are based on the literature in National Health and Nutrition Examination Surveys, US[14]. We plan on upgrading the water consumption to be based on Japanese consumption habits and body weight in future. Every member has their preference on whether they can consume tap water or not. The tap water consumption would be zero if the member prefers not to drink.
Figure 2: Flow chart of the model
tap water. If the member prefers to consume tap water, their tap and bottled water consumption are calculated randomly to add up to their daily water consumption. The average and daily household water consumption is a cumulative value over all its members. Currently, the decision-making model is simple and based on the inventory of bottled water available with the household. The household head checks the inventory and the quantity required for the consumption of the household. If it is sufficient, there is no action required for the interval. If it is insufficient, the head moves to the nearest store to make the purchase. The purchase quantity is based on average household consumption and inventory days. Inventory days is the average number of days the goods remain in inventory before being sold, as originally defined in the supply chain management. Similarly here, for a consumer, it is the number of days, when the consumer wants to store the inventory for a periodical purchase. Hence, the consumer buys the stock such that it would be sufficient for the predefined inventory days and is normally expected to make the next purchase after those many days. The purchase interval is decided based on the exhaustion of the stock. The purchase is made in the interval when the inventory is insufficient. When a consumer agent meets a stockout at a store, it heads to the next nearest store in its vicinity, until it can make a purchase. Consumer increases the purchase quantity, on the occurrence of a disaster, to stockpile the product for 3-7 days for the entire household. The consumer decision-making algorithm is shown in Fig. 2, with the consumer actions in red (dashed symbols).

2.3. Time flow of the simulation

The time interval of the model is fixed and one-time interval is considered as one day. The first few intervals of the simulation are in normal sale condition, after which a disaster is introduced into the model. The flow of the simulation is divided into 3 time phases. Phase 1 is a pre-disaster phase. Phase 2 starts at the onset of the disaster. Phase 3 starts when an SCA takes any control measures.

2.3.1 Phase 1

The pre-disaster Phase 1 is a normal sale time, where all the agents try to maximize their utility. The consumers place orders depending solely on their requirement and available inventory. The supply meets the demand in all the intervals of Phase 1.

2.3.2 Phase 2

Phase 2 starts when the disaster is triggered. People get anxious from the information of radioactive iodine increase in the city tap water. Due to the fear of contamination, all consumers stop the consumption of tap water. Some households, for example, households with infants or toddlers, resort to stockpiling. Hence, the demand for bottled water increases unusually,
causing a supply chain disturbance, which cascades through the hierarchy leading to a supply chain disruption.

2.3.3 Phase 3

Phase 3 begins when an SCA employs a strategy to mitigate the supply chain disruption. Currently, the quota policy has been used in the model, to control the consumer demand. The retail stores impose the quota policy to the consumers by limiting sale to 2 units per person (1 unit = 1 liter). When consumers receive information about the quota policy, all the household members move to the store to make a purchase which was initially made only by the head of the household. The reaction of the consumer to the quota policy is also included in the model, where all the members of the household visit the store to make a purchase.

The present work has considered the following three cases; 1) Normal case with only Phase 1, without a disaster, 2) Disaster case with Phase 1 and Phase 2 and 3) Strategy case with Phase 1, 2 and 3 occurring in the same order. The results of the three cases are shown and analysed in the following section.

3. Results of test simulation

3.1. Initial settings

The environment for the test simulation is a virtual grid of 100 x 100 size, in which all the agents are generated randomly, as shown in Fig. 3. The consumer agents are uniformly distributed. Currently, for trial purpose, only 6 SCAs and 200 households have been considered. The location of the consumer agents and store agents are in blue, red and pink dots respectively. Each consumer accesses the nearest store, hence the selection of the store depends on

![Figure 3: Example of agent spatial distribution in the environment](image-url)
the spatial distribution. The results in this work are unaffected with the location, given the uniform distribution of the consumers. But, the actual city map data, which we plan to use in future, might have an effect due to the localized residential clusters. The scope of the simulation is very small, considering its initial stages. The simulation is run for 50 intervals in which the disaster is set to occur in the 25th interval, while the strategy is applied from the 26th interval.

The values used in the calculations of supply chain model are considered such that the transient period for the model is considerably low. For instance, each SCA’s inventory, average sale and its standard deviation are calculated and updated regularly. Their initial values can be set to zero, but it takes around 10-14 intervals, for the system to stabilize and the run time needs to be increased accordingly. Hence, to reduce the transient time, the initial values of all SCA’s have been considered such that they adapt to the customer demand and obtain a stable initial state of the system in a shorter time. The initial average sale of the retail level SCAs is calculated based on the possible number of consumers in its vicinity, while the same for the higher tier SCAs is the sum of average sale of all its customers. The initial opening inventories of each SCA is twice the average sale multiplied with the lead time intervals. The stabilized system is where all SCAs manage their inventories and sales without hurdles, which can be seen in the initial intervals of Fig. 5 ~ 7. The simulation is coded using Java language on eclipse development environment. The run time for trial simulations on a quad core processor takes around 2-3 minutes, while a simulation of entire tokyo city, with a household population of 6.69 million, would require high computational resources.

3.2. Results and analysis

The cumulative demand for all the three cases is shown in Fig. 4. It can be seen (orange line) that the demand increases hugely after the disaster triggers compared to the normal case (blue line). The strategy case (grey line) shows that the increased demand due to the disaster stays

![Figure 4: Cumulative demand in all three cases](image-url)
high as the demand is not satisfied by the supply. Hence, consumers keep increasing their purchase quantity as their requirement is not fulfilled.

Figure 5 to 7 shows the change of inventory-sale ratio by time. A measure to understand the performance of an SCA is considered as a ratio of inventory to sale, which is the sum of sale and lost sale (after stockout).

\[
\text{Inventory – Sale Ratio} = \frac{\text{Inventory}}{\text{Sale + Lost sale}}
\]  

(5)

If the ratio > 1, the blue region in Fig. 5, it means that the SCA is in a safe condition and has sufficient inventory to meet its demand, and if the ratio < 1, the red region in Fig. 5, the SCA falls into the stockout zone and is seen as a disturbance. In order to focus on the stockout zone, the y-axis, indicating the inventory-sale ratio has been shown from 0 to 2.5. The value moves way above 2.5 but, as the SCA is already safe, it has not been shown in the figure. Each line shows the cumulative inventory – sale ratio of all the agents in that tier. Fig. 5 shows the supply chain performance in the normal case. It can be seen that a few store agents have moved into the stock out zone, even in the normal phase. This was due to an increased demand than expected for that particular store, but there was no cumulative stockout as the consumer could make a purchase at another store.

![Normal case](image)

Figure 5: SCA performance in normal case

In Fig. 6, the disaster triggers in the 25th interval, it can be seen that the demand is so huge that all the SCAs are in stockout zone for consistently more than 10 intervals. This indicates a crash in the supply chain, in line with our expectations, as all the stakeholders in the supply of the product would be at a loss to satisfy the demand at every tier level.
In Fig. 7, it can be seen that the limiting of the sales strategy has avoided the supply chain disruption. However, the retail level line in the graph would continue to be in the stock-out zone as the consumer demand is not satisfied by the retail stores in the limiting sale strategy case.

3.3. Discussion

The results obtained show the effect of the panic buying and the consumer quota policy on the supply chain. Consumer behavior affects the supply chain negatively, causing a disruption. The strategy employed by the lower level SCA proved effective in preventing the disruption and affecting all the stakeholders of the supply chain. The obtained results are reasonable and consistent with our intuition of the effects of limiting the sale for the consumers. The increased demand for a product is a positive sign for the SCAs and an immediate price increase is a likely reaction in such a situation. But, considering the disaster scenario, the current model is limited to the inventories and quantity of sale of the SCA and there is no involve-
ment of the monetary elements such as the price of the product, sales, profits etc. In future, the model can be extended to understand the financial impact due to disaster on the supply chain stakeholders.

The validation of the model is a difficult task for agent-based models. The primary method of validation of this model can be performed by comparing the obtained results with the actual data of the supply chain stakeholders. But, procurement of such information is quite difficult as the data is confidential to the respective businesses and is not obtainable unless associated with an organization. We would like to develop another possible method to validate the model by using the consumption and demand distributions of the consumers in future.

4. Conclusions

A simulation model is being developed to understand the response of the supply chain due to consumer panic buying in the aftermath of a large-scale disaster. A simplistic model of the same along with the preliminary reaction of the supply chain due to the disaster and the quota policy has been presented in the paper. The initial results of the test cases have shown that the quota policy is useful in curtailing the disturbance from moving up the hierarchy. Such tools would help the government to identify the people resorting to excessive buying and work on reducing panic buying among the people and are quite useful for the industries to take measures to mitigate the disruptions before or after the disaster. As part of future work, the consumer model would be refined to accommodate the factors affecting the decision-making process such as the number of children, the experience of disaster, quality of tap water, etc., and also increasing the scope of the simulation.

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