Mitigating transportation disruptions in a supply chain: a cost-effective strategy

Albertzeth, G., Pujawan, N., Hilletofth, P. & Tjahjono, B.

Mitigating transportation disruptions in a supply chain: a cost-effective strategy

Gustav Albertzeth, Nyoman Pujawan
Department of Industrial Engineering
Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo Surabaya 60111, Indonesia
E-mail: pujawan@ie.its.ac.id

Per Hilletofth
Department of Industrial Engineering and Management, School of Engineering, Jönköping University, P.O. Box 1026, SE-551 11, Jönköping, Sweden, E-mail: prof.p.hilletofth@gmail.com

Department of Industrial Engineering and Management, University of Gävle, SE-801 76, Gävle, Sweden, E-mail: prof.p.hilletofth@gmail.com

Benny Tjahjono
Centre for Business in Society,
Coventry University, UK
E-mail: benny.tjahjono@coventry.ac.uk

Abstract

Transportation disruptions can be damaging to a supply chain because goods may not arrive on time and this jeopardizes the service level to the customers. While supply chain disruptions have gained significant attention from scholars, little has been done to explore these disruptions in the context of transportation. The study described in this paper aims to address disruptions occurring in the transportation of goods from a plant to a distribution centre. We modelled this real case to obtain insights on the effectiveness of different strategies to mitigate transportation disruptions. We evaluated four mitigation strategies and compared the outcomes in terms of service level and total costs: (1) the risk acceptance strategy, (2) the redundant stock strategy, (3) the flexible route strategy, and (4) the redundant-flexibility strategy. The results suggest that the best strategy differs depending on the budget that managers are willing to deploy to improve the service level. The simulation experiments and the use of the Incremental Cost Effectiveness Ratio (ICER) would be instrumental in helping decision makers in selecting the best disruption mitigation strategies where the best option would likely be different under varying circumstances.

Keywords: *Transportation disruptions, mitigation strategy, redundant stock, flexible route, simulation modelling, cost-effectiveness analysis*

1. Introduction

All supply chains are inherently vulnerable and they will experience, sooner or later, one or more unanticipated events that disrupt the normal flow of goods and materials (Christopher *et al.*, 2007). This increased risk of disruption has been further exacerbated by recent trends and practices in supply chain management such as the complexity due to global sourcing, reliance on external partners due to outsourcing, single sourcing strategies, and lean supply chains that are focused on reducing inventory (Christopher and Peck, 2004, Hendricks and Singhal, 2005, Sansone *et al.*, 2017). A disruption is hereby defined as an event that interrupts the material flows in the supply chain, resulting in an abrupt termination of the movement of goods (Wilson, 2007). Tang *et al.* (2008) suggested that a disruption occurs due to a radical transformation of the supply chain system through the non-availability of certain production, warehousing and distribution facilities, or transportation options because of unexpected events caused by human or natural factors.

There are many examples of an unexpected event causing a supply chain disruption. In March 2000, Ericsson experienced a supply disruption of critical cellular phone components because their key supplier (the Philips plant in New Mexico) caught on fire. The supply disruption at Philips cost Ericsson $200 million in lost sales (Latour, 2001). The Thailand flood in 2011 forced Western Digital to close two factories and led to the paralysis of transportation facilities on a large scale (Liu *et al.,* 2016). In 2002, the union strike at a U.S. West Coast port disrupted transhipment and deliveries and it took six months to get back to normal operations and schedules (Cavinato, 2004). The catastrophic event of Iceland's Eyjafjallajokull volcano eruption in 2010 disrupted air transportation to and from Europe. The eruption crippled the air transportation within the area and had a negative impact on the economy. Some of the notable impacts include the grounded cargo shipment from Africa that made Kenya's farmers dump tones of vegetables and flowers destined for the UK, causing financial loss of $1.3m a day (Wadhams, 2010). Interruptions in the supply of automotive parts forced BMW to suspend production at three of its plants in Germany. It also forced Nissan to stop production in two factories in Japan (Wearden, 2010). From these cases, it is clear that any disruption tends to cause a ripple effect on the supply chain and can be detrimental in terms of both cost and company value if it is underestimated or completely ignored (Chopra and Sodhi, 2004, Christopher *et al.*, 2007, Schmidt and Raman, 2012).

Indonesia is geographically prone to natural disasters and therefore is at risk of supply chain disruptions. The quality of road infrastructure greatly varies across different regions of Indonesia. The eastern part of Indonesia is mostly less developed compared to the western part

of Indonesia. In many islands, the majority of the transportation infrastructure, be they roads or bridges in many areas across the archipelago, is relatively under-developed. Various disruptions may occur due to heavy rains, landslides, and floods. This has led to a vulnerability to transportation disruptions.

While the impacts of disruptions are apparent, not all companies are willing to invest in risk mitigation strategies. Decision makers may still see the mitigation actions merely as costs and therefore many of them are reluctant to go beyond the risk acceptance option. On the other hand, the negligence of most companies to invest in a risk mitigation program will obviously have many negative impacts to the supply chain including low service level to customers on one side and high inventory costs on the other side. It is therefore important for decision makers to have a framework that can help them assess how a mitigation strategy impacts both costs as well as the service level, and if multiple mitigation options are available, they need to be able to compare the effectiveness of those options.

There has been growing interest from academics to study transportation disruptions. A few have investigated the impact of transportation disruptions in supply chains and concluded that it would lead to a drop in the supply chain performance (Wilson, 2007, Yang and Wu, 2007, Figliozzi and Zhang, 2010). Azad *et al.* (2013) considered transportation disruptions when designing a supply chain network. Li *et al.* (2015) proposed real-time schedule recovery policies as a way to cope with transportation disruptions in liner shipping. Liu *et al.* (2016) predicted transportation disruptions by the use of a grey neural network. Although there is an increased number of papers published in the area of transportation disruptions, finding papers that are based on a real context was challenging. Talluri *et al.* (2013) argue that simply proposing mitigation strategies is inadequate. They urged that the effectiveness of a strategy must be evaluated in the practical context with respect to its cost and non-cost factors.

The purpose of this research is to investigate the effectiveness of different mitigation strategies against transportation disruptions in a real problem setting. The use of a real problem setting in the supply chain disruption literature is scarce and our work would therefore add valuable insights to the theory and context of transportation disruptions. We model a case of transporting products from a factory to a distribution centre in the Sulawesi island of Indonesia where transportation disruptions frequently occur. We propose a number of mitigation strategies and then evaluate their impacts in terms of the cost effectiveness ratio. The latter enables the decision makers to obtain the best mitigation strategy under different ranges of an available budget that the decision makers are willing to deploy for mitigation. The trade-off between mitigation costs and its effectiveness in improving service level or reducing lost sales

has been a major issue in supply chain decisions, including when a decision maker has to decide which mitigation strategy to choose. This, however, has not seemed to receive adequate attention in the body of literature. Our work also contributes to this important aspect of disruption mitigation not only by proposing and evaluating mitigation strategies but also by recommending the most cost-effective strategy under a certain range of budget deployment.

The remainder of this paper is structured as follows. A review of related work in the body of literature is presented in Section 2 followed by the outline of research methodology in Section 3. The description of the system under study is presented in Section 4 before the detailed elaboration on how the simulation model is developed. Thereafter, the experimentation of the simulation model is presented in Section 6 followed by a discussion of results in Section 7. Finally, the research is concluded in Section 8.

2. Literature Review

2.1. Transportation disruption

Disruptions in supply chains have received significant attention from researchers in the last decade. The damaging impacts of disruptions and the increasing frequency of their occurrence have made supply chain disruptions a critical issue to address by every supply chain manager. According to Sheffi *et al.* (2003), there are six types of supply chain disruptions: *supply*, *demand*, *transportation*, *facilities*, *freight breaches,* and *communications*. Sheffi *et al.* (2003) defined it as a delay or unavailability of the transportation infrastructure which makes it impossible to move goods either inbound or outbound. While other disruptions may stop the production of goods, transportation disruption only halts the flow of goods. It is unique because even though the goods are halted in transit, other operations in the supply chain remain unaffected (Wilson, 2007).

Giunipero and Eltantawy (2004) stressed that transportation disruption posed a great risk, and if severe, could cripple the entire supply chain. Houshyar *et al.* (2013) argued that transportation disruption thus instigates a drop in the supply chain performance, as it could cause late deliveries and disturb production, leading to lost sales. It also jeopardizes the security of valuable goods in transit Guiffrida and Jaber (2008). Lost sales, transport costs, and other intangible costs such as loss of reputation may impact the companies financially and are difficult to quantify (Figliozzi and Zhang, 2010).

Wilson (2007) examined the effects of transportation disruption on the attributes of supply chains by using system dynamics and found that transportation disruption affected the first suppliers and their inventory. Using the same technique, Yang and Wu (2007) investigated

the effect of transportation disruption on supply chain performance by observing how each of the actors in the supply chain responded to a transportation disruption at a certain echelon in the supply chain. By measuring the service level, inventory fluctuation, etc., they also suggested various strategies for mitigating the risks from a transport disruption.

Zhang and Lam (2015) investigated transportation disruption caused by typhoons at two selected ports, Ningbo and Shanghai, and they developed an approach for estimating the economic losses in terms of the variation in the daily cargo throughput and the climate. Nonetheless, Bravo and Vidal (2013) found that cost function was not considered in many transportation models. They then proposed a framework to guide the transportation considerations that considered trade-off analysis, private or outsourced fleet considerations, and the role of time and distance in transportation cost analysis. Doan *et al.* (2018) developed an optimization model for network design considering transportation risk.

Two most common strategies to manage the risk of disruptions according to Tomlin (2006) are *mitigation* and *recovery*. The former requires a company to act in advance of a disruption, while the latter is taking action only during (or after) the occurrence of a disruption. Ouyang *et al.* (2015) demonstrated various measures to mitigate the fragility of transportation systems in China in terms of the complementary relationship of the infrastructure system and they proposed a network-based approach to model the vulnerability of complementary transportation systems. Zhen *et al.* (2016) suggested that backup transportation was a very efficient way to reduce profit loss. Therefore, less insurance coverage needed to be purchased in advance of a disruption. Cui *et al.* (2016) found that their proposed model could yield a supply chain system design that minimized the impacts from probabilistic disruptions and also leveraged expedited shipments and inventory management to balance trade-offs between transportation and inventory costs.

Hishamuddin *et al.* (2013) developed a recovery model for a two-echelon supply chain to tackle a transportation disruption that was not known in advance; thus the company did not have the opportunity to take mitigation measures before the occurrence of the disruption. They proposed a heuristic approach to determine a recovery plan for the supplier and the retailer that was subject to the system's costs and constraints. This allowed adjustments in the production schedule after the transportation disruption so as to minimize the overall recovery costs. Liu *et al*. (2016) developed a model of grey neural networks to help companies better predict market demand and subsequently optimize procurement, production, and inventory management after the occurrence of a transportation disruption caused by the snow storm in the Hunan province

in 2008. Chen and Zhang (2009) proposed a policy for dispatching vehicles, which optimized vehicle capacity and dispatching time along a route should a transportation disruption occur.

2.2. Risk mitigation

There exist several strategies to deal with supply chain disruptions or particularly with transportation disruptions. Chopra and Sodhi (2004) proposed several strategies to mitigate various risks in the supply chain. From these strategies, we identified that adding capacity, adding inventory, having redundant suppliers, increasing responsiveness, increasing flexibility, and increasing capability were among the plausible options to mitigate disruption risks. Tang (2006) noted that postponement, strategic stock, flexible supply base, make-and-buy, economic incentives, flexible transportation, revenue management, dynamic assortment planning, and silent product rollover were the robust strategies to mitigate supply chain disruptions.

Wilson (2007) proposed alternative routes, alternative modes of transportation, alternative suppliers, transhipment between warehouses, VMI, carrying additional inventory, having redundant suppliers, postponement, and mass customization to protect against transportation disruption risk in a supply chain. Stecke and Kumar (2009) proposed several actions to mitigate the effects of transportation disruption risk in a supply chain; these were mainly in the forms of flexibility and redundancy. These actions include maintaining multiple manufacturing facilities with flexible and/or redundant resources, carrying extra inventory, securing alternate suppliers, choosing flexible transportation options, standardizing and simplifying processes, creating component commonality and postponement, influencing customer choice, and insurance. Chen and Ji (2009) chose to adopt less risky transportation modes to avoid transportation disruption risks and to outsource to third-party logistics (3PL) providers in order to reduce transportation disruption risks.

Resilience is one of the goals in supply chain design. A supply chain is considered resilient if it is capable of maintaining its desired performance level even though disruption has occurred. Sheffi *et al*. (2003) identified two approaches to attain resilience in a supply chain: *flexibility* and *redundancy*. They argued that while redundancy is easy to build and less expensive in the short term, building flexibility is difficult and costly. However, flexibility appears to be more cost-effective compared to redundancy in the long term. For that reason, Pujawan (2004) reminded companies not to pursue a high level of flexibility unless the market indicates a strong need for it. Nonetheless, Rice and Caniato (2003) advised that, when it is feasible, one should endeavour to combine flexibility and redundancy.

Redundancy requires firms to maintain capacity to respond to disruptions in the supply chain, largely through investments in capital and capacity prior to the point of need (Rice and Caniato 2003). Simchi-levi *et al.* (2008) proposed an investment in redundancy to manage the risk of disruptions in a supply chain. A more detailed application of redundancy as a mitigation strategy against disruptions was presented by Son and Orchard (2013). They applied the redundant strategy to mitigate supply disruption by proposing Q-policy which basically adds extra quantity to the initial order of the EOQ and R-policy which built an exclusive stock that was preserved to protect the retailer or distributor from stock-outs during the disruption period.

Flexibility requires firms to create capabilities in the firms' organization to respond against disruptions in a supply chain by using the existing capacity that can be redirected or reallocated (Rice and Caniato 2003). Ishfaq (2012) showed that companies can improve the resilience of their supply chains by maintaining flexible transportation operations (routes and modes) in response to transportation disruption events. Fan *et al.* (2016) created flexibility in a supply chain via a postponement strategy to create slack time against supply chain disruptions as a result of diversified speed of transportation modes. Angkiriwang *et al.* (2014) classified flexibility strategies into reactive and proactive. A reactive strategy is akin to redundancy where companies may use buffering for inventory and lead time, but a proactive strategy requires more fundamental actions such as postponement, network redesign, altering product configuration, and negotiating with suppliers for a flexible supply contract.

Depending on the situations, companies may go beyond applying purely redundancy or flexibility strategies. Rice and Caniato (2003) noted that a firm will likely choose a mixture of flexibility and redundancy by taking into consideration the different cost and service characteristics offered by flexibility and redundancy. Schmitt (2011) also argued that a combined policy between inventory reserves and back-up capabilities could give the best protection against supply chain disruption.

3. Methodology

Taking into account the aim of this research, which is to investigate the effectiveness of different mitigation strategies against transportation disruptions in a real problem setting, simulation was chosen as the research method. The selection is based on the fact that a simulation study is appropriate for solving logistics and supply chain problems when the analytical techniques are difficult to implement (Law, 2007), especially if the system incorporates stochastic variables (Pujawan *et al.*, 2015) and where "what-if" analysis is necessary (Terzi and Cavalieri, 2004). Furthermore, when the characteristics of the logistics

7

and transportation system are difficult to model with analytical approaches, then simulation modelling is often used (Riddalls *et al.,* 2000). Particularly relevant to the context of this research is the fact that simulation is capable of modelling the system and its complex interrelationships and at the same time it enables a low cost investigation to make conclusions about how the actual system might behave (Rossetti, 2015).

The literature is rich in guidance on how to conduct a simulation study (e.g., Banks, 1998, Law, 2007, Sadowski, 2007, and Rossetti, 2015). We followed the procedure suggested by Banks (1998) which was also used by Pujawan *et al.* (2015). Since the objective of this study was to compare and evaluate alternative mitigation strategies at the tactical or operational decision making level (Brailsford and Hilton (2001) and Tako and Robinson (2009)), the Discrete-Event Simulation (DES) technique was employed.

The study was conducted in four successive steps (Figure 1). The first step is developing the simulation model. The model was developed based on an understanding of the real system after substantial effort was spent on information gathering about the system and relevant data collection. The data were collected to provide inputs for the model. The input data include demand data, travel time, the occurrence of transportation disruptions, and cost data. The first three data were stochastic functions and we then used the distribution fitting functions in ARENA® to find the appropriate distribution for each data. The simulation model was developed and run in ARENA® version 14.

INSERT FIGURE 1 ABOUT HERE

The second step is verification and validation. Verification ensures that the simulation model is working as it should and that the logics are executed properly. Validation is concerned with the issue of whether the conceptual simulation model is an accurate representation of the real system (Kleijnen, 1995; Banks, 1998). The third step is running the simulation experiments. This step, to some extent, follows the practical approach proposed by Tjahjono and Fernández (2008). In so doing, scenarios were created to assess current practices in a supply chain where transportation disruptions are present.

The final step is analysis of the results. As we aim to obtain better outcomes than the current situation, we have chosen the Incremental Cost-Effectiveness Ratio (ICER) as a basis for the comparison. ICER is a multi-criteria decision making tool with proven capability in assessing and comparing the cost-effectiveness of alternate strategies, especially when the effectiveness measure is difficult to be monetized (Boardman *et al.,* 2010). ICER is ideal in

cases where each alternative requires investment and the results may not be measured in terms of monetary values.

In this study, each alternative corresponds to a strategy proposed to deal with transportation disruptions. We will follow the methodology proposed by Karlsson and Johannesson (1996) for making comparisons among alternatives using cost effectiveness analysis.

4. System description

In this research, we model a transportation disruption in a wheat flour transportation system from the flour mills (also referred to as the plant in this paper) to the distribution centre (see Figure 2). The plant and the distribution centre are owned by different companies. The flour mills obtained wheat from overseas. The long supply lead time due to the distance of the wheat suppliers requires the plant to have a sufficiently large amount of wheat inventory. The wheat is stored in a silo to ensure that the production process can take place continuously. Though the plant produces 12 brands in total, in this study, we focus only on the five most popular ones. In terms of volume, these five brands account for about 90% of the total. The distribution centre does not exclusively distribute and sell wheat flour but also various other products such as palm oil, sugar, and instant noodles. Both the plant and the distribution centre are located in the island of Sulawesi in Indonesia. The distance between the two facilities is about 700 kilometers and they are connected through low to medium quality roads, which are the only viable transportation mode in this case. Shipment is normally done by trucks with the capacity of 25 tons for each truck. In this study, we count the inventory costs of the finished goods. The inventory costs of the wheat are not taken into account, as this is not affected by any scenario that we evaluate in this study.

INSERT FIGURE 2 ABOUT HERE

Disruptions are often expected, especially during the rainy season where roads are often blocked by landslides, floods, and the like. In case of the normal route being disconnected, an alternative route must be taken, but this causes a longer delivery time. The delivery time through the normal route is about two days, while the alternative route takes about four days. Once the transportation is disrupted, the company is obviously unable to replenish the distribution centre's inventory (at least for the duration of the disruption) and the retailers' demand will be met from distribution centre's inventory. Depending on the duration of the

disruptions and the on-hand inventory at the beginning of the disruption, the distribution centre could likely experience stock-outs. Here we assume that any unmet demand is considered as lost sales (no backorder).

The recovery process, which includes repairing the infrastructures, will commence as soon as the disruption occurs, thus the duration of the disruptions equals the repair time, which is represented by a lognormal probability distribution. Replenishment, known as delivery hereafter, from the plant resumes as soon as the recovery process is completed.

A map of Sulawesi is shown in Figure 3. The flour plant is located in Makassar city, South Sulawesi, and is highlighted by A. The distribution centre in Poso city, Central Sulawesi, is highlighted by C. There are two routes that connect A and C. The regular route is (A-C) which directly connects Makassar city and Poso city with a distance of around 700 kilometers. The alternative route (A-B-C) connects Makassar city and Poso city via Mamuju city (B circle) with a distance around 1,040 kilometers. Thus, the alternative route is about 50% longer in distance compared to the regular route. Transporting for a distance of over 700 kilometers under a poor road condition is difficult and disruptions during certain time periods certainly pose even more challenges.

INSERT FIGURE 3 ABOUT HERE

Even though there are other distribution centres that the plant serves using trucks as the transportation mode for the delivery, we chose this particular distribution centre in Poso city because it is the furthest distance from the plant's location. Therefore, it has the longest transit lead time, which in turn is very sensitive to any transportation delay.

5. Model development

The model was built based on the case described above. We observed the delivery process and the typical disruptions that happened as well as demand and cost data. Data were collected to enable the model building. We built the DES model and designed the experiments to test the four mitigation strategies: (1) risk acceptance strategy, (2) redundant stock strategy, (3) flexible route strategy, and (4) redundant-flexibility strategy. The risk acceptance strategy is the current strategy that the company adopts, while redundant stock, flexible route, and redundant-flexibility strategies were proposed as a manifestation of a resilient supply chain against disruptions through flexibility and redundancy (Sheffi *et al.*, 2003).

INSERT FIGURE 4 ABOUT HERE

The four strategies that we modelled and compared in this study are shown in Figure 4 and the description of each case is presented in Table 1. Firstly, we set off from an ideal system (Box 1) reflecting the situation without any transportation disruptions. We then collected logistics and marketing data from the real system. Secondly, we generated natural disaster events which caused a transportation disruption in the delivery activity but no mitigation strategy was imposed (Box 2). Thirdly, we experimented with Boxes 3, 4 and 5, representing the delivery activity under transportation disruptions, and each of the boxes has a different mitigation strategy: redundant stock (Box 3), flexible route (Box 4), and the combination of the two (Box 5).

INSERT TABLE 1 ABOUT HERE

The simulation model for each strategy consists of 3 simulation logics: (1) disruption logic, (2) delivery logic, and (3) demand logic. In order to induce the transportation disruptions into the delivery process, we created disruption logic. The input for the disruption logic was obtained from the National Disaster Mitigation Agency (BNPB). We first determined that an affected area of South Sulawesi covering 80% of the distance between Makassar to Poso is in the South Sulawesi region. After that, we focused on the frequency of landslide, flood, and landslide-flood as these are the major sources of road infrastructure failures in South Sulawesi. The natural disaster data were collected from 2007 to 2016. The frequency of natural disasters shown in Table 2 was then used as the basis for generating disruptions in the simulation logic.

INSERT TABLE 2 ABOUT HERE

The delivery logic in the simulation model is needed to represent delivery activity from the plant to the distribution centre. We used the historical delivery data provided by the company. This historical data consists of delivery dates, delivery quantity linked to delivery date, and transit time from the plant to the distribution centre. These three data were used directly as inputs for delivery logic. The demand logic function is needed to generate the distribution centre's demand for each brand of flour on a daily basis. We assumed that the demand from the distribution centre to the plant is an exact reflection of the aggregation of retailers' demand to the distribution centre.

While the delivery logic differs for each strategy, the demand and disruption logics were deliberately made exactly the same. In the risk acceptance strategy, delivery would cease when a disruption occurs until the recovery process was completed. In the redundant stock

11

strategy, a certain amount of redundant stock was placed initially at the distribution centre, so the distribution centre would be able to replenish the retailers for a certain period. In the flexible route strategy, an alternative route was used instead of waiting until the disruption was over and the recovery process was completed. In the redundant-flexibility strategy, both the redundant stock at the distribution centre and the flexible route were applied. At the end of the simulation run, we recorded two response variables: (1) the average percentage of lost sales which was also the measure of the service level (acted as our effectiveness measure) and (2) the average cost for executing the strategy (acted as our cost measure). We used the lost sales and service level interchangeably in this paper with an understanding that the service level can be obtained by subtracting the percentage of lost sales from 100%. For each strategy applied, the element of transportation cost (T) will always exist and is expressed in the equation below:

$$T = TR * RD * (Q/Cap) \tag{1}$$

where

TR = transportation rate (Rupiahs/Ton)

RD = distance between the plant and the distribution centre using regular route (Kms)

Q = volume of the delivered finished products (Tons)

Cap = adjusted truck capacity which is set as 25 tons.

Risk acceptance strategy

We associate the base case with the risk acceptance strategy as there is basically no strategy applied to mitigate the risks of disruptions. Here, the plant is basically waiting until the road is fixed to resume the delivery. In this strategy, inventory is held at the plant and thus extra inventory holding cost is incurred due to the goods being unable to move to the distribution centre during the event of disruptions. The extra holding cost here is calculated based on the duration of the disruption, the quantity held, and the inventory holding cost rate. We assume that the annual holding cost rate is 30% of the product value and thus the daily holding cost is obtained by simply dividing it by 365, the number of days in a year. The extra holding cost can therefore be expressed as:

$$EHC = \frac{BSP*HCR}{t} * DD * Q \tag{2}$$

where

EHC = extra holding costs (Rupiah)

BSP   = selling price of the brand from the plant to the distribution centre (Rupiah)

DD   = the duration of disruption (day)

t   = 365 days in a year

HCR = set to be 30% or 0.3.

The flow chart of the risk acceptance strategy is shown in Figure 5.

INSERT FIGURE 5 ABOUT HERE

Redundant stock strategy

The redundant stock strategy is similar to the risk acceptance strategy with the exception that the plant placed extra inventory, also known as redundant stock, in the distribution centre at the beginning of the delivery period. The reason behind this scenario is that it is good to have inventory closer to customers as a mitigation strategy for the road disruption. However, naturally the distribution centre is not willing to hold much inventory as there are costs associated with it. To entice the distribution centre to hold this extra inventory, 50% of the redundant holding cost (RHC) is charged to the plant. The flow chart of the simulation model for the redundant stock strategy is shown in Figure 6. The total cost for this strategy is calculated as $T + EHC + RHC + RTC$ where RTC is redundant transportation cost. The cost components are defined as follows:

$$RHC \ = \ R * BSP \ * \ HCR * 0.5 \tag{3}$$
$$RTC \ = \ (R/Cap) * TR * RD \tag{4}$$

where

R = redundant stock quantity.

INSERT FIGURE 6 ABOUT HERE

Flexible route strategy

In the flexible route strategy, the plant does not have to wait until the road is fixed. The plant instead persuades the trucking company to use the alternative route when a disruption occurs in the regular route. The flow chart of the simulation model for the flexible route strategy is shown in Figure 7. As a compensation, the plant will pay an additional cost, called the extra distance costs (*EDC*), to the trucking company. The total cost for this strategy is $T + EDC$. *EDC* is defined as follows:

$$EDC \ = \ TR * AD * (Q/Cap) \tag{5}$$

where

AD = distance from the plant to the distribution centre using the alternative route.

INSERT FIGURE 7 ABOUT HERE

Redundant-flexibility strategy

In the redundant-flexibility strategy, the redundant stock and flexible route strategies are combined. When a transportation disruption occurs, the truck will use the alternative route causing a delivery time of 4 days which is longer than the delivery time of the regular route. Given that in the current situation there is no extra stock allocated to cover the disruptions, in the very beginning of delivery period, the plant placed redundant stock at the distribution centre with the volume equal to demand for the delivery period of 4 days. The flow chart of the simulation model for the redundant-flexibility strategy is shown in Figure 8. The total cost of this strategy is $T + RHC + RTC + EDC$.

INSERT FIGURE 8 ABOUT HERE

Verification and validation

As suggested by Law (2007), we verified our model by checking the distribution centre's inventory level produced by our simulation model with the one produced by manual calculations. In addition, we also observed the occurrence of stock-outs (in which period and for how long). Figure 9 shows an example of the model verification. The red circle at the top graph shows negative inventory level, while the bottom only shows the zero-inventory level. These red circles indicate a stock-out period which is captured by both the simulation model and manual calculations. The reason behind this differentiation is to verify that our simulation model does not integrate a backorder policy (as intended). We revealed that the inventory profiles obtained from manual calculation were very similar with those obtained from the simulation, and hence the simulation model is verified.

INSERT FIGURE 9 ABOUT HERE

If a real system exists, then it is advisable to compare the simulation output with the existing system to perform model validation. However, there are cases that the system under study does not exist, for example when the aim of the simulation study is to propose a new design of a system. The scenarios depicted in the risk acceptance strategy, redundant stock

strategy and flexible route strategy do exist in real life, but the one portrayed in redundant-flexibility strategy does not, making it difficult to objectively compare the results of the simulation model with that of the real systems. Due to that challenge, we employed the validation approach proposed by Law (2007). We observed three aspects in the validation process, namely (1) the products delivered, (2) the number of natural disasters generated, and (3) simulation general behaviour.

For the products delivered, we compared the sample of actual shipments with the simulation output. The ten replications gave the mean value of 11,129 kilograms with the standard deviation of 3,980 while the actual shipment was 9,695 kilograms. This suggests that the amount shipped by the simulation model is not statistically different from that of the actual shipment.

We also compared the actual number of disasters with the simulation output. From ten replications we obtained the mean value of 32 occurrences with the standard deviation of 2, while the mean value of the actual occurrences was 33. It can therefore be concluded that there is no statistical difference between the simulated and actual data.

The third validity test was to check the behaviour of the simulation model by comparing the result of our simulation model with those of a similar model. We used Wilson (2007) as a benchmark. In Wilson (2007), the inventory level kept by the distribution centre during the disruption was flat or experienced stock-outs. After the disruption was over and the plant resumed the deliveries, the inventory level at the distribution centre then increased significantly. The same phenomenon was also demonstrated by our model.

6. Results and analysis

6.1. Simulation results

The run length of each experiment was one year in simulation time and each experiment was replicated 10 times. The average cost and percentage of lost sales were recorded for the four strategies. Table 3 shows the performance of the four strategies across all five brands.

INSERT TABLE 3 ABOUT HERE

The results suggest that the risk acceptance strategy is the worst in terms of the service level but the best in terms of cost. The other three strategies can improve the service level (i.e., reduce the percentage of lost sales), but they come with additional costs. The redundant stock strategy is the most expensive, and in most cases it does not offer the best service level either.

The redundant-flexibility strategy offered the best service level except for one particular brand (brand C), and the costs are still much lower than that in the redundant stock strategy. The flexible route is less costly but produces a lower service level compared to the redundant-flexibility strategy.

Unsurprisingly, there is no dominant strategy across all brands. However, if we exclude brand C, we would say that the redundant stock strategy is dominated either by the flexible route strategy or by the redundant-flexibility strategy or by both. Furthermore, given that the lost sales performance of the risk acceptance strategy is quite high, we would argue that the company should invest in risk mitigation strategies.

6.2. Incremental Cost Effectiveness Ratio (ICER)

As we are concerned with more than one performance measure (i.e., costs and service level), a multi-criteria method is needed to compare the strategies. In the earlier section we discussed the results which suggested comparing the performance of one strategy against another. As the service level and cost are basically traded-off (i.e., cost normally increases when we attempt to improve the service level), we need to use a method to assess how much money a decision maker needs to spend for each scale of service level improvement. In order to do this, we have selected the *Incremental Cost Effectiveness Ratio* (ICER) because it provides us with an estimation of the cost incurred in each strategy for a company to increase the service level by one percent.

In general, ICER is useful to assess the effectiveness of switching from one strategy to another or the cost of using one strategy in preference to another (Petitti, 1999). ICER can be mathematically expressed by the following equation:

$$ICER_{(i)} = \frac{C_{(i)} - C_{(i-1)}}{E_{(i)} - E_{(i-1)}} \quad (6)$$

where
$ICER_{(i)}$ = the cost-effectiveness ratio when switching strategy $(i-1)$ to i
$C_{(i)}$ = the cost for strategy i
$E_{(i)}$ = effectiveness of strategy i.

For us, ICER was an obvious choice, because our research is concerned with the evaluation of four disruption mitigation strategies that are competing against each other. The decision makers may have a limited amount of money and therefore can only implement a strategy that could provide a moderate impact but with relatively low costs. According to Petitti

(1999), before the cost is valued, the contributors of the cost should be defined. One of the cost contributors that is relevant to this research is direct cost, which we interpreted as the monetary value incurred with the implementation of a strategy (Petitti, 1999).

Effectiveness, on the other hand, is not measured in monetary value. In relation to the transportation disruptions, we used the same measurement as Wilson (2007) which is unfulfilled customer orders or lost sales as the degree of effectiveness.

An algorithm to calculate ICER was introduced by Johannesson and Weinstein (1993) and further elaborated via a hypothetical case by Karlsson and Johannesson (1996). We summarized and adapted this algorithm to handle the context of this research:

- *Step 1*. Define what cost and effectiveness terms are referring to;
- *Step 2*. Measure/calculate the cost and effectiveness for each strategy;
- *Step 3*. List strategies in ascending order of either effectiveness or costs;
- *Step 4*. Identify and eliminate a strongly dominated strategy (has increased costs and reduced effectiveness compared with the next immediate alternative) and/or;
- *Step 5*. Identify and eliminate a weakly dominated strategy (has equal cost with reduced effectiveness or increased costs with the same effectiveness compared with the next immediate alternative);
- *Step 6*. Calculate ICER using equation (6) above;
- *Step 7*. If ICER$_i$ > ICER$_{i+1}$ (ICER changed in descending order) then strategy i is considered to be extended and dominated by strategy $i + 1$, thus it should be eliminated;
- *Step 8*. Repeat steps 6 and 7 if necessary;
- *Step 9*. Produce recommendation of acceptable strategy based on the ICER.

When $i = 1$, we consider this as the status quo strategy, which refers to the current strategy. Consistent with equation (6), this status quo strategy is automatically skipped in step 6. Strongly dominated in step 4 means that strategy i is less effective and is more costly compared to strategy $i + 1$. Weakly dominated in step 5 means that strategy i is either giving the same effectiveness with higher cost or less effective with the same cost compared to strategy $i + 1$. Extended dominated in step 7 means that strategy i is less effective than strategy $i + 1$, because switching directly from strategy $i - 1$ to strategy $i + 1$ gives better effectiveness with lower cost than switching from strategy i to strategy $i + 1$ which gives less effectiveness with greater cost.

The results of the analysis based on ICER are presented in Table 4. The table specifically shows the recommended strategy under the range of Willingness to Pay (WTP), that is, the strategy a decision maker has to take given the amount of money he or she is willing to spend for each one percent of improvement in the service level. For example, for brand A, if the decision maker is willing to spend less than 949,940 Indonesian Rupiahs, then the choice should be the status quo or to stay with the current risk acceptance strategy. If the decision maker is willing to spend beyond that amount but lower than 3,593,292 Indonesian Rupiahs for any one percent improvement in the service level, then the chosen strategy should be the flexible route. If spending is not a concern, then improvements can go further and in such a case, the recommended strategy would be the redundant-flexibility strategy.

Looking at the overall results, the general trend is to choose the Risk Acceptance strategy when the WTP is very low. This means that the managers are basically not willing or have low willingness to invest in risk mitigation strategies. On the other extreme, the redundant-flexibility strategy is mostly chosen if the WTP is high. In the middle range, the flexible route appears in all cases. The redundant stock only appears for brand C and D because in other brands, redundant stock is a dominated strategy and hence will not be considered in any range of the WTP values. For example, on brand A, redundant stock strategy is dominated by the flexible route and the redundant-flexibility strategies as the cost incurred is higher but the service level is lower. In this study, however, we have not counted the cost associated with loss of customers in the future due to being out of stock. It may somehow affect the decision under certain circumstances; this is an issue that could potentially be included in future studies.

7. Discussion

Choosing the best strategy to address a problem is often a difficult decision to make. The decision may not be based on the effectiveness or cost alone, but it could be both. It is well known that in any supply chain problem, cost and service level are traded-off and hence any improvement in service level would be achieved with additional cost. However, it is also important to compare which strategy would deliver highest increase in the service level in relation to the improvement cost or mitigation strategy.

The mitigation strategies proposed in this research are to ensure resilience which enables the flour plant to recover to their initial performance after the disruptions occurred. The strategies available and the best choices may vary from case to case, but the four strategies

considered in this research are quite universal for handling uncertainty or disruptions. Angkiriwang *et al*. (2014) classified the two approaches to handle uncertainties, namely reactive and proactive. The reactive approach is basically implemented by adding buffers in the form of extra inventory, safety lead time, or extra capacity. The proactive approach requires more fundamental changes like redesigning the supply network and therefore the cost incurred would typically be higher. If we reflect from these two classifications, our findings suggest that the reactive approach (i.e., simply adding inventory to handle disruptions) is not the best option and the company has to find a more fundamental approach, including the combination of reactive and proactive approaches.

The redundant stock strategy that we proposed in this study basically means adding inventory at the distribution centre. The effort is relatively straightforward, but the additional cost is obvious. The cost of the redundant stock strategy is caused by the tied up capital, the warehouse costs, the maintenance costs (Sheffi, 2005), and other components of inventory holding costs. This may not be always an acceptable strategy if there is a limitation in the product shelf life, a restriction of the warehouse capacity, or reluctance of the distribution centre's manager to keep a high inventory level. In addition, the level of inventory buffer should be decided through a consensus between the distribution centre and the plant.

The redundant-flexibility strategy combines the redundant stock and the flexible route strategy and creates a balance between the advantages offered by these two strategies. The high cost of holding the inventory buffer can be reduced by decreasing the amount of redundant stock and delivering this amount via an alternative route. The risk acceptance strategy which is currently applied has no investment for risk mitigation. This strategy absorbs the negative impact of transportation disruptions directly without any protection. Thus, our simulation study shows that the lost sales from this risk acceptance strategy is the most severe compared to those proposing mitigation strategies. The acceptance behaviour of this strategy could have stemmed from these following reasons.

Firstly, even though most managers are conscious that their supply chain is inherently risky, they often choose to do nothing in order to avoid extra costs and/or because they do not know how to deal with the risk. Secondly, Simchi-Levi *et al*. (2015) believe that managers choose to do nothing against the risk of disruptions not only because they are worry about misallocating financial resources (i.e., tailoring mitigation strategies) that may result in a poor financial performance report but they also worry that investing in such mitigation strategies would not give them the spotlight whether or not an actual disruption occurs. Thirdly, companies consider natural disasters as a *force majeure* that should be simply accepted.

However, Chopra and Sodhi (2014) mentioned that doing nothing will likely give the most severe impact, while Sheffi (2015) point out that most customers are very demanding and will not simply accept excuses for supplier's incapability of delivering products due to natural disasters.

8. Conclusion

This research presents a simulation model to evaluate different strategies in mitigating risks from transportation disruptions. We modelled a company producing several brands of wheat flour and a distribution centre that distributes those products in the island of Sulawesi in Indonesia that is geographically challenging and thus prone to transportation disruptions. The four strategies, namely the risk acceptance strategy (which is the current situation), the redundant stock strategy, the flexible route strategy, and the combination of the flexible route and the redundant stock strategies were simulated, and their impacts were compared in terms of service level and total costs. The three alternative strategies proposed demonstrated a better service level compared to the current, risk acceptance strategy, but all came with additional costs. In most cases, the Redundant Stock strategy was dominated by the Flexible Route or the Redundant-Flexibility strategy. The ICER analysis recommends the strategy that a decision maker has to choose under different ranges of investment that he is willing to spend. If the budget for financial investment available is tight but improvement is absolutely necessary, then the decision maker should choose the Flexible Route strategy. If the budget is not tight and the decision maker is willing to invest to get the best service level, then in most cases, the Redundant-Flexibility strategy should be the option.

Our study is based on a real case and thus provides contextual insights on how the transportation disruptions affect the supply chain and how effective the mitigation actions can be in addressing such disruptions. The ICER analysis is particularly useful in providing managers with a framework to select the best strategies under different ranges of a deployable budget to mitigate the disruptions. The recommended strategy may be subject to different parameter values and hence analysis may need to be done for a specific case. We therefore suggest continuing this study to investigate the robustness of the recommended strategy under different parameter values or problem settings.

The issue of transportation disruptions is an important research topic which should receive more attention in the field of supply chain management. Various strategies maybe proposed and evaluated, but we believe that there is 'no one size fits all'. Our future work would focus on identifying the conditions under which a certain strategy is preferable.

Furthermore, how the risks maybe collaboratively mitigated by more than one party in a supply chain is indeed an important issue in supply chain risk and thus calls for further research in this field.

References

Angkiriwang, R., Pujawan, I.N., and Santosa, B., 2014. Managing uncertainty through supply chain flexibility: reactive vs. proactive approaches. *Production & Manufacturing Research*, 2 (1), 50–70.

Azad, N., Saharidis, G.K.D., Davoudpour, H., Malekly, H., and Yektamaram, S.A., 2013. Strategies for protecting supply chain networks against facility and transportation disruptions: An improved Benders decomposition approach. *Annals of Operations Research*, 210 (1), 125–163.

Banks, J., 1998. *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practices*. 1st ed. Wiley Publishing, Inc.

Boardman, E.A., Greenberg, D., Vining, A., and Weimer, D., 2010. *Cost-Benefit Analysis. Concepts and Practice*. 4th ed. New Jersey: Pearson Education, Inc.

Brailsford, S. and Hilton, N., 2001. A comparison of discrete event simulation and system dynamics for modelling health care systems. *Proceedings from ORAHS 2000*, 18–39.

Bravo, J.J. and Vidal, C.J., 2013. Freight transportation function in supply chain optimization models: A critical review of recent trends. *Expert Systems with Applications*, 40 (17), 6742–6757.

Cavinato, J.L., 2004. Supply chain logistics risks: From the back room to the board room. *International Journal of Physical Distribution & Logistics Management*, 34 (5), 383–387.

Chen, T. and Ji, G., 2009. Study on supply chain disruption risk. *Proceedings of the 2009 6th International Conference on Service Systems and Service Management, ICSSSM '09*, 404–409.

Chen, X. and Zhang, J., 2009. Optimal dispatching policy under transportation disruption. *50th Annual Transportation Research Forum 2009*, 2, 634–643.

Chopra, S. and Sodhi, M., 2004. *Managing Risk To Avoid Supply-Chain Breakdown*. MITSloan Management Review. MITSloan.

Chopra, S. and Sodhi, M.S., 2014. Reducing the Risk of Supply Chain Disruptions. *MIT Sloan Management Review*, 55 (3), 73–80.

Christopher, M. and Peck, H., 2004. Building the resilient supply chain. *International Journal of Logistics Management*, 15 (2), 1–13.

Christopher, W., Johnny, M., and Robert, B., 2007. The Severity of Supply Chain Disruptions : Design Characteristics and Mitigation Capabiliti. *Decision Sciences*, 38(1) (1), 131–156.

Cui, J., Zhao, M., Li, X., Parsafard, M., and An, S., 2016. Reliable design of an integrated supply chain with expedited shipments under disruption risks. *Transportation Research Part E: Logistics and Transportation Review*, 95, 143–163.

Doan, L., Amer, Y., Lee, S., and Phuc, P., 2018. Optimizing the Total Cost of an E-waste Reverse Supply Chain Considering Transportation Risk. *Operations and Supply Chain Management,* 11 (3), 151 - 160.

Fan, Y., Schwartz, F., and Voß, S., 2016. Flexible supply chain planning based on variable transportation modes. *International Journal of Production Economics*.

Figliozzi, M.A. and Zhang, Z., 2010. A Study of Transportation Disruption Causes and Costs in containerized maritime transportation. *Transportation Research Board*, 1–17.

Giunipero, L.C. and Eltantawy, R.A., 2004. Securing the upstream supply chain: a risk management approach. *International Journal of Physical Distribution & Logistics Management*, 34 (9), 698–713.

Guiffrida, A.L. and Jaber, M.Y., 2008. Managerial and economic impacts of reducing delivery variance in the supply chain. *Applied Mathematical Modelling*, 32 (10), 2149–2161.

Hendricks, K.B. and Singhal, V.R., 2005. An Empirical Analysis of the Effect of Supply Chain Disruptions on Long-Run Stock Price Performance and Equity Risk of the Firm. *Production and Operations Management*, 14 (1), 35–52.

Hishamuddin, H., Sarker, R.A., and Essam, D., 2013. A recovery model for a two-echelon serial supply chain with consideration of transportation disruption. *Computers and Industrial Engineering*, 64 (2), 552–561.

Houshyar, A.N., Baghdadabad, M.R.T., Hoshyar, A.N., and Sulaiman, R. Bin, 2013. Simulating Effects of Transportation Disruption on Supply Chain Based on Vendor Managed Inventory Approach. *International Journal of Modeling and Optimization*, 3 (2), 116–119.

Ishfaq, R., 2012. Resilience through flexibility in transportation operations. *International Journal of Logistics Research and Applications*, 15 (4), 215–229.

Johannesson, M. and Weinstein, M.C., 1993. On the decision rules of cost-effectiveness analysis. *Journal of health economics*, 12 (4), 459–467.

Karlsson, G. and Johannesson, M., 1996. The Decision Rules of Cost-Effectiveness Analysis. *PharmocoEconomics Fe*, 9 (2), 113–120.

Kleijnen, J.P.C., 1995. Statistical validation of simulation models. *European Journal of Operational Research*, 87 (1), 21–34.

Latour, A., 2001. Trial by fire: A blaze in Albuquerque sets off major crisis for cellphone giants-Nokia handles supply shock with aplomb as Ericsson of Sweden gets burned-was SISU the difference? *Wall Street Journal*, 1–6.

Law, A.M., 2007. *Simulation Modeling & Analysis*. 4th ed. McGraw-Hill.

Li, G., Fan, H., Lee, P.K.C., and Cheng, T.C.E., 2015. Joint supply chain risk management: An agency and collaboration perspective. *International Journal of Production Economics*, 164, 83–94.

Liu, C., Shu, T., Chen, S., Wang, S., Lai, K.K., and Gan, L., 2016. An improved grey neural network model for predicting transportation disruptions. *Expert Systems with Applications*, 45, 331–340.

Ouyang, M., Pan, Z., Hong, L., and He, Y., 2015. Vulnerability analysis of complementary transportation systems with applications to railway and airline systems in China. *Reliability Engineering and System Safety*, 142 (January 2018), 248–257.

Petitti, D.B., 1999. *Meta-Analysis, Decision Analysis, and Cost-Effectiveness Analysis*. 2nd ed. Monographs in Epidemiology and Biostatistics. Oxford University Press.

Pujawan, I.N., 2004. Assessing supply chain flexibility: a conceptual framework and case study. *International Journal of Integrated Supply Management*, 1 (1), 79–97.

Pujawan, N., Arief, M.M., Tjahjono, B., and Kritchanchai, D., 2015. An integrated shipment planning and storage capacity decision under uncertainty. *International Journal of Physical Distribution & Logistics Management*, 45 (9/10), 913–937.

Rice, J.B. and Caniato, F., 2003. Building a secure and resilient supply network. *Supply Chain Management Review*, 7 (5), 22–30.

Riddalls, C.E., Bennett, S., and Tipi, N.S., 2000. Modelling the dynamics of supply chains. *International Journal of Systems Science*, 31 (8), 969–976.

Rossetti, M.D., 2015. *Simulation Modeling and Arena*. New Jersey: John Wiley & Sons Ltd.

Sadowski, S.K., 2007. *Simulation with Arena*. 4th ed.

Sansone, C., Hilletofth, P., and Eriksson, D., 2017. Critical operations capabilities for competitive manufacturing: a systematic review. *Industrial Management & Data Systems*, 117 (5), 801–837.

Schmidt, W. and Raman, A., 2012. When supply-chain disruptions matter, 34.

Schmitt, A.J., 2011. Strategies for customer service level protection under multi-echelon supply chain disruption risk. *Transportation Research Part B: Methodological*, 45 (8),

1266–1283.

Sheffi, Y., 2005. *The Resilient Enterprise*. 1st ed. Cambridge: The MIT Press.

Sheffi, Y., 2015. *The Power of Resilience*. 1st ed. Cambridge: The MIT Press.

Sheffi, Y., Rice, J.B., Fleck, J.M., and Caniato, F., 2003. Supply Chain Response to Global Terrorism : A Situation Scan. *EurOMA POMS Joint International Conference*, 1–6.

Simchi-levi, D., Kaminsky, P., and Simchi-levi, E., 2008. *Designing and managing the supply chain: concepts, strategies, and case studies.* 3rd ed. Boston, MA: McGraw-Hill/Irwin.

Simchi-Levi, D., Schmidt, W., Wei, Y., Zhang, P.Y., Combs, K., Ge, Y., Gusikhin, O., Sanders, M., and Zhang, D., 2015. Identifying Risks and Mitigating Disruptions in the Automotive Supply Chain. *Interfaces*, 45 (5), 375–390.

Son, J.Y. and Orchard, R.K., 2013. Effectiveness of policies for mitigating supply disruptions. *International Journal of Physical Distribution & Logistics Management*, 43 (8), 684–706.

Stecke, K.E. and Kumar, S., 2009. Sources of Supply Chain Disruptions, Factors That Breed Vulnerability, and Mitigating Strategies. *Journal of Marketing Channels*, 16 (3), 193–226.

Tako, A.A. and Robinson, S., 2009. Comparing discrete-event simulation and system dynamics: users' perceptions. *Journal of the Operational Research Society*, 60 (3), 296–312.

Talluri, S.S., Kull, T.J., Yildiz, H., and Yoon, J., 2013. Assessing the Efficiency of Risk Mitigation Strategies in Supply Chains. *Journal of Business Logistics*, 34 (4), 253–269.

Tang, C., 2006. Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics*, 9 (1), 33–45.

Tang, C.S., Teo, C.-P., and Wei, K.K., 2008. *Supply Chain Analysis*. Optimization.

Terzi, S. and Cavalieri, S., 2004. Simulation in the supply chain context: A survey. *Computers in Industry*, 53 (1), 3–16.

Tjahjono, B. and Fernández, R., 2008. Practical approach to experimentation in a simulation study. *Proceedings - Winter Simulation Conference*, (January), 1981–1988.

Tomlin, B., 2006. On the Value of Mitigation and Contingency Strategies for Managing Supply Chain Disruption Risks. *Management Science*, 52 (5), 639–657.

Wadhams, N., 2010. Iceland volcano: Kenya's farmers losing $1.3m a day in flights chaos. *The Guardian*, pp. 5–7.

Wearden, G., 2010. Nissan and BMW car production hit by volcano disruption. *The Guardian*, pp. 1–3.

Wilson, M.C., 2007. The impact of transportation disruptions on supply chain performance. *Transportation Research Part E: Logistics and Transportation Review*, 43 (4), 295–320.

Yang, T. and Wu, J., 2007. The Impact of Transportation Disruptions on Performance of E-Collaboration Supply Chain. *In*: *Research and Practical Issues of Enterprise Information Systems II*. Boston, MA: Springer US, 663–667.

Zhang, Y. and Lam, J.S.L., 2015. Estimating the economic losses of port disruption due to extreme wind events. *Ocean and Coastal Management*, 116, 300–310.

Zhen, X., Li, Y., Cai, G. (George), and Shi, D., 2016. Transportation disruption risk management: business interruption insurance and backup transportation. *Transportation Research Part E: Logistics and Transportation Review*.
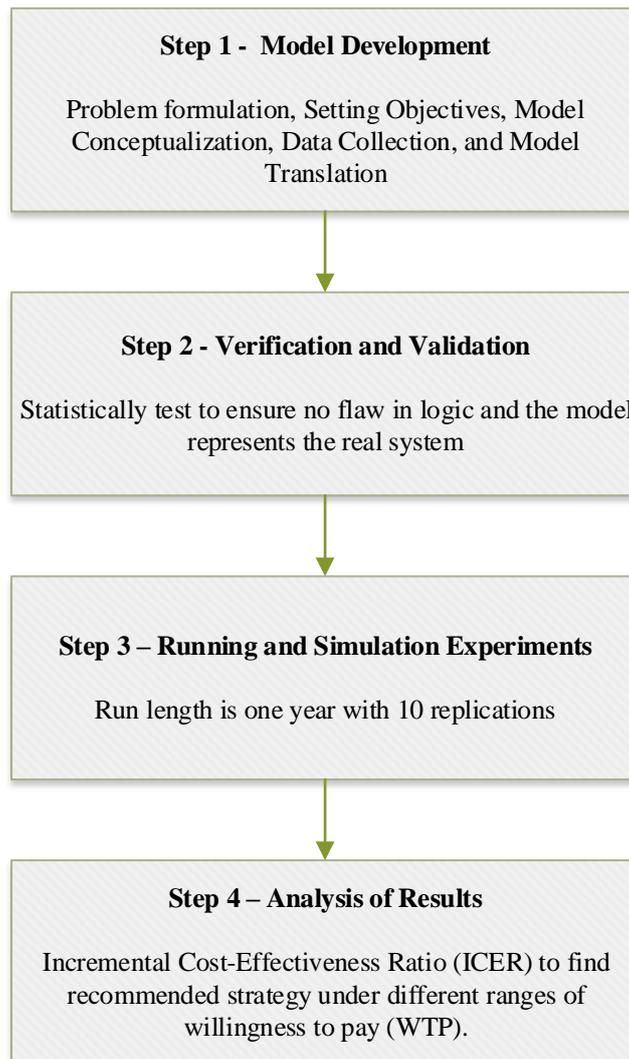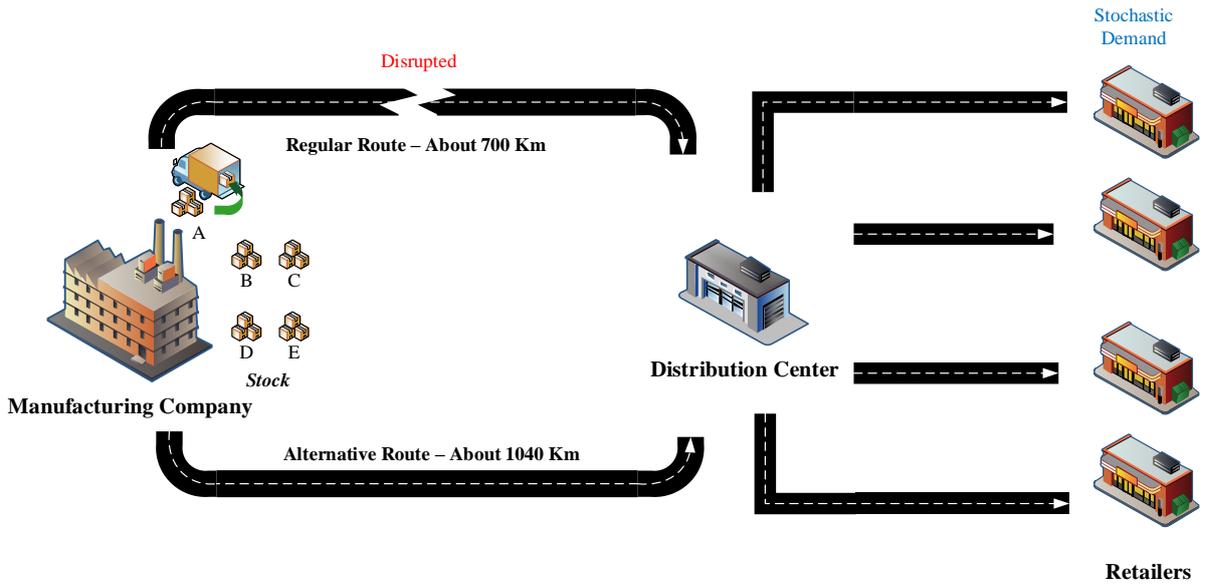
Step 1 - Model Development
Problem formulation, Setting Objectives, Model Conceptualization, Data Collection, and Model Translation

Step 2 - Verification and Validation
Statistically test to ensure no flaw in logic and the model represents the real system

Step 3 – Running and Simulation Experiments
Run length is one year with 10 replications

Step 4 – Analysis of Results
Incremental Cost-Effectiveness Ratio (ICER) to find recommended strategy under different ranges of willingness to pay (WTP).

Figure 1. Research process
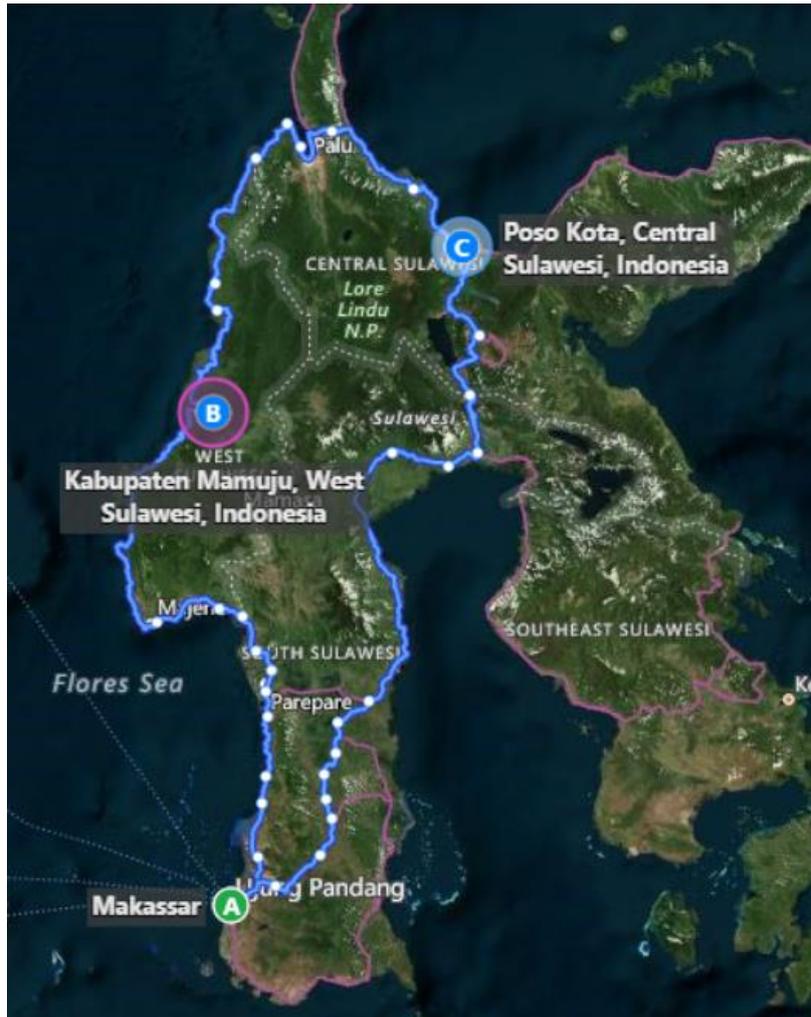
Figure 2. Illustration of system configuration

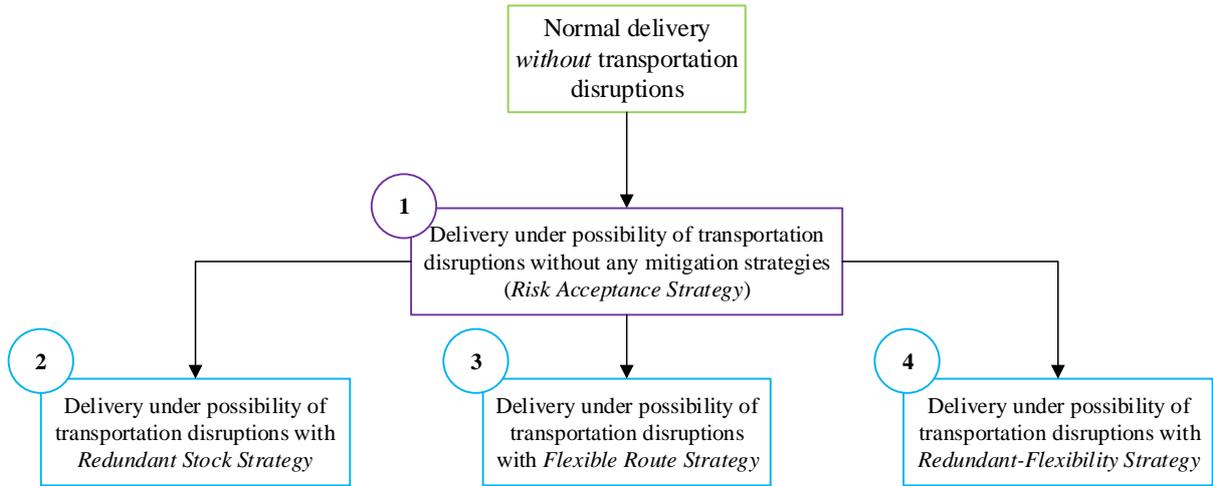Figure 3. The map showing the two delivery routes from A to C

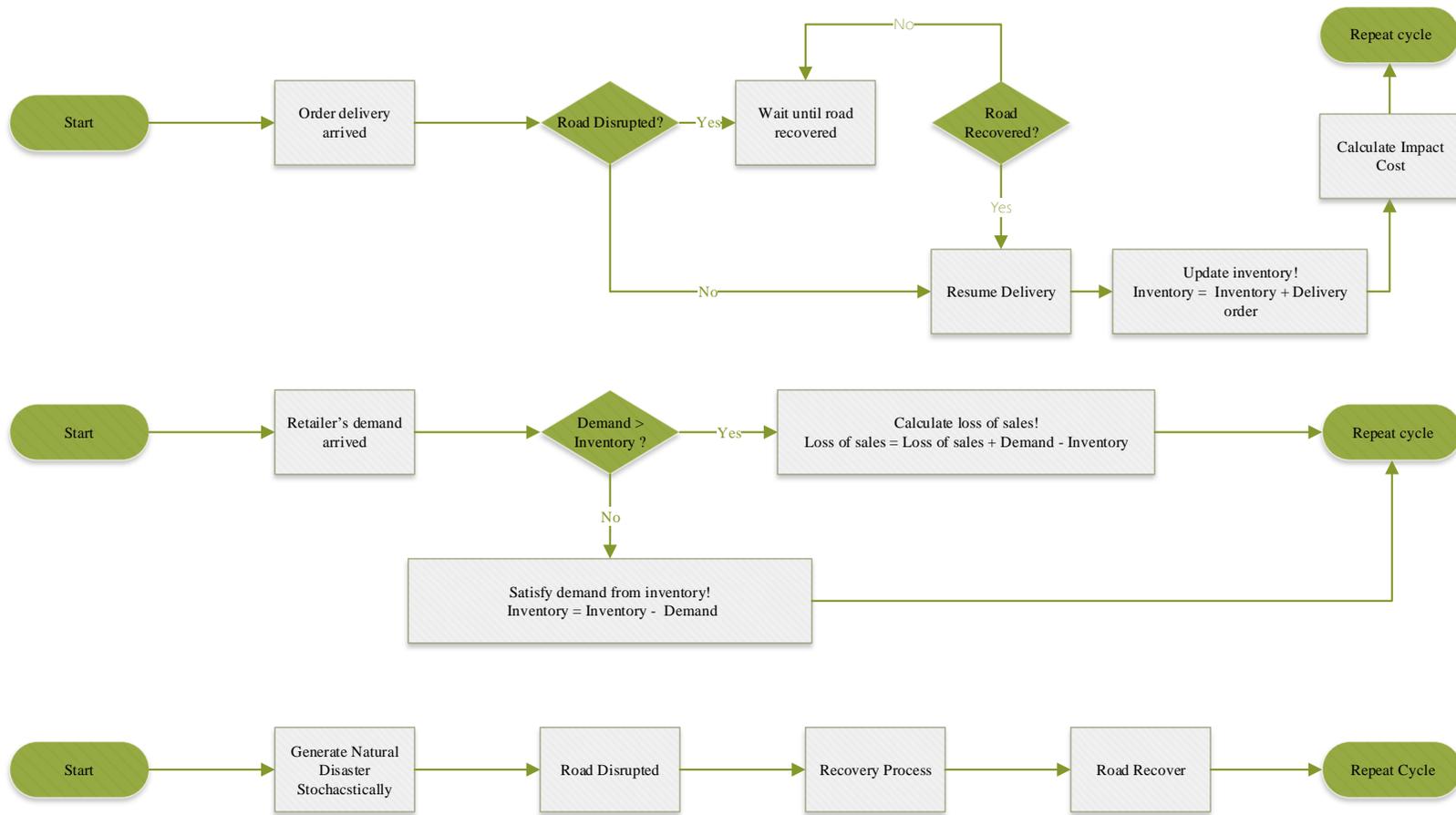Figure 4. Structure of mitigation strategies

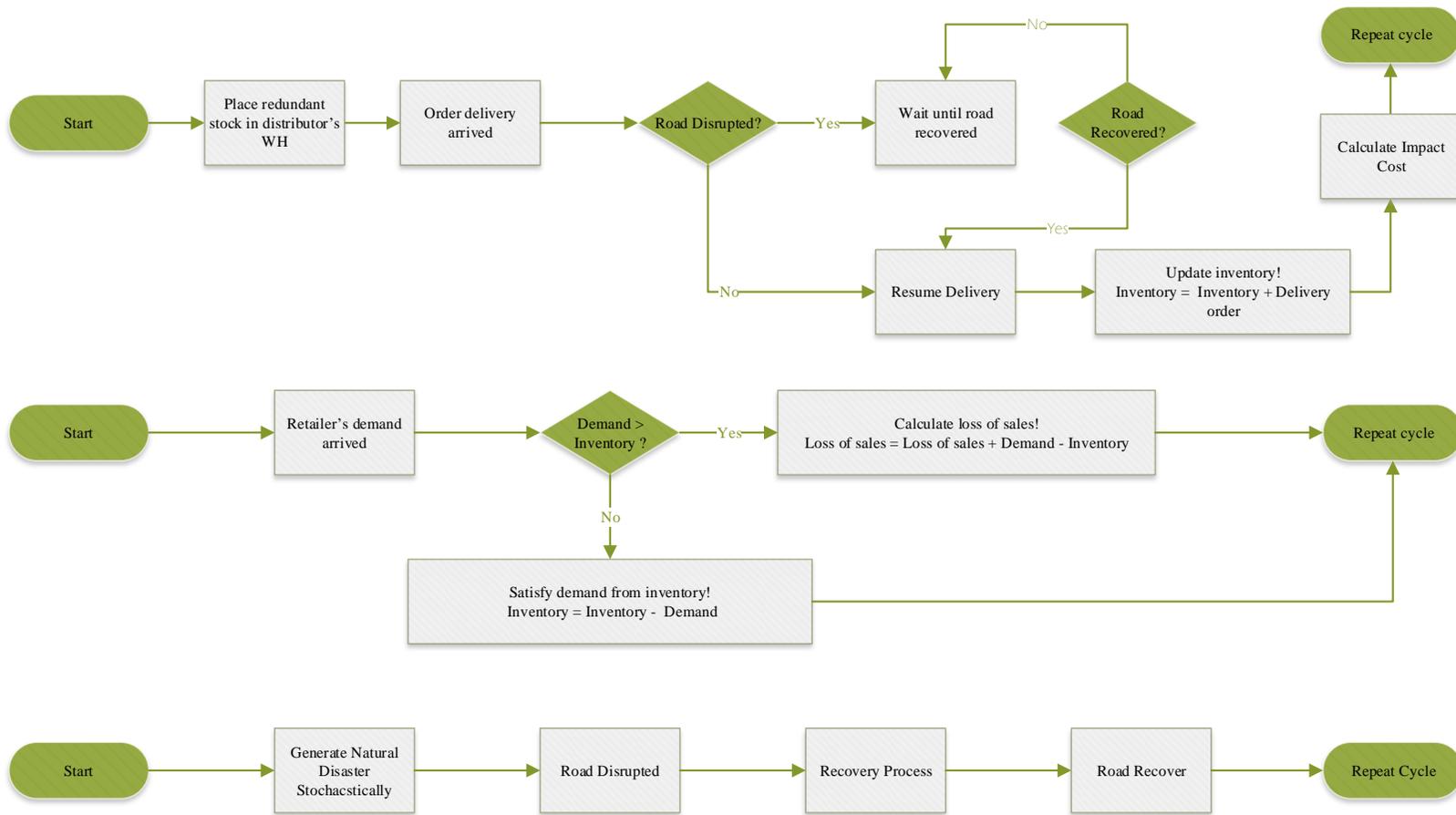Figure 5. Risk acceptance strategy simulation model

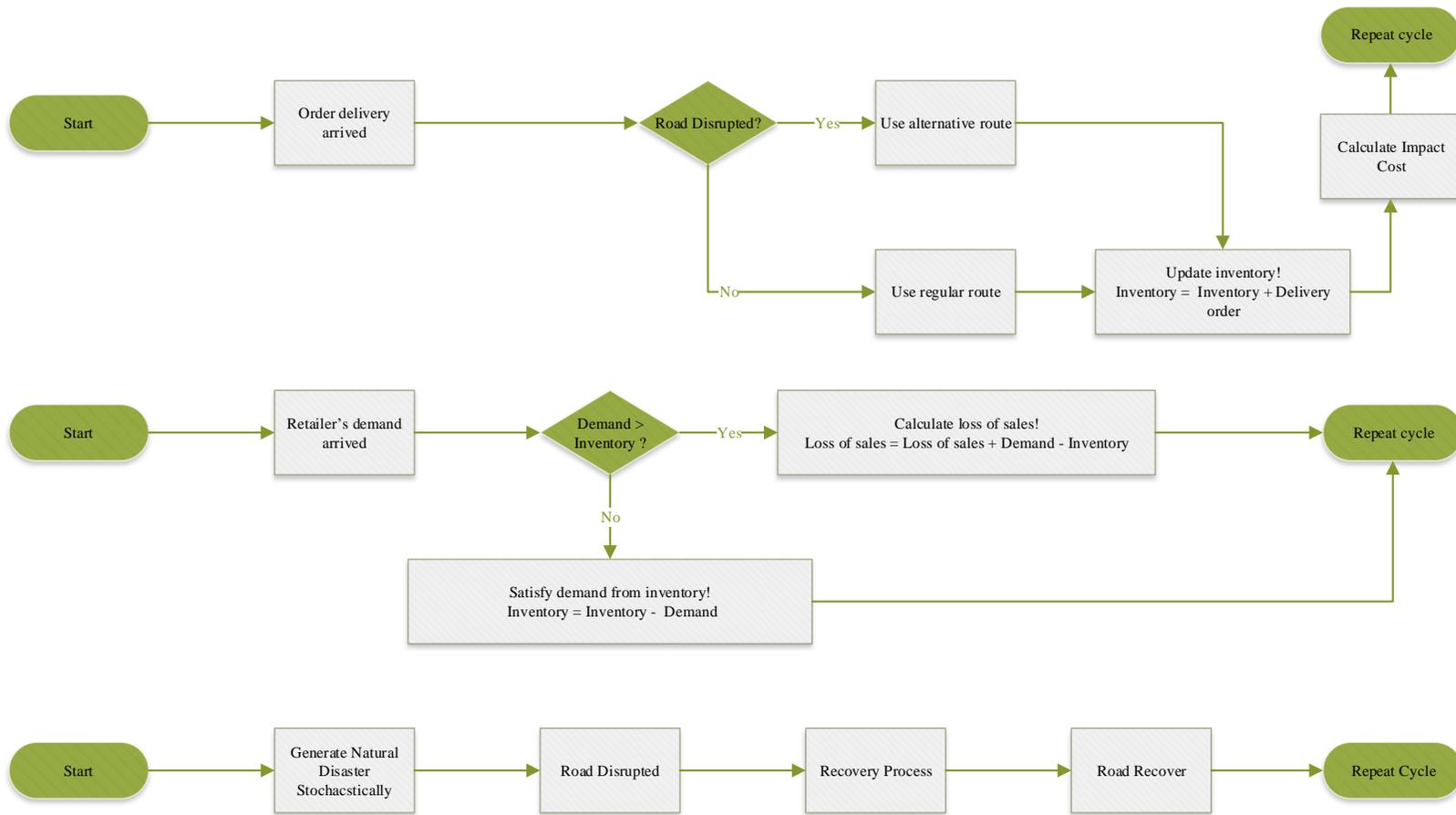Figure 6. Redundant stock strategy simulation model

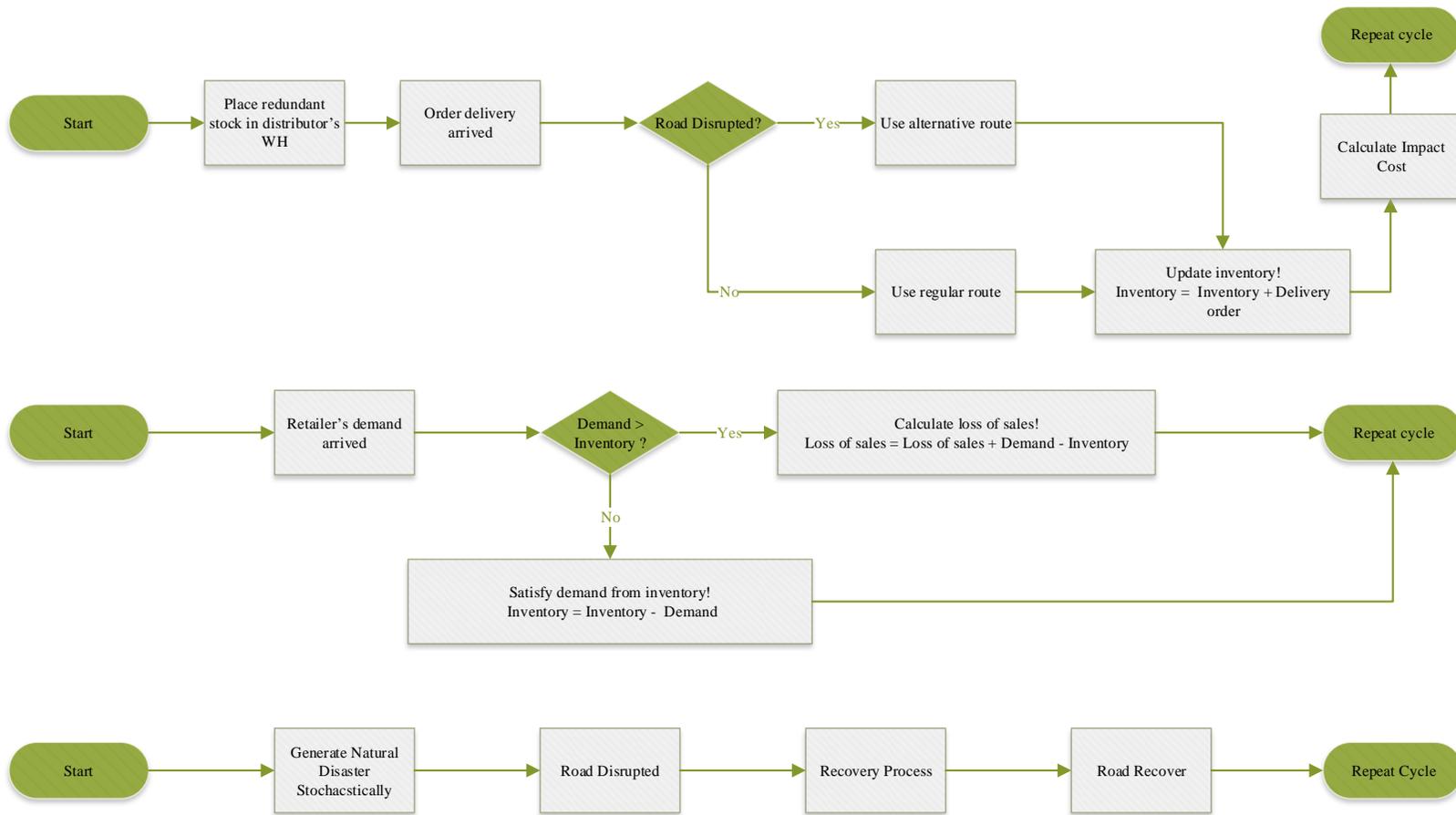Figure 7. Flexible route strategy simulation model

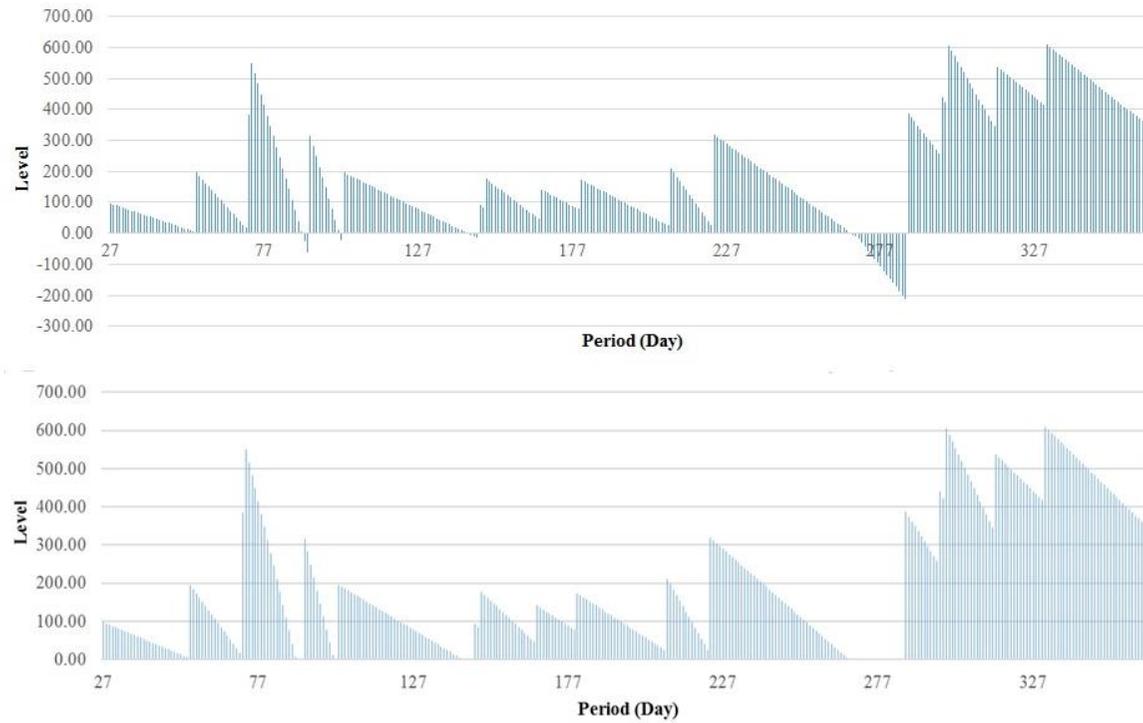Figure 8. Redundant-flexibility strategy simulation model

Figure 9. Inventory level from manual calculations (top) and simulation (bottom)

33

Table 1. Description of the four scenarios

Scenario	Description
Risk Acceptance	This is the base case scenario where no mitigation strategy is applied and inventory of flour is held at the plant, DC does not keep extra stock.
Redundant Stock	Inventory is held at the distribution center, 50% of the redundant holding cost is charged to the plant
Flexible Route	Shipment is through an alternative route during the road disruptions in the regular route, the plant pay extra distant cost. No redundant stock is applied.
Redundant-Flexibility	This scenario is combining the two earlier scenarios. Shipment is through alternative route, redundant stock is held at the distribution center.

Table 2. Frequency of natural disasters per year

Year	Disaster Frequency
2007	32
2008	34
2009	21
2010	78
2011	20
2012	22
2013	30
2014	21
2015	28
2016	40

Table 3. Summary of simulation results

Brand	Strategy	Cost	Lost of Sales (%)
	Risk Acceptance (RA)	Rp 147,289,350.00	17.16
A	Redundant Stock (RS)	Rp 207,171,186.00	6.24
	Flexible Route (FR)	Rp 159,790,585.00	4.00

	Redundant-Flexibility (RF)	Rp 167,623,964.00	1.82
B	Risk Acceptance (RA)	Rp 92,087,625.00	13.77
	Redundant Stock (RS)	Rp 124,092,600.00	5.27
	Flexible Route (FR)	Rp 97,897,645.00	5.27
	Redundant-Flexibility (RF)	Rp 101,665,046.00	3.8
C	Risk Acceptance (RA)	Rp 80,059,701.00	12.93
	Redundant Stock (RS)	Rp 118,387,422.00	1.27
	Flexible Route (FR)	Rp 85,663,678.00	10.10
	Redundant-Flexibility (RF)	Rp 89,993,430.00	7.82
D	Risk Acceptance (RA)	Rp 67,362,589.00	6.07
	Redundant Stock (RS)	Rp 85,421,999.00	1.20
	Flexible Route (FR)	Rp 72,808,077.00	1.41
	Redundant-Flexibility (RF)	Rp 74,979,778.00	0.51
E	Risk Acceptance (RA)	Rp 57,228,533.00	7.57
	Redundant Stock (RS)	Rp 70,866,450.00	2.86
	Flexible Route (FR)	Rp 60,355,923.00	1.69
	Redundant-Flexibility (RF)	Rp 62,162,344.00	0.87

Table 4. Recommended mitigation strategy based on willingness to pay

Brand	Willingness to Pay (WTP)			Recommended Strategy
A	WTP	<	Rp 949,940.87	Risk Acceptance
	Rp 949,941.87	to	Rp 3,593,292.12	Flexible Route
	Rp 3,593,293.12	≥	WTP	Redundant-Flexibility
B	WTP	<	Rp 683,531.76	Risk Acceptance
	Rp 683,531.76	to	Rp 2,562,856.82	Flexible Route
	Rp 2,562,857.82	≥	WTP	Redundant-Flexibility
C	WTP	<	Rp 236,168.51	Risk Acceptance
	Rp 236,168.51	to	Rp 1,899,013.47	Flexible Route
	Rp 1,899,014.47	to	Rp 4,565,312.89	Redundant-Flexibility
	Rp 4,565,313.89	≥	WTP	Redundant Stock
D	WTP	<	Rp 734,716.09	Risk Acceptance
	Rp 734,716.09	to	Rp 10,341,432.33	Flexible Route
	Rp 10,341,433.33	to	Rp 18,063,668.57	Redundant Stock
	Rp 18,063,669.57	≥	WTP	Redundant-Flexibility
E	WTP	<	Rp 531,869.05	Risk Acceptance
	Rp 531,869.05	to	Rp 2,202,951.44	Flexible Route
	Rp 2,202,952.44	≥	WTP	Redundant-Flexibility