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Dynamic Decision Modeling for Inland Waterway Disruptions

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Table of Contents

Table of Figures

Table of Tables

Abstract

Inland waterway system is an essential part of the U.S. transportation system, which provides efficient and economic freight transportation through 12,000 miles of navigable waterway. An unexpected event (such as a natural event or unscheduled maintenance) may block a section on the inland waterway and lead to disruption of the transportation. Considering the broad economic and societal impacts caused by the disruption, closures of the inland waterway system can become a significant problem for the shippers and other stakeholders involved in barge transportation. When the disruption occurs, there exist two available actions: (1) waiting at the current location until the locked traffic to clear, and (2) rerouting using alternative transportation modes. However, the uncertainty inherent in disruptions makes the decision making process complicated.

In this research, we construct a framework for decision making under uncertainty when disruption on the inland waterway occurs. A comprehensive transportation cost model is developed which reflects objectives and goals of the stakeholders who are directly or indirectly involved with freight transportation. In addition, the uncertainty of the closure is studied in terms of the expected closure duration affecting the transportation cost. A supporting spreadsheet-based tool is devised to facilitate real-time decision making. The numerical experiment reveals the significance of the private indirect cost in decision making and the existence of a threshold-type policy. The investigation concerning historical data of the closure events shows the significant relationship between the weather condition and the duration of the disruption. Having a more accurate estimate of the disruption duration will improve the decision making process.

1. Project Description

1.1. Background

The inland waterway system is an important component of the U.S. marine transportation system, which provides efficient and economic freight transportation for bulk cargo between inland points and deep water ports (U.S. House Committee on Transportation and Infrastructure, 2013). It is comprised of rivers, bays, channels, and inner route; and, nationally, 25,000 miles of inland and intracoastal waterways including 12,612 miles of commercially significant shallow-draft waterways are operated and maintained for commerce (Bureau of Transportation Statistics, 2016). The U.S. Army Corps of Engineers (USACE) performs operations, maintenance, and construction of the inland waterway infrastructure such as locks and dams and navigation channels (Kreis et al., 2014). With 239 lock chambers operated at 193 sites and 1,930 cargo handling docks located along the waterways (U.S. Army Corps of Engineers, 2016), the system directly serves 41 states (U.S. Army Corps of Engineers, n.d.) throughout inland points, the Atlantic seaboard, the Gulf Coast, and the Pacific Northwest (U.S. Army Corps of Engineers, 2009).

Considering the lower unit cost and higher capacity of the barge transportation compared to rail and truck, the waterway is especially preferred for the transportation of large amount of bulk cargoes such as petroleum, coal, grain, and raw materials (U.S. Army Corps of Engineers, 2009). Since 2000, 6 to 7 percent of domestic U.S. commerce, measured in ton-mile, moves on the waterway system (Transportation Research Board, 2015). Each year, more than 566 million tons of freight valued at $152 billion travel through the inland waterway system (American Society of Civil Engineers, 2013). Particularly, USACE reported 575.5 million tons of cargo appraised at $229 billion was transported on the system in 2015 (Waterways Council, Inc., n.d.).

The availability of the inland waterway system is affected by scheduled and unscheduled closures. A natural or an unexpected event may block a section on inland waterways and lead to disruption of the system. For instance, the reasons for lock closure include routine maintenance, weather, accident, equipment failure, or other unforeseen events (Transportation Research Board, 2015). More specifically, ice, droughts, or flood can make water levels non-navigable; earthquake can damage the infrastructure of the system (Tong, 2014). Delayed transportation time by the unavailability generates additional cost for shippers and carriers and imposes needless cost to stakeholders directly or indirectly associated. The main lock chamber at the Greenup Locks and Dam at the Ohio River was closed at September 8, 2003 for scheduled maintenance. However, serious cracking was discovered and the closure was extended for emergency repairs. Consequently, the closure lasted for 52 days and the lock reopened at October 31, 2003. About $41.9 million was estimated as the additional cost associated with the closure event (Planning Center of Expertise for Inland Navigation, 2005). Between June 13 and July 5, 2008, the Mississippi River Lock 12 and Lock 25 were closed in sequence due to non-navigable water level by flooding. During the closure period, it incurred additional cost of more than $19.8 million to shippers and carriers (Jackson, 2009).

1.2. Motivation and contribution

There exist different uncertain events that cause disruption of the inland waterway. For example, weather condition is a main source of uncertainty that affects the state of the system. Although forecasting is possible, the prediction is imperfect and uncertainty cannot be eliminated. Terrorist attack or unexpected infrastructure failure are other uncertain events that may lead to temporary waterway closure. It is usually not an easy task to predict how long the disruption may last and what impacts it may bring. Even when such estimates are obtained, the prediction is likely to be imprecise without close investigation.

When the disruption occurs, cargoes can be rerouted using other transportation modes immediately; or stay at the current location on inland waterway and wait until the locked traffic to clear. However, the uncertainty inherent in disruptions has made the decision making process complicated. Staying on the waterway do not incur additional transportation cost, but may generate the cost by late delivery. On the other hand, rerouting cargoes do not incur late delivery penalty, but cause additional transportation cost. The decision maker needs to find the trade-offs given the observed condition at closure and make judgment based on imperfect predictions of the future.

The decision making given the disruption affects different stakeholders who have their own goals. The Coast Guard needs to ensure maritime safety and security, while the shippers are trying to minimize their losses. A collaborative planning considering all stakeholders' goals can have the greatest overall societal benefits. Thus, a multi-objective decision making model taking into account the uncertainty associated with specific disruptive events can facilitate timely and optimal decisions for all stakeholders.

To the best of our knowledge, this is the first study that develops a real-time decision making support tool in the event of inland waterway disruption, which takes into account both the uncertainty associated with disruptions and the goals and objectives of all decision makers. There are many stakeholders involved upon a disruption event and waterway closure: federal, state and local transportation agencies, the USACE, the U.S. Coast Guard, port administration, transportation service providers, shippers, and recipients. In this research, involvement with these maritime stakeholders will ensure the practicability of the decision models. The multi-criteria decision making models developed from this research can also be generalized or applied to other problems. And the tools developed from this study can help make real-time optimal decisions that can be updated and adjusted.

1.3. Objectives

The overall goal of this research is to facilitate decision making in the event of disruption on inland waterways considering uncertainty associated with the event. To reach this goal, we set the research objectives as follows:

- To define the problem
- To develop a multi-objective decision making model
- To construct a decision making framework
- To devise a decision support tool

To define the problem

This is the fundamental objective that forms the base of our research. With this objective, the research team seeks to understand the history of disruptive events for inland waterways, their consequences, and current practices in the event of waterway closure. It also helps the team gather information on actions or options after waterway closure for various parties involved, such as the USACE, port administration, and shippers. Then, we characterize the risks and uncertainty associated with inland waterway disruptions. It is critical to understand what risk a disruptive event may bring, and what is the uncertain nature associated with the event. A decision can be made if these characteristics are known and quantified.

To develop a multi-objective decision making model

We seek to develop a multi-objective decision making model that incorporates uncertainty and considers objectives from all stakeholders. We first identify factors that are related to the decision making process for each stakeholder. It is essential to understand what the key concerns are for each decision maker in the process. A multi-objective cost model is proposed from different perspectives: economic impact, safety issues, traffic congestions, environmental concerns, etc.

To construct a decision making framework;

A decision making framework shows sequential decision making process and which tools and techniques are applied to handle uncertainty of the problem. Additionally, it provides various approaches to help decision makers analyze the expected result from different perspectives. It underlies the decision making supporting tool for the operations manager who has to choose the most feasible alternative when the waterway is temporarily shut down. The framework gives structural justification to the decision making model.

To devise a decision making support tool

In this research, we design a user-friendly decision making support tool that can assist alternative transportation mode selection for practitioners. In order for practitioners to use our model and generate the optimal decision given disruption, we design a user-interactive decision support tool that can easily be updated and adjusted. The tool should represent real situations and be useful in practice.

1.4. Literature Review

We summarize literature related to our research problem and methodology area in this section. We first introduce decision making under uncertainty in general; then present existing delivery cost models; and lastly summarizing studies on maritime transportation under disruption.

1.4.1. Decision making under uncertainty

Decision making is a quotidian event for us. Naturally, for a long time, it has been drawing attention from a broad range of disciplines: cognitive psychology, economics, political science, marketing, social psychology, engineering, philosophy, and so on. Various *how, what,* and *why* questions concerning finding the optimal decision have been defined and studied in numerous research papers (Johnson and Busemeyer, 2010). Decision making is well-studied research area and a great deal of papers exists. However, their results are very specific and unique to the problem except for foundational studies. Thus, in this section, we review the fundamental notions of decision making and basic concept of solution procedure.

Situations where decision making occurs can be featured by the uncertainty inherent in the outcomes of a decision: *risk*, *uncertainty*, and *certainty* situation. In the risk situation, outcomes of a choice are defined with well-specified probability; in the uncertainty situation, probability of outcomes involves ambiguity; while in the certainty situation, the outcome of a choice is clearly defined deterministically (Johnson and Busemeyer, 2010). Risk and uncertainty are concepts developed from the recognition that the result of a choice is not deterministic; that is, diverse outcomes can be emerged from a decision. The difference between risk and uncertainty is the extent of confidence in defining the number, value, and likelihood of the outcomes (Thompson, 2005).

Almost all real-world decision making problems are under uncertainty. It is difficult to recognize every possible outcomes and even impossible to establish their probabilities with one hundred percent confidence. However, for the decision making purpose, managers tend to treat the situations as if they were not uncertain but risky. To find the optimal decision rationally, outcomes and their probabilities are required regardless of their confidence. Thus, the associated uncertainty is often unavoidably ignored in the decision making process. In management accounting techniques, risk and uncertainty are usually handled as the same thing (Thompson, 2005). In this context, risk and uncertainty are frequently used together without distinction in a number of papers and books.

Despite occurring in various situations, decision making under uncertainty commonly have three elements: the set of alternatives, the set of possible outcomes and their probabilities, and a monetary value model associated with each decision and outcome (Winston and Albright, 2009). Well-organized decision making procedures provide efficient and logical sequential steps for identifying the essential elements and finding the optimal decision. Although their details are different according to the given situations, the procedure generally involves the same basic phases: identifying the problem, analyzing alternatives, and choosing the most feasible alternative (Krajewski et al., 2007). Fundamentally, we follow this decision making procedure in finding the most feasible decision under the closure event and developing the decision support tool.

1.4.2. Delivery cost model

In the decision making procedure, one of the most difficult and important tasks is developing a value model incorporating decisions and uncertain factors. The value calculated by the model serves as the criterion of judgment, and it can determine the performance of the constructed decision making procedure. Generally, the problem is framed as a mathematical model; it calculates the expected profit or cost of each decision and the associated outcome in monetary value. Sometimes, the utility concept is used which reflects a decision maker's attitude toward profit, loss, and risk in quantifying the value (Anderson et al., 2003).

Litman and Doherty (2009) provided a comprehensive but brief literature review concerning freight transportation cost studies. A large number of transportation cost models reviewed in the paper aim for a comprehensive model that includes total direct and indirect costs incurred during the process such as vehicle cost, fuel cost, labor cost, parking cost, material handling cost, accident cost, congestion cost, pollution cost, infrastructure cost, insurance cost, taxes, etc.

Generally, these costs are simply classified as internal cost and external cost according to whether the cost is incurred and paid within the transportation system. For instance, vehicle operating cost and material handling cost are typical internal cost (Janic, 2007) while infrastructure maintenance cost, congestion and accident cost, and emissions cost are typically classified as external cost (Austin, 2015).

Some papers introduce their own classifications. The Government Accountability Office (GAO, 2011) categorized these costs into private cost, public cost, and external cost in terms of the total social cost. Transport Canada (2008) adopted full cost concept consisting of financial costs and social costs. Hanssen et al. (2012) used a generalized transportation cost model which is composed of pecuniary cost related to the price for the transport service and the cost based on the transport time.

Additionally, considering transportation as a part of logistics and supply chain, some models include inventory holding cost during transport or penalty cost to untimely delivery (Grout, 1998; Guiffrida and Nagi, 2006; Shin et al., 2009; Bergquist et al., 2016).

Although there are numerous transportation cost models for different decision purposes, almost all these are developed to analyze short-run marginal costs, long-run costs, or total social costs (Litman and Doherty, 2009). Thus, for our research, we seek to develop a cost model suitable for real-time decision making upon notification of closure.

1.4.3. Maritime transportation under disruption

In this section, we introduce studies that focus on inland waterway transportation under disruption. Firstly, we explore the significance of identifying ways to reduce the negative impact of disruption on supply chain and maritime. Secondly, existing models that provide guidance to evaluate the impact of disruption on supply chain and maritime are summarized. Lastly, the models that gave directions on how to deal with disruptions, especially decision making models with stochastic modeling embedded, are reviewed.

Supply chain under disruption has been proven to cause negative impacts on human's lives. Caldwell et al. (2002) conducted a preliminary analysis of potential impacts that global climate change may have on the movement of freight. They examined implications for the physical facilities and infrastructure as well as the patterns or demand for the shipment of freight. They found that waterway transportation was vulnerable to the effects of global climate changes. They also recommended more focus on transportation research in order to gain a better understanding of both the magnitude and the distribution of climate change impacts. Koetse and Rietveld (2009) presented a survey of the empirical literature on the effects of climate change and weather conditions on the transport sector. They indicated that an increased frequency of low water levels may considerably increase the costs of inland waterway transportation. Figliozzi and Zhang (2009) focused on estimating and understanding the costs and causes of transportation related supply chain disruptions. Choice experiments were designed to estimate the cost of disruptions for containers in international maritime trade. The results indicate that disruption costs are significantly higher than the traditional values for freight travel. In general, waterway transportation is vulnerable for the freight shipments under climate changes; disruption on waterway can leave a huge negative impact on the economy and civilians' lives.

In addition to reviewing the impacts of disruptions, researchers have also tried to develop models that would provide better results for evaluating the disruption effects. MacKenzie et al. (2012) studied the economic impact of an inland port by combining a simulation and a multiregional input–output model. They applied their model on a case study involving an Oklahoma port on the Arkansas River and the results indicated that if a financial penalty was imposed on companies for late delivery of commodities, companies would move their products by train rather than wait for the port to reopen. These decisions saved billions of dollars in production losses for the states that use the port. Implications of these results for policymakers concerned about limiting the consequences of port closures were discussed. Meijeren et al. (2011) investigated what impact can be expected from climate change on the competitive position of inland waterways transportation. A list of measures was developed from intensive literature review. These measures were then analyzed with the goal of reducing the negative impact of climate change on inland waterways transportation. Rose and Wei (2013) developed a model for the estimation of the total economic consequences of a seaport disruption considering major types of resilience. The model combined both demand-driven and supply-driven input–output analysis. The model was applied to a 90-day disruption at a major port area in Texas. They found that regional gross output could decline by as much as $13 billion at the port region level. However, the resilience could reduce these impacts by nearly 70%. Brown and Badurdeen (2014) focused on disruption management. The disruptions in their case referred to events characterized by a low likelihood of occurrence and a large impact. Because of their limited rate of occurrence, disruptions are associated with a high uncertainty with respect to their expected impact. Many previous publications tried to improve modeling of the disruption impact while others emphasized on issues including the design of methods for supply chain performance measurement, disruption monitoring and detection, evaluation of recovery strategies, and methods of optimal supply chain design. In Brown and Badurdeen (2014), design features considered are flexibility, redundancy, and operating efficiency. In Behdani et al. (2011), the application of agent-based models for abnormal situation management in supply chains is presented. Two views of what an abnormal situation entails (i.e., performance-based and plan-based) were considered. The possible implementations of both perspectives were illustrated by agent-based models of an oil refinery supply chain and a lube oil supply chain facing with disruptions in transportation or demand.

In order to deal with disruptions, researchers proposed different decision making models. Uncertainties are greatly associated with disruptions. Hence, stochastic models are heavily used in the decision making publication. Clarke et al. (2009) developed an air traffic flow management algorithms that utilize available stochastic weather information for improved decision making. Sumalee et al. (2011) proposed a multi-modal transport network assignment model considering uncertainties in both demand and supply sides of the network. These uncertainties are caused by adverse weather conditions with different degrees of impacts on different transportation modes. Di Francesco et al. (2013) addressed the problem of repositioning empty containers in maritime networks under possible port disruptions. A stochastic programming approach was considered incorporating the uncertainties associated with future outcomes. Baroud et al. (2014) introduced stochastic metrics of network resilience that allow a quantitative analysis under uncertainty of the time needed for a disrupted network to regain full operation after a disruptive event. An optimization problem to determine the most effective link recovery sequence is presented, aiming to minimize the time to full network resilience. As a case study, an inland waterway transportation network of the Mississippi River Navigation System was considered. The analysis shows that the methodologies presented can be of great use to the decision-making authorities and risk managers overseeing the reliability and resilience of critical infrastructures to disruptive events. The same group of researchers (Baroud et al., 2014) also discussed a modeling paradigm for quantifying system resilience, primarily as a function of vulnerability and recoverability. Stochastic measures of resilience were introduced to account for the uncertainties. A data-driven case study for the inland Port of Catoosa in Oklahoma was presented.

Markov chains and Markov decision models are commonly used dealing with uncertainty. Lewis et al. (2006) presented a Markov decision process model to help stakeholders quantify the productivity impacts of temporary closures of a container seaport on global supply chains. The model determined an optimal inventory management policy and calculated the long-run average cost for a firm that uses a seaport subject to unexpected closure. The results of a numerical study indicated that the expected length of a seaport closure negatively affects supply chain productivity more than the probability of closure. In addition, their results indicated the importance of contingency planning and disruption management for all stakeholders, including private firms and public agencies. Zhou et al. (2011) introduced a framework for representing an air traffic flow and flow-management action operating under weather uncertainty. They used a queuing model whose service rates are modulated by an underlying Markov chain describing weather-impact evolution to capture traffic management in an uncertain environment. Liu and Lam (2012) presented a model for intermodal transportation network which evaluated the impacts of disruptions occurring at a focal port. They focused on mitigation strategies of port utilization and port alliance. A discrete-time Markov chain was constructed for disruption frequency and duration. Numerical studies were conducted to demonstrate the possible effects of port disruption on terminal operators, shipping companies, cargo owners, shipping routes and inland transport. Nilim et al. (2002) addressed the single aircraft rerouting problem due to severe weather using a Markov decision process model and a stochastic dynamic programming algorithm, where the evolution of the weather is modeled as a stationary Markov chain. The solution provided a dynamic routing strategy for an aircraft that minimizes the expected delay. Gurning et al. (2013) proposed a Markov chain approach for the estimation of the risk probabilities that could result in delays, deviations and disruptions due to various maritime risks in a wheat supply chain. They also used a simulation model to further study maritime disruption management strategies. Gurning and Cahoon (2011) assessed four major mitigation strategies (i.e., inventory and sourcing mitigation, contingency rerouting, recovery planning, and business continuity planning) to determine their suitability for managing potential disruptions in the wheat supply chain. They used a Markovian-based to evaluate the mitigation strategies in the context of wheat transport from Australia to Indonesia. They measured and predicted supply chain costs and time functions in relation to disruptive events. This will allow the wheat supply chain to be better prepared both when attempting to manage maritime disruptions as well as when re-evaluating their supply chain operation planning in terms of mitigating future maritime disruptions.

2. Methodological Approach

In this section, we present the framework of the decision making model and the design of the supporting tool for the decision makers. Firstly, we illustrate and describe the decision making problem in this study. In the following sub-section, the framework is defined which shows the decision making procedures and the approaches used. The delivery cost model and the closure duration estimating model, which are critical components of the model, are discussed in detail in the following sections. Based on the developed framework, the decision making support tool is devised; and then, using a numerical example, we show how the supporting tool works in practice.

2.1. Decision making under an unexpected closure event on inland waterway

Unlike roads and rails, a detour is very rare on navigable inland waterway, which can be used to circumvent a closed section, lock, or dam due to an unexpected event such as bad weather condition and unscheduled maintenance. Generally, a barge blocked by a closed section waits until the section reopens; and rerouting is not considered because it may incur additional transportation cost. Hereafter, to separate out from the general meaning, the waiting action and rerouting action of a barge are referred to as the waiting and the rerouting, respectively.

From the traditional viewpoint of transportation cost which involves only directly related elements such as vehicle operating cost and material handling cost, the rerouting has no benefit over the waiting. However, in the extended concept of the cost, the situation is different. In terms of supply chain management, inventory holding cost and untimely delivery cost are indirectly associated with transport. These costs are closely connected with time and accrue as delivery time increases. Thus, it can be considered that unexpected waiting also incurs additional costs. In short, comparing the waiting and the rerouting, the waiting incurs lower direct cost and higher indirect cost while the rerouting generates higher direct cost and lower indirect cost. Therefore, depending on the waiting time, the rerouting can be a better action than the waiting.

Unfortunately, we cannot know the closure duration in advance when a section of inland waterway is disrupted by an unexpected event. Accordingly, the waiting time derived from the duration is unknown when we make a choice between the waiting and the rerouting. Considering this situation, the decision making problem is not easy to solve and a solution is not always clear.

Naturally, uncertainty is inherent in the closure duration and the associated probability distribution is also unknown. These features are passed down to the waiting time. This is the reason why the problem is considered as the decision making problem under uncertainty.

For this problem, without loss of generality, we assume that transport starts at the shipper's location and ends at the recipient's location. The recipient's location can be any point and is not restricted to a terminal on the inland waterway. Thus, the final destination can be any location and the transportation involves barge, train, and/or truck. Due to geographic limitation, inland waterway has low accessibility and requires combination with other land transportation modes to reach the final destination. Therefore, inland waterway is generally used as a part of intermodal transportation including rail and/or road.

In this research, the cost is calculated based on the remaining transportation from the current location to the final destination. The waiting and the rerouting follow quite different delivery processes in the remaining transport, leading to different total cost. These processes are illustrated in Figure 1 and 2 for the waiting and the rerouting decision, respectively. The sub-process in the shaded rectangle in Figure 2 is involved only when the rerouted delivery includes intermodal transportation of trail and truck.

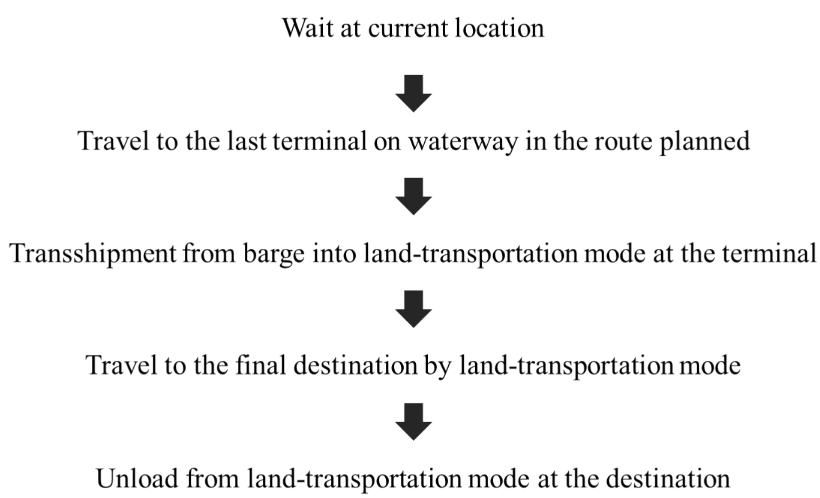


Figure 1. The procedure of delivery in case of the waiting

Travel from current location to the available nearest terminal

⬇

Transshipment from barge into land-transportation mode at the terminal

(*In case of intermodal transportation*) ⬇

Travel to a terminal by land-transportation mode

⬇

Transshipment between land-transportation modes at the terminal

⬇

Travel to the final destination by land-transportation mode

⬇

Unload from land-transportation mode at the destination

Figure 2. The procedure of delivery in case of the rerouting

Figure 3 shows the difference in routes of the waiting and the rerouting on a transportation network. We assume that the new route corresponds to the minimum cost path from the nearest available terminal to the final destination.

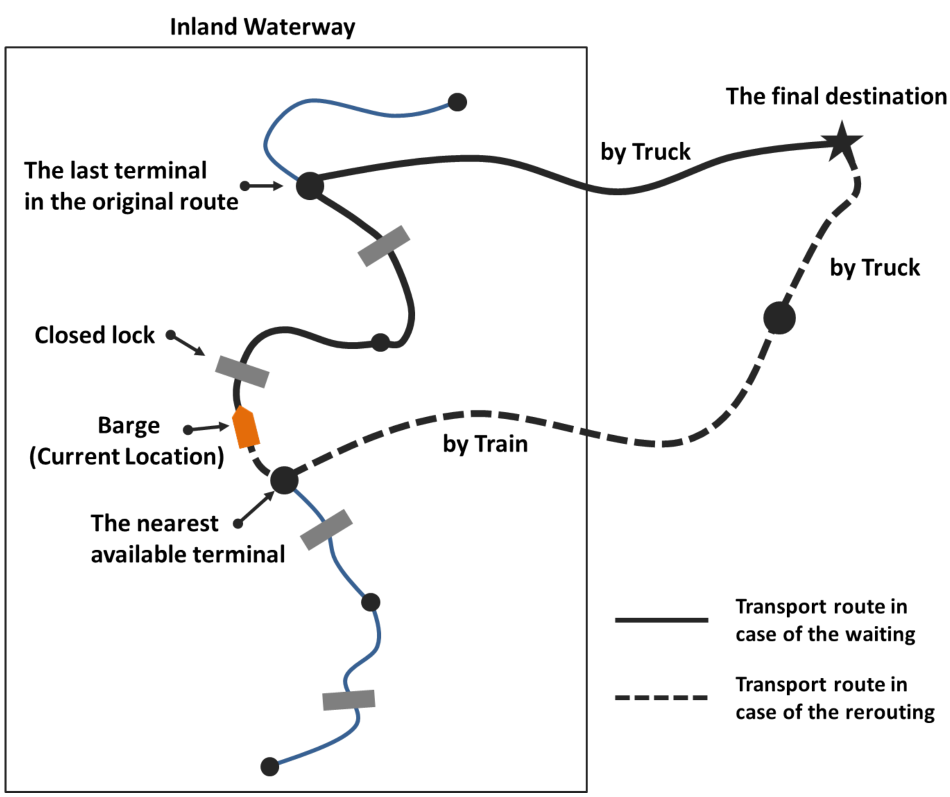


Figure 3. Different travel routes of the waiting and the rerouting

2.2. Decision making framework

In this section, we define a formal framework of the decision making process under an unexpected closure event on the inland waterway. It underlies the decision making supporting tool for the operations manager who has to choose the most feasible alternative when the waterway is temporarily shut down. The framework shows structural justification of the decision making model and fundamental motivation of the development.

Although details are different according to given circumstances, decision making basically follows a typical procedure. At first, a problem is clearly identified and recognized; then, possible alternatives are analyzed and compared; and finally, the optimal option is defined for implementation (Krajewski, Ritzman, and Malhotra, 2007). As mentioned above, basically, we follow this three-step procedure of decision making.

The framework is formalized by specifying each step. It shows the sequential procedure of decision making and elements of each stage including specific techniques and tools applied. Figure 4 shows the framework developed for our research. Details of the framework are given in the following sub-sections.

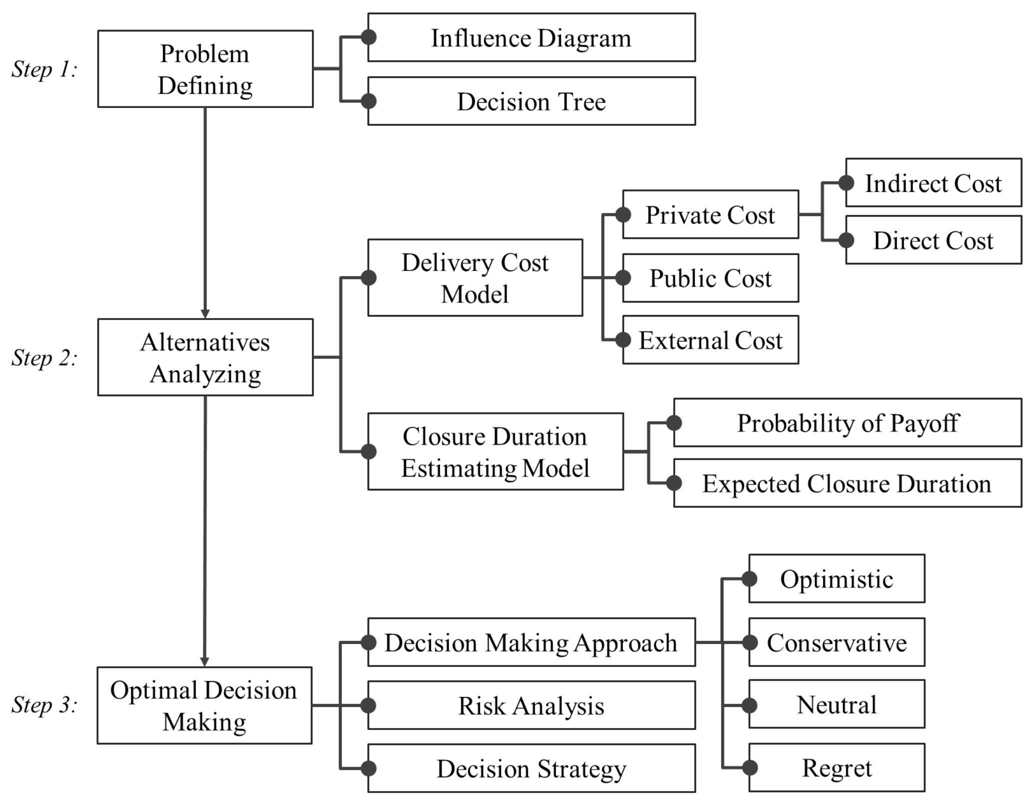


Figure 4. The framework of the decision making model

2.2.1. Defining the problem

The decision making problem of our research is to choose the most feasible alternative between the waiting and the rerouting to minimize the cost when an unexpected closure event occurs on the inland waterway. The most important uncertain factor in the problem is the duration of the closure that has a considerable influence on the transportation cost. Because of the uncertainty, we make a decision without confidence on results by the choice. In this section, we define the problem using formal terms and ways to eliminate vagueness and secure clarity in building a decision making model.

2.2.1.1. Elements

For more clarity, we can formulate the problem using formal terms of decision alternatives, uncertain future events (chance events), and the consequence defined by each alternative and each outcome of the chance event. The decision making procedure is as follows. A decision maker first chooses a decision alternative; then one of the outcomes of uncertain event is arisen; and finally, a consequence happens (Anderson, Sweeney, and William, 2003).

Decision alternatives

From the above problem state, clearly, decision is to select the best action under an unexpected disruption event. Thus, the problem has the following alternative set, $\boldsymbol{A}$.

$$\boldsymbol{A} = \{Waiting, Rerouting\}$$

Waiting means staying at the current location on inland waterway until reopening and then resuming transport through the original route. On the other hand, *Rerouting* indicates transshipping freight into another transportation mode such as rail and truck and rerouting the original transport path.

Uncertain future events

In this problem, chance event associated with uncertainty is the duration of closure of inland waterway. Note that the possible outcomes of a chance event have to be defined so exclusively that only one outcome occurs at a time. Sometimes, it is referred to as the states of nature. In our problem, outcomes are given as the duration time of the closure and thus, the set of the states of nature, $\boldsymbol{S}$, is given as follows:

$$\boldsymbol{S} = \{0, 1, 2, \dots\}.$$

The values represent multiples of the time unit such as 8-hour, 12-hour, 1-day, and so on.

The consequence

The consequence is generally represented as a quantity to be maximized or minimized by the selection of a decision alternative. It works as decision criterion (Parnell et al., 2013). In this problem the consequence is given as a cost to be minimized. The consequence defined by a particular combination of a decision alternative and a state of nature is called as a payoff.

Two issues arise from the consequence in modeling decision making. The first issue is that the closure duration is not a convenient expression of outcomes since we cannot apply it directly in computing the consequence. Thus, instead of the duration time, we use waiting time at current location on the disrupted inland waterway as the outcome. It measures from the decision making point to reopening as multiples of the time unit. Although it is still associated with uncertainty, waiting time is influenced by alternatives. For instance, if *Rerouting* alternative is selected, waiting time is definitely zero. The second issue relates to the outcomes in developing the decision making model is the maximum value of the duration time. Theoretically, the duration time can be infinite since the situation is not risky but uncertain and the definite maximum duration time is unknown. Of course, in real situations, the duration time is not infinite and bounded by an empirical number. However, this value is also too big to make decision making model efficient. Fortunately, unlike the duration time, the maximum waiting time can be set reasonably considering the expected cost and cargo value. For instance, we can rationally assume that if the expected cost is over predetermined percentage of cargo value, a shipper decides to find an alternative instead of current delivery. Let T be the maximum waiting time. Then, according to alternatives, the sets of outcomes are given as follows:

$$\boldsymbol{S}_{Waiting} = \{0,1,2, \dots, T\}$$
$$\boldsymbol{S}_{Rerouting} = \{0\}$$

To summarize the problem, at first, managers choose an alternative between *Waiting* and *Rerouting*; then, waiting associated with the alternative occurs under uncertainty in duration time; and finally, the cost incurs as the result of the decision and the uncertain waiting time.

2.2.1.2. Formulation

To identify the problem more clearly, we use two graphical techniques: influence diagram and decision tree.

Influence diagram

An influence diagram is a concise graphical description (Parnell et al. 2013), representing the relationships among the decision, the chance event, and the consequence by nodes and arrows (Anderson et al., 2003). Nodes having different shapes are used to indicate the elements of the decision making model. An arrow shows flow of the influence and a relationship between two nodes.

In our project, we use rectangle, oval and octagon to depict the decision, the chance event, and the consequence, respectively. Especially, double oval is employed to represent a particular uncertain factor called calculated or determined uncertainty. The element has uncertainty only because it is derived from other uncertain factors. Then, the influence diagram of the decision making problem under the disruption event is given as in Figure 5:

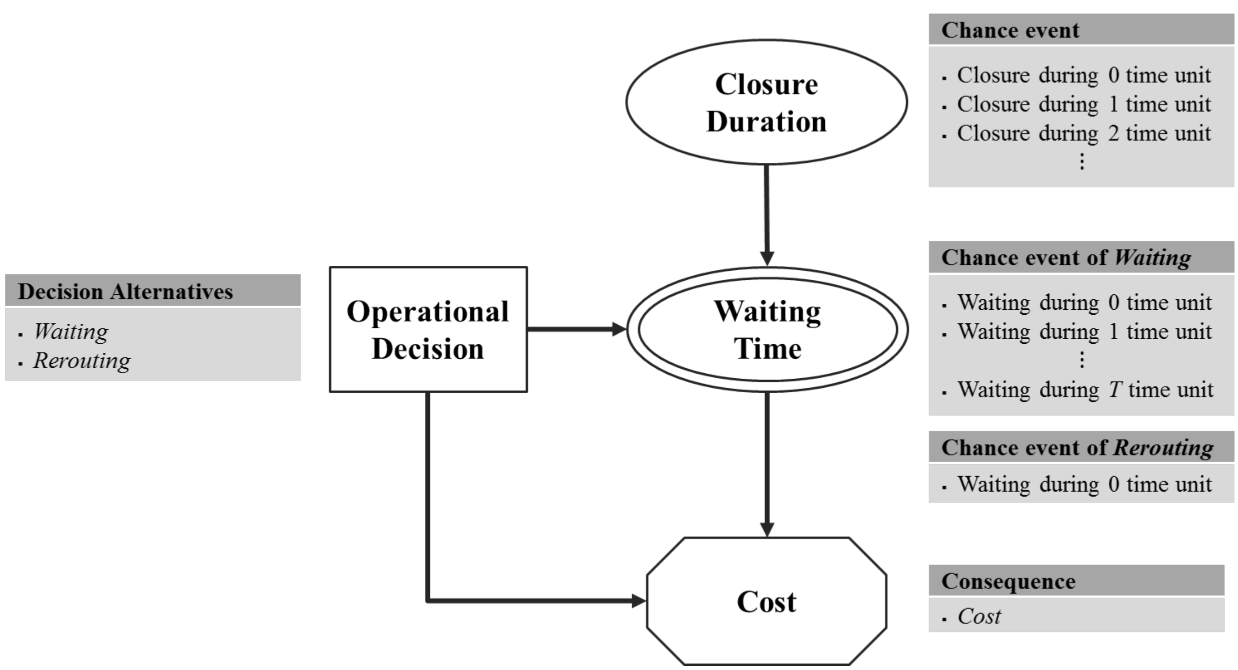


Figure 5. Influence diagram of the decision making under the disruption

Decision tree

Decision tree is a graphical supporting tool generally used in a wide range of operation management decisions which provide schematic representation of decision making process. It is applicable to and useful for any decision making problem (Krajewski et al. 2007). A basic decision problem can be depicted very simply as a three-step procedure. We make a decision; observe an outcome; and receive a payoff (Winston and Albright, 2009). Decision tree perspicuously shows the sequence of decisions and outcomes along with the payoffs by a schematic picture.

Square nodes depict decision points and their leaving branches indicate alternatives. Circular nodes represent a chance event and branches emanating from them correspond to possible outcomes. At the end of the last branch, payoff is given which is calculated by a corresponding combination of an alternative and an outcome. The problem of decision making under the closure can be expressed by decision tree as in Figure 6:

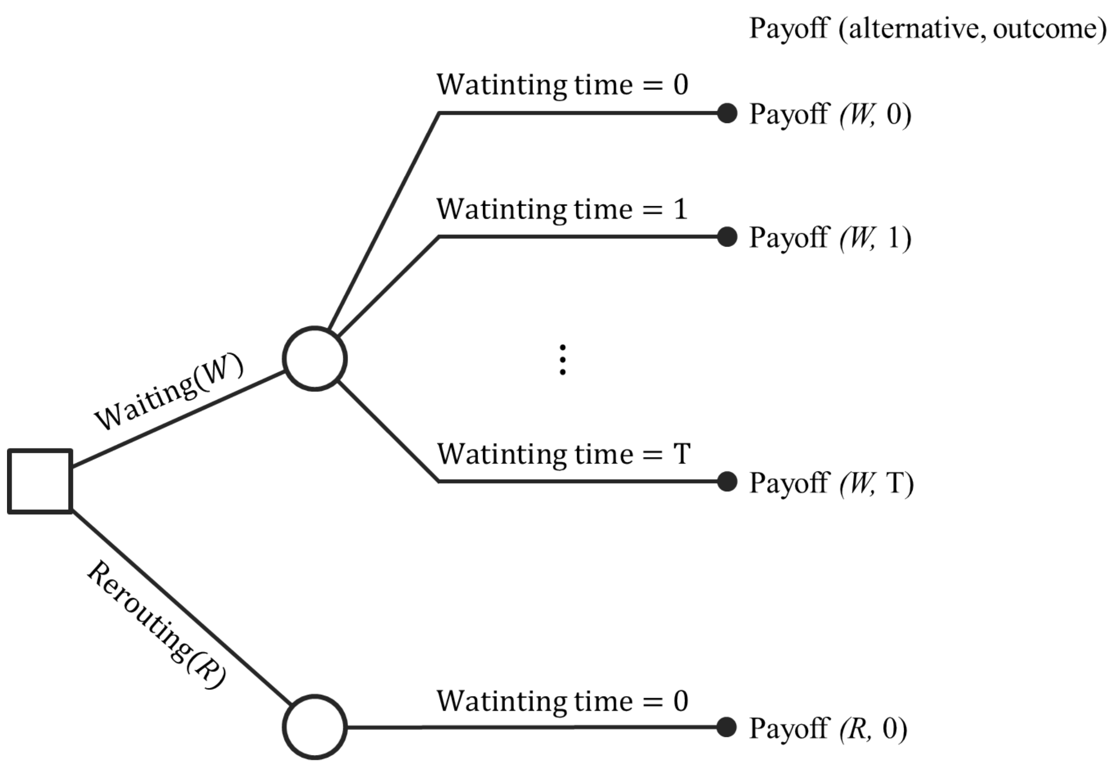


Figure 6. Decision tree of the decision making under the disruption

2.2.2. Analyzing alternatives

After identifying the problem, we analyze decision alternatives in terms of their possible payoffs. Thus, in this step, the primary tasks are to calculate payoffs of all possible combinations of an alternative and a state of nature and to estimate probabilities of each payoff.

2.2.2.1. Delivery cost model

In our decision making process, we consider a cost model beyond typical and classical transportation cost models. The model comprehensively involves internal and external costs which are directly or indirectly incurred by the transport from the current location to the final destination. To avoid confusion, we refer to the total cost as delivery cost instead of transportation cost. Hereafter, transportation cost indicates the sum of the costs that are directly connected with transportation such as vehicle operating cost and material handling cost. Table 1 shows specific costs that are involved in the delivery cost model.

Table 1. Delivery cost elements

<table>
<tr><th colspan="3">Cost category</th><th>Specific cost</th></tr>
<tr><td rowspan="4">Delivery</td><td rowspan="2">Private</td><td>Direct</td><td>Vehicle operating
Terminal handling</td></tr>
<tr><td>Indirect</td><td>Untimely delivery
in-transit inventory
Cargo value decreasing</td></tr>
<tr><td colspan="2">Public</td><td>Infrastructure construction
Infrastructure operation
Infrastructure maintenance and repair</td></tr>
<tr><td colspan="2">External</td><td>Emission
Accident
Congestion</td></tr>
</table>

The category of the cost model basically follows the Government Accountability Office (2011)'s total social cost model except for private cost. Private cost consists of direct cost and indirect cost which are imposed on a shipper who has ownership on cargo. The direct cost is paid by a transportation operator and transferred to the shipper as the price of transportation service. On the other hand, with regard to the indirect cost, there is no superficial payment except for penalty cost paid to the recipient because of late delivery. It is estimated as the pecuniary value of secondary negative effects by transportation which are imposed on the shipper and the recipient. Public cost is the cost incurred from public investment and service which are mainly related to infrastructure on transportation network. It is paid by government budget and can be funded by related taxes and fees. External cost indicates monetary value of negative impacts on society which are generated while transporting. The cost is not directly paid by either the transport operator or government; and imposed on other members of society who are directly suffered from the secondary result on society.

In this decision making model, delivery cost model involves variables corresponding to the alternative and the outcome. In Figure 7, calculation flow is shown from the decision and the chance event. Especially, double octagon is used to indicate the final consequence that is calculated from intermediate consequences.

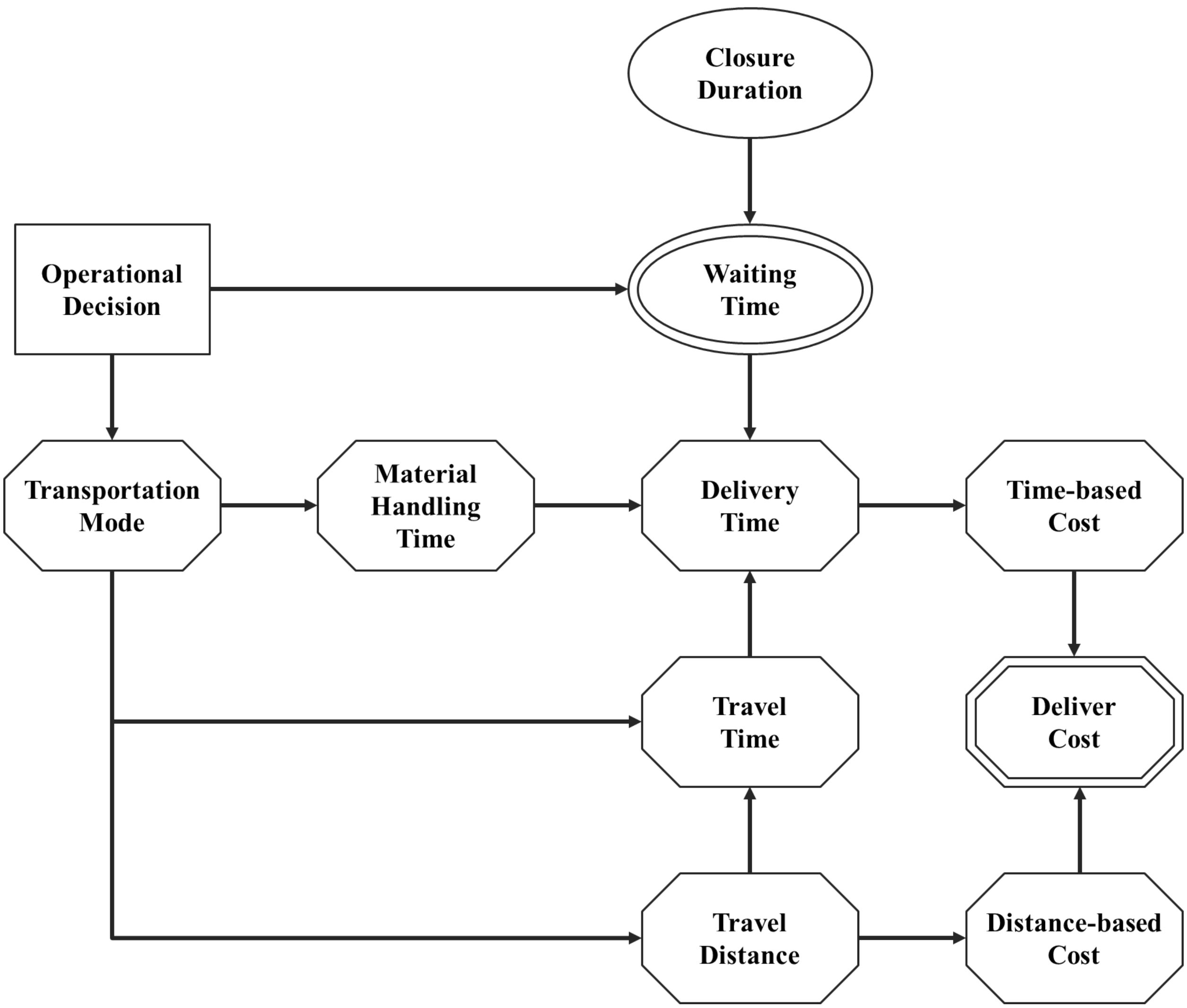


Figure 7. Influence diagram showing the flow of the delivery cost calculation

Cost elements can be categorized into time-based cost and distance-based cost. In our model, indirect private cost is a time-based cost; and direct private cost, public cost, and external cost are distance-based cost.

Given a decision alternative and an outcome, at first, transportation modes are decided which would be used to complete the remaining delivery from the current location to the final destination. Then, the expected travel distance and the expected material handling time involving loading/unloading time and waiting time at terminals are defined for each transportation mode. Next, using the expected travel distance and driving speed of the modes, the expected travel time is calculated. Then, by summing the travel time, the material handling time, and the waiting time on disrupted inland waterway, the expected delivery time is calculated. From the expected travel distance and expected delivery time, distance-based cost and time-based cost are calculated, respectively. Finally, the total delivery cost which is calculated by adding time-based cost and distance-based cost, giving as the final consequence.

2.2.2.2. Closure duration estimating model

Under uncertain situation, we try to find the optimal decision. Unlike a risky situation, probability distribution of the chance event is unknown. We just assume the chance event follows a certain probability distribution based on observed and collected data. With an assumed probability distribution, we solve the decision making problem as if it is not under uncertainty but risk. Thus, it is very important to define plausible probability distribution of the chance event. It is no exaggeration to say that it sways the performance of the decision making model.

In our model, we estimate a probability distribution of the chance event using history data concerning the closure duration of locks and dams. Consequently, we can derive probabilities of possible payoffs; and the expected delivery costs of each alternative are given as the weighted average of corresponding payoffs. This information is very essential in selecting an alternative as the optimal solution.

From a little different viewpoint, we develop a mathematical model calculating the expected closure duration such as a regression model. We believe that the closure duration is affected from some factors such as weather condition, level of waterway, and age of a lock and a dam. For instance, worse weather condition, lower level of waterway, and an older lock and dam are likely to lead to longer closure duration. A formula is available to calculate the expected closure duration when these factors are given.

At the beginning, the confidence of the probability distribution and the formula would be not high because of limited data. Fortunately, this problem can be solved by data collected from nationwide inland waterway and cumulated in the future. We believes that these data can improve the probability distribution model and the formula.

2.2.3. Optimal decision making

It is common that a decision maker uses the expected value as the only criterion in decision making (Males, 2002). Despite the name, the expected value does not occur in practice as the result of the choice. What the expected value means is that the average value that would be expected over time if the same decision making problem occurs regularly and then, the same alternative is chosen every time. Thus, the choice based on the expected value is likely to be the best long-term decision (Thompson, 2005).

Of course, in one-time decision making, the expected value is still an attractive and useful criterion. However, the expected value does not show the danger of tremendous losses and the chance of enormous profit that can be arisen as the result of the decision. Focusing solely on the expected value can make us ignore the feature of uncertainty in decision making that outcomes happen stochastically or randomly. For better decision making, we need to include some criteria, techniques and tools in our decision making model which are beyond expected value approach.

To help understand clearly, we used the following example throughout this section in which the maximum waiting time, T, is 3. It is illustrated on Figure 8.

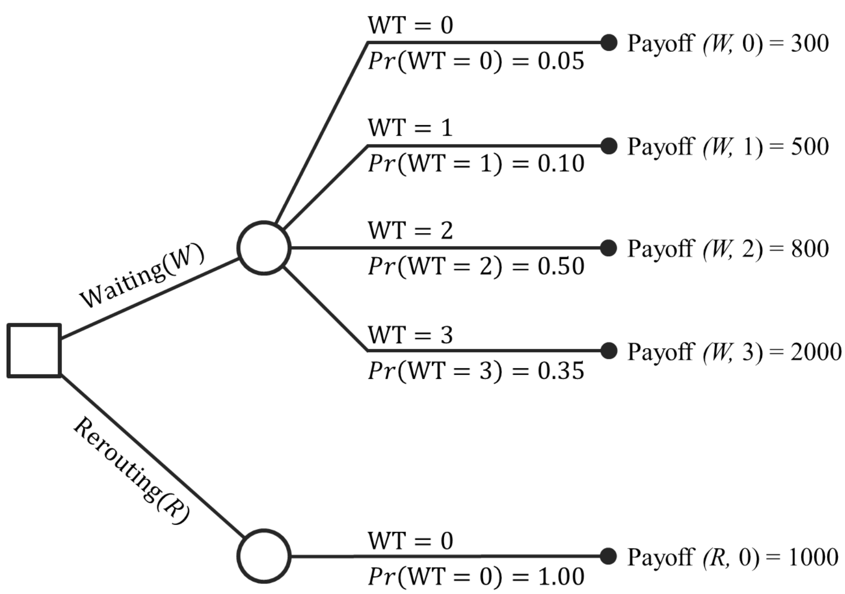


Figure 8. Decision tree expression of the example used in Section 2.2.3.

2.2.3.1. Decision making approach

In our problem, payoff of the rerouting is given as the deterministic value and that of the waiting is given as the range. Note that when the rerouting is selected, the waiting time on disrupted inland waterway is definitely zero. Therefore, from the rerouting, only one outcome occurs and a deterministic payoff is given in spite of uncertainty. Considering this feature, our problem can be categorized as the choice problem of deterministic value versus range. Unfortunately, in this case, there is no certain preference among alternatives (Males, 2002).

Due to the ambiguousness in choice that is naturally inherent in our problem, we cannot clearly say which alternative is better than the others. Thus, we introduce several approaches that can help decision makers look at the problem from various angles and make better decisions. In this section, we depict four approaches: the optimistic approach, the conservative approach, the neutral approach, and the minimax regret approach. To facilitate explanation of these approaches, the possible payoffs associated with each alternative are arranged on a single line and payoff table as in Table 2 and Figure 9:

Table 2. Payoff table of the example used in Section 2.2.3.

		Decision alternatives	
		Waiting	Rerouting
Outcomes	W= 0	300	1000
	1	500	1000
	2	800	1000
	3	2000	1000

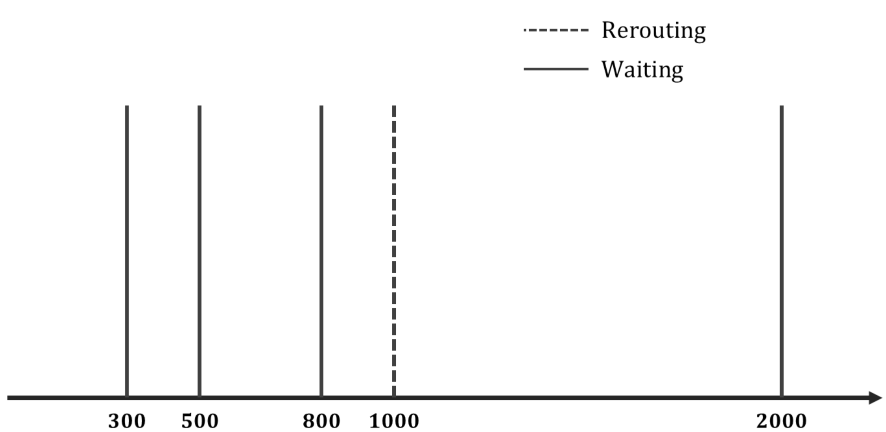


Figure 9. Arrangement of possible payoffs on single line

Optimistic approach

The optimistic approach chooses the optimal alternative based on the best payoff. For a problem whose objective is to minimize cost, the alternative from which we can expect the smallest cost is selected as the optimal decision. In case of minimization problem, it is also known as minimin approach (for maximization problem, maximax approach). Sometimes, it is referred to as risk-seeking approach. In the example, the waiting is selected by optimistic approach since its minimum payoff, 300, is less than the payoff of the rerouting, 1000. Figure 10 shows graphical comparing.

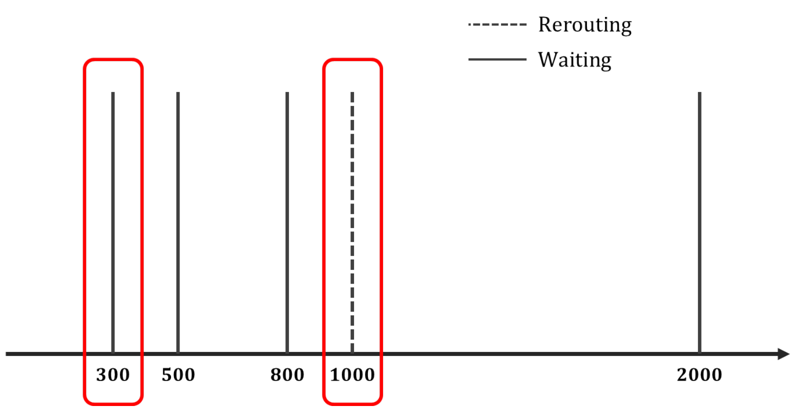


Figure 10. Comparing the payoffs of alternatives in optimistic approach

Conservative approach

The conservative approach compares alternatives based on the worst payoff. In a cost minimization problem, the optimal decision is given as the alternative that provides the best of the worst possible payoffs. For a minimization problem, it is also known as the minimax approach (for maximization problem, maximin approach). In addition, it is called as risk-averse approach. In the example, the rerouting is selected by the conservative approach because the worst payoff of the waiting, 2000, is greater than its payoff, 1000. Figure 11 shows graphical comparing.

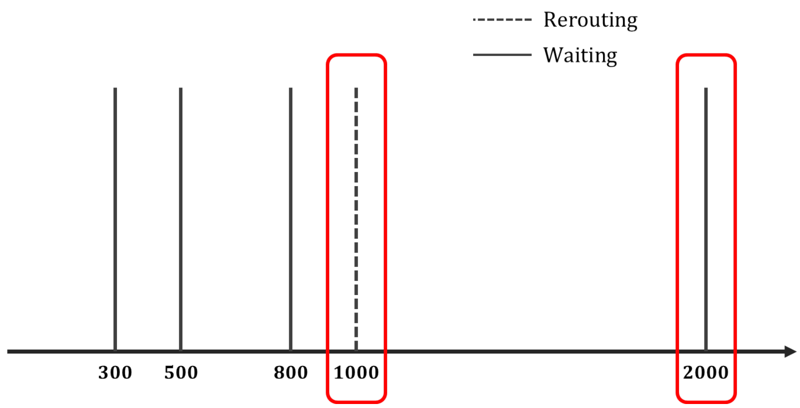


Figure 11. Comparing the payoffs of alternatives in the conservative approach

Neutral approach

The neutral approach uses the weighted average of payoffs as the criterion. In a problem of minimization, the alternative having the smallest expected cost is given as the optimal alternative. It is also known as the expected value approach and risk-neutral approach. In the example, by neutral approach, the rerouting is given as the optimal decision because its payoff, 1000, is less than the expected payoff of the waiting, 1165.

$$\begin{aligned} EV(\text{Payoffs of Waiting}) &= 0.05 * 300 + 0.10 * 500 + 0.50 * 800 + 0.35 * 2000 \\ &= 1165 \end{aligned}$$

Minimax regret approach

The minimax regret approach employs the regret concept instead of using payoff value directly. Regret is calculated as the difference between the payoff for the best decision and the payoff for other decisions. For the example, regret is calculated as in Table 3.

Table 3. Regret of the example used in Section 2.2.3.

		Decision alternatives	
		Waiting	Rerouting
Outcomes	W= 0	0	700
	1	0	500
	2	0	200
	3	1000	0
Maximum Regret		1000	700

The minimax regret approach recommends the decision alternative having the minimum of the maximum regret as the optimal alternative. Thus, in the example, the rerouting is recommended since its maximum regret, 700, is less than the maximum regret of the waiting, 1000.

2.2.3.2. Risk analysis

The risk profile for an alternative shows possible payoffs as well as corresponding probabilities. Sometimes, reviewing the risk profile, a manager make a choice from the different point of view beyond the expected value (Anderson et al., 2003). It can lead to the choice of the alternative having worse expected value. For this problem, the risk profile can be given as Figure 12:

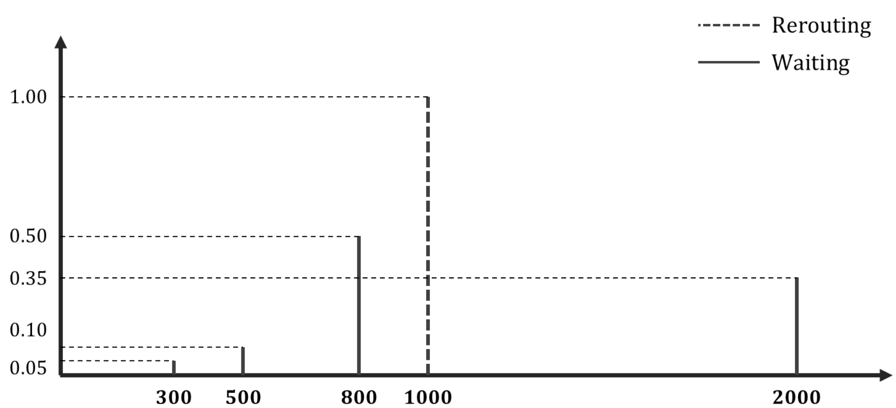


Figure 12. Risk profile showing payoffs of the example used in Section 2.2.3. with their probabilities

From the risk profile, we can interpret that with a probability of 0.65, the waiting gives a better result than the rerouting; with a probability of 0.35, the rerouting gives a better result than the waiting. Perhaps, some decision makers select the waiting based on this analysis even though its expected cost, 1165, is greater than the expected cost of the rerouting, 1000.

2.2.3.3. Decision strategy

Assume that we can estimate the expected duration of the closure with a high level of confidence when it occurs. Then, with the fairly certain information of the duration, we can make the decision by comparing the alternatives as if they generate deterministic results. If the supposition is feasible in practice, we can make a decision more efficiently and quickly by using this certainty with a decision strategy.

The decision strategy is a decision rule that answer to which alternative should be selected using available information. In our model, decision strategy determines the optimal alternative when the expected duration of the disruption is given. For instance, decision strategy says that if the expected closure time is 5.6 days, the wait is a better decision than the rerouting. In case of our problem, decision strategy can be specified as a kind of threshold policy in which the optimal decision is easily defined by comparing the threshold value and the given expected value. For instance, if the expected duration is less than 8.9 days, the optimal alternative is waiting and otherwise, rerouting. Figure 13 illustrates the threshold policy.

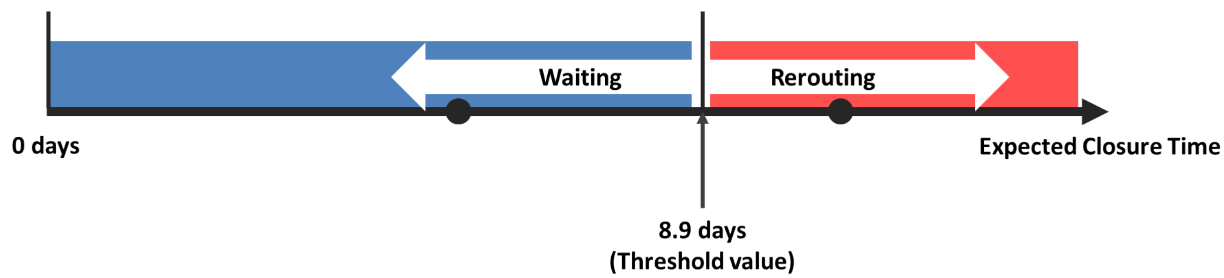


Figure 13. Decision strategy of the example used in Section 2.2.3.

2.3. Delivery cost model

In this section, we explain details of the cost model. Although the general structure and formulas are the same for the two alternatives, detail cost functions are different for each alternative. In addition, the composition of total delivery cost varies slightly according to contract conditions and definition of the range of stakeholders.

2.3.1. Cost elements

The delivery cost model comprehensively contains cost elements that are directly or indirectly and internally or externally connected with transportation. In our research, we first categorize these cost elements into three categories: private cost, public cost, and external cost.

2.3.1.1. Private cost

It is the cost imposed on shipper as the form of the price. Depending on the presence of payment, cost elements are divided into direct cost and indirect cost.

2.3.1.1.1. Direct cost

Typical cost elements in this category are vehicle operating cost and terminal handling cost. Vehicle operating cost can be calculated by summing fuel and oil cost, labor cost, tire wear cost, parking fees, etc. Terminal handling cost includes terminal fees and material handling cost. Terminal fees are charges that a transportation mode has to pay for using terminal which are imposed per mode. Material handling cost indicates costs incurred by using facilities and equipment to load and unload cargo. It varies according to cargo type and its features such as containerization, special handling requirement, and hazard. Terminal handling cost might vary across terminals. Transportation mode, in addition, might be another factor affecting terminal handling cost.

These costs are directly paid by the transportation service provider and transferred to the shipper as the form of price. Thus, direct cost can be calculated using the price information. If general unit price of transportation service is available, we can use it to calculate the expected private direct cost.

However, before using general price, we need to consider some issues. In practice, the price varies depending on the service provider and sometimes, it is discounted in case of long-term contract and high-volume cargo. Additionally, terminals have different tariff and different fees are imposed. These differences can make calculated delivery cost far from reality; and consequently, reduce the performance of the decision making model. For a better result in practice, we recommend to use real price quoted by the service provider based on cargo type and volume and contract condition; and to refer to real tariff of terminals.

For research purpose, in our study, we provide and use general unit price to calculate direct cost. As mentioned above, private direct cost, which includes vehicle operating cost and terminal handling cost, is covered by payment from the shipper. Therefore, this cost can be derived from the average revenue of a transportation service provider. Table 4 is the average revenue per ton-mile of different transportation modes.

Table 4. Unit revenue (unit private direct cost) of transportation modes.

$ per ton-mile

Mode	Barge	Truck	Rail
Revenue	0.0183	0.1424	0.0235

National Transportation Statistics, Table 3-20 Average Freight Revenue per Ton-Mile (Updated January 2016), http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html

2.3.1.1.2. Indirect cost

Typical cost elements of this category are in-transit inventory cost, penalty cost of untimely delivery and cargo value decreasing cost.

In-transit inventory cost

From the view of supply chain management, cargo is considered as the inventory held because of transportation lead time. To reveal its feature, it is called the in-transit inventory. In-transit inventory cost mainly involves the opportunity cost of loss investment revenue caused by capital tied up with cargo (Gong et al., 2012). Unlike in-site inventory cost, some factors of general inventory cost are not to be considered such as physical storage cost and obsolescence cost. In terms of inventory carrying cost, it can be calculated as the interest charges with regard to the resources captured in in-transit inventory. Thus, basically, the interest rate and unit price of the items are required.

Untimely delivery cost

Untimely delivery missing predetermined delivery window is classified into two categories: delivery earliness and delivery tardiness (Shin et al., 2009). These cause additional cost in supply chain. Early deliveries incur the cost associated with unexpected inventory holding and handling and on-site traffic congestion; and late deliveries give rise to excess cost by inventory shortage leading to production schedule change, the loss of potential sales, and the loss of goodwill (Guiffrida and Jaber, 2008). These costs are occasionally referred to as delivery earliness cost and delivery tardiness cost, respectively.

Usually, the buyer's inconvenience and potential losses are transferred to supplier as the form of the penalty cost. It is becoming more general to impose penalty to not only early delivery and but also late delivery (Guiffrida and Nagi, 2006). The buyer does not impose the cost unilaterally and it is set by contract and agreement between the supplier and the buyer.

We assume that if the shipper and the recipient are the same stakeholder, untimely delivery cost is imposed on the recipient as the form of delivery earliness or tardiness cost. For instance, if ownership is transferred from the supplier to the buyer at the beginning of the delivery, the shipper and the recipient are the same stakeholder. Recipient owns cargo and is the decision maker. In addition, we suppose that if the shipper and the recipient are different stakeholders, untimely delivery cost is paid by the shipper as the form of the penalty cost. For example, if ownership is transferred from the supplier to the buyer at the end of the delivery, the shipper and the recipient are different stakeholders. The shipper possesses cargo and is the decision maker.

Cargo value decreasing cost

During transportation, some events that affect cargo condition can be occurred such as breakage, spoilage and deterioration, and it decreases cargo value. (Tong, Nachtmann and Pohl, 2015) employs the concept of the cargo value decreasing rate. They suppose that given disruption events, the cargo value diminishes in terms of economic value, societal benefit, and customer satisfaction as time goes. It gives a deterministic decreasing rate and cost for several commodity types. In our research, we assume that cargo value decreases stochastically as time elapse and focus on only economic value of cargo based on its price.

2.3.1.2. Public cost and external cost

Public cost is the cost incurred from public investment and service related to transportation. Generally, it involves construction, maintenance, and operation of public infrastructure such as highway and inland waterway. More specifically, pavement of damaged road; maintenance and repair of locks and dams on inland waterway; construction new highway; and dredging of waterway channels are public investment and service. The fund required to do the public works is raised through government budgets, taxes, and fees (Government Accountability Office, 2011).

External cost is the monetary value of negative secondary impact caused by transportation such as traffic congestion, accident risk, and exhaust emissions of particulate matter (PM) and carbo dioxide (CO_2) (Austin, 2015). More specifically, health and environmental damage due to pollution; and time costs due to congestion are included in this category (Government Accountability Office, 2011).

Generally, transport service price involves taxes and fees levied by government. The money funded by them is distributed by government for public investment and service and to cover external cost. Although it is not enough to pay whole public and external cost, taxes and fees are completely used to cover part of the cost. In short, the price corresponds to the sum of not only the whole private direct cost but also a portion of public and external cost. As mentioned above, private direct cost is derived from transportation service price. Thus, to avoid overlap, we need to separate the portion of public and external cost corresponding to taxes and fees imposed in the price. For clarity, hereafter, public and external cost in which the portion is excluded is called the unpriced public and external cost or unpriced cost for short. Note that unpriced public and external cost is calculated by subtracting taxes and fees associated with transportation from the sum of public and external cost.

Government Accountability Office (2011) provides unpriced public and external cost. Table 5 shows the lower bound of unpriced cost per ton-mile of different transportation modes as in 2010. These values are used to calculate the expected delivery cost.

Table 5. Unpriced public and external cost

$ per ton-miles

Mode	Barge	Truck	Rail
Public cost	0.004	0.021	0.000
External cost	0.006	0.059	0.009
Taxes and fees	0.002	0.018	0.000
Unpriced cost	0.008	0.062	0.009

United States of Government Accountability Office (2011), *A Comparison of the Costs of Road, Rail, and Waterways Freight Shipments That Are Not Passed on to Consumers*

2.3.2. Cost function

For convenience, we use the following indexes:

B, R, T transportation mode index, Barge, Rail and Truck, respectively

k cargo type index

The following notations are used.

K the set of cargo types on board

w^{k}, W weight of cargo k and total weigh of cargo on board

v^{k}, V value of cargo k and total value of cargo on board

pc^{M} unit cost of private direct cost of transportation mode M

uc^{M} unit cost of unpriced public and external cost of transportation mode M

d^{M} travel distance assigned to transportation mode M

s^{M} general driving speed of transportation mode M

2.3.2.1. Distance based cost

Private direct cost and unpriced public and external cost are calculated based on travel distance. We assume that transportation route after leaving inland waterway follows minimum cost path.

Private direct cost (priced cost)

Private direct cost is calculated as follows:

$$PDC = W * \{(pc^{\mathrm{B}} * d^{\mathrm{B}}) + (pc^{\mathrm{R}} * d^{\mathrm{R}}) + (pc^{\mathrm{T}} * d^{\mathrm{T}})\}$$

In case of the waiting, d^{B} is the distance from the current location to the last terminal on waterway route originally planned; and d^{R} and d^{T} are defined by the minimum cost path from the last terminal to the final destination. In case of the rerouting, d^{B} is the distance from the current location to the nearest available terminal on waterway; and d^{R} and d^{T} are defined by the minimum cost path from the nearest terminal to the final destination.

Unpriced public and external cost

Unpriced cost is given by

$$UPEC = W * \{(uc^{\mathrm{B}} * d^{\mathrm{B}}) + (uc^{\mathrm{R}} * d^{\mathrm{R}}) + (uc^{\mathrm{T}} * d^{\mathrm{T}})\},$$

where d^{B},d^{R}, and d^{T} are determined as in private direct cost function.

2.3.2.2. Time based cost

Private indirect cost consists of transit inventory holding cost, untimely delivery cost, and cargo value decreasing cost and are calculated based on delivery time.

Travel time

Travel time is calculated as follows:

$$TT = (d^{\mathrm{B}}/s^{\mathrm{B}}) + (d^{\mathrm{R}}/s^{\mathrm{R}}) + (d^{\mathrm{T}}/s^{\mathrm{T}}),$$

where d^{B},d^{R}, and d^{T} are determined as in private direct cost function.

Waiting time on waterway and at a terminal

Available waiting times and expected waiting time on inland waterway can be given by estimated probability distribution. In addition, a forecasting model can be used to calculate the expected waiting time on inland waterway. Definitely, waiting time on waterway is zero in case of the rerouting. We assume waiting time at a terminal is given as the average time estimated from observed and collected date. WW and WT indicate waiting time on the waterway and at a terminal, respectively.

Material handling time

Loading and unloading time vary according to the cargo type, required equipment and transportation mode. For instance, container cargo takes less time than bulk cargo. In addition, cargo weigh and volume and the number of transshipment affect total material handling time. Thus, the expected material handling time is calculated considering these factors. If general unit working time is available which indicates required time to load or unload unit volume of weight of certain cargo type, a mathematical function can be developed. Let MT indicates the total material handling time.

Delivery time

The expected delivery time is calculated as follows

$$DT = TT + WW + WT + MT.$$

In-transit inventory holding cost

For our research, we employ the model of Nachtmann and Oztanriseven (2014) in which specially, the daily holding cost per ton, $\$3.77/\mathrm{ton}$ is used instead of interest rate. Then, in-transit inventory holding cost per working day, $IIHC$, is given as follows:

$$IIHC = 3.77 * W * 1.4 * DT$$

1.4 is multiplied considering the difference between actual days (7 days) and working days (5 days) in a week. At first, weekly cost is calculated by multiplying daily cost and seven; and then, it is divided by five to find the cost per working day. It gives 1.4 as a moderating factor.

Untimely delivery cost

For our research, we calculate untimely delivery cost indirectly using the penalty cost model of Nachtmann and Oztanriseven (2014) that levies the cost by the week. The model imposes the penalty of 3% of the total value of cargo on first week of delay; and the penalty of 7% of the value on each additional week of delay. There is no penalty on an early delivery. Based on current date, due date, and expected delivery time, we calculated the expected weeks of delay, t^{DW}. Then, the expected untimely delivery cost, UDC, is given as follows:

$$UDC = \begin{cases} 0, & t^{DW} = 0 \\ 0.03V + 0.07(t^{DW} - 1)V, & t^{DW} \geq 1 \end{cases}$$

Cargo value decreasing cost

Cargo value decreasing cost is calculated based on the expected cargo state at the end of delivery. Expected cargo state is expressed as the ratio to the current state. Given cargo state transition matrix, **A,** and current cargo state vector, **ccs**, we can take cargo state vector after t, **ecs**, as follows:

$$\mathbf{ecs}^t = \mathbf{ccs} \times \underbrace{\mathbf{A} \times \mathbf{A} \times \ldots \times \mathbf{A}}_{t} = \mathbf{ccs} \times \mathbf{A}^t$$

Let cs be the cargo state and $E(cs)^t$ indicate the expected cargo state after time t. Then, the following instance shows how the expected cargo state after time t is calculated.

$$cs \in \{1,\ \ 0.5,\ \ 0\}$$

$$\boldsymbol{ccs} = \begin{matrix} cs = 1 & 0.5 & 0 \\ (1 & 0 & 0) \end{matrix}$$

$$\mathbf{A} = \begin{matrix} & 1 & 0.5 & 0 \\ 1 & 0.99 & 0.01 & 0 \\ 0.5 & 0 & 0.99 & 0.01 \\ 0 & 0 & 0 & 1 \end{matrix}$$

After $t = 1$,

$$\mathbf{ecs^1} = \mathbf{ccs} \times \mathbf{A} = (1 \quad 0 \quad 0) \begin{pmatrix} 0.99 & 0.01 & 0 \\ 0 & 0.99 & 0.01 \\ 0 & 0 & 1 \end{pmatrix} = (0.99 \quad 0.01 \quad 0)$$

$$E(cs)^1 = 1 * 0.99 + 0.5 * 0.01 + 0 * 0 = 0.995$$

After $t = 2$,

$$\mathbf{ecs^2} = \mathbf{ccs} \times \mathbf{A^2} = (1 \quad 0 \quad 0) \begin{pmatrix} 0.99 & 0.01 & 0 \\ 0 & 0.99 & 0.01 \\ 0 & 0 & 1 \end{pmatrix}^2 = (0.9801 \quad 0.0198 \quad 0.0001)$$

$$E(cs)^2 = 1 * 0.9801 + 0.5 * 0.0198 + 0 * 0.0001 = 0.99$$

Using the expected cargo state at the end of delivery, the expected cargo value decreasing cost, $CVDC$, is calculated as follows:

$$CVDC = \sum_{\mathrm{k} \in K} v^{\mathrm{k}} \left(1 - E\left(cs^{\mathrm{k}}\right)^{DT}\right).$$

Note that cargo value and the decreasing rate is different according to the cargo type.

In addition, we can define the probability of possible states and decreased rate. In the previous example, $\mathbf{ecs^2}$ can be interpreted as below: after $t = 2$, cargo state is 1 with probability of 0.9801, 0.5 with probability of 0.0198, and 0 with probability of 0.0001; or, the decreased rate of cargo value is 0 with probability of 0.9801, 0.5 with probability of 0.0198, and 1 with probability of 0.0001. Consequently, cargo value decreasing cost can be given as not a single value but a set of possible values with their distribution. It means that if required, the cargo value decreasing cost can be handled as an uncertain factor in our decision making problem.

Since no stochastic model exists concerning cargo value decreasing rate, in our research, we assume a probability distribution of the decreasing rate. It is developed using Poisson distribution; the minimum decreasing rate is zero and the maximum decreasing rate is limited by a certain value. The state transition matrix is derived from the generated probability distribution. Table 6 is the example of the probability distribution.

Table 6. Example of generating the probability distribution of decreasing rate

Ave.	Decreasing rate											Sum
	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010	
0.0050	0.0067	0.0337	0.0842	0.1404	0.1755	0.1755	0.1462	0.1044	0.0653	0.0363	0.0318	1.0000

2.3.3. Decision maker

In calculating delivery cost, there are two considerable issues: the relationship between decision maker and recipient; and decision maker's attitude. Note that decision maker is the shipper who has ownership of the cargo.

The relationship between decision maker and recipient

The first relationship is that the decision maker and the recipient are different stakeholders. For instance, if the decision maker is a supplier and the recipient is a buyer, and the ownership is transferred at the end of the delivery, the decision maker and the recipient are different stakeholders. In this case, the penalty cost by late and early delivery is paid by the decision maker instead of the untimely delivery cost. The second relationship is that the decision maker and the recipient is the same stakeholder. For example, if the ownership is transferred to the buyer at the beginning of the delivery, the recipient is both the shipper and the decision maker. In addition, if the cargo is moved from one facility to another facility which one company possesses together, the recipient is the decision maker. In this case, economic loss corresponding to untimely delivery cost is imposed to the decision maker instead of the penalty cost. However, there is no actual payment. Whether there exists real payment can affect psychological stability of the decision maker. Thus, in the same situation, according to the relationship, decision maker select different alternatives.

Decision maker's attitude

Our cost model considers different objectives of different stakeholders who are associated with the decision. One problem is that stakeholders such as the government and society cannot force the decision maker to select the alternative minimizing total delivery cost. Since usually, the decision maker is a member of business who seeks a profit. Thus, he or she would select the alternative minimizing private cost; the public cost and external cost are not the decision maker's concerns.

2.4. Uncertainty on inland waterway

In this section, we analyze history data of the closure by maintenance-related causes and weather-related causes to find a plausible probability distribution and estimate the average closure duration. In addition, we investigate the relationship between the closure and weather condition.

2.4.1. Navigation notices data collection

In this project, length of closure plays an important role in determining the total cost incurred when an unexpected inland waterway disruption occurs. Due to this, data was collected from the USACE website to help predict the length of closure, depending on many factors.

We focus on data about closures, such as length of closure, reason for closure, and location of closure. We then separate unexpected maintenance-related closures and weather-related closures in order to analyze whether there was a trend. Publically available data for the following districts are collected: Pittsburgh, Mobile, Tulsa, Little Rock, Detroit, Huntington, Louisville, Vicksburg, Norfolk, and St. Louis. Since each district has its own website to report navigation notices, the amount of data for each district was not uniform, leading to difficulties in drawing conclusions about the data collected.

Figure 14 shows the distribution of closure duration over all closure data collected. This includes weather-related closures and maintenance-related closures that have been reported.

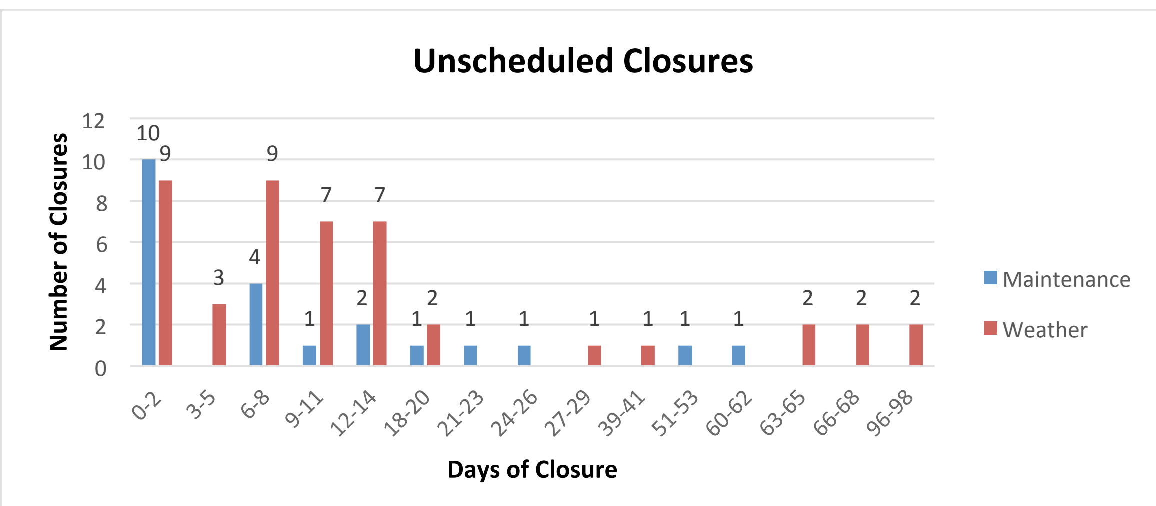


Figure 14. Closure length distribution

From Figure 14, it can clearly be observed that a large proportion of both the weather- and maintenance-related closures last a week or two and a smaller proportion last for over a few weeks. An average time of closure due to maintenance-related causes was calculated to be 11.25 days. An average time of closure due to weather-related closures was calculated to be 17.91 days. An overall average closure length was calculated to be approximately 15 days.

2.4.2. Closure and weather

To further analyze the relationship between unscheduled unavailabilities of inland waterway and weather information, we choose the Arthur V. Ormond Lock as an example and collect the closure information over the years, as well as information on the temperature, humidity and precipitation each year. Table 7 shows these data from 2006 to 2015. Both total closure duration (unavailable time) and number of closures are recorded and shown in Columns 2 and 3. Yearly average numbers for temperature, humidity and precipitation are shown in Columns 4 through 6. Note the correlation between each of the weather status and the closure time as well as the number of closures are summarized in the last two rows. It can be seen that the correlation between total unavailability time and the annual precipitation level are highly correlated (0.602).

Table 7. Closure and weather information for Arthur V. Ormond lock

Year	Closure time	Closure Number	Temperature	Humidity	Precipitation
2006	11.05	6	61.4167	70.6225	48.13
2007	456.52	15	62.1667	70.5925	41.37
2008	304.32	19	60.25	72.4667	61.77
2009	212.22	4	60.5833	72.8308	52.93
2010	52.03	12	61.8333	69.1975	34.95
2011	505.4	21	64.5833	68.3975	53.44
2012	87.82	7	64.5833	65.6558	31.9
2013	45.98	15	60.5	70.4275	42.88
2014	19	5	59.3333	71.781	40.39
2015	607.63	5	61.5833	73.3642	58.88
correlation with time			0.31691557	0.26894854	0.601851
correlation with number			0.27271592	-0.2185207	0.198281

We then plot the relationship between total unavailabilities and each of the weather condition in the following figures. Visually we can again see the clear relationship between the unavailabilities and weather condition, particularly the precipitation.

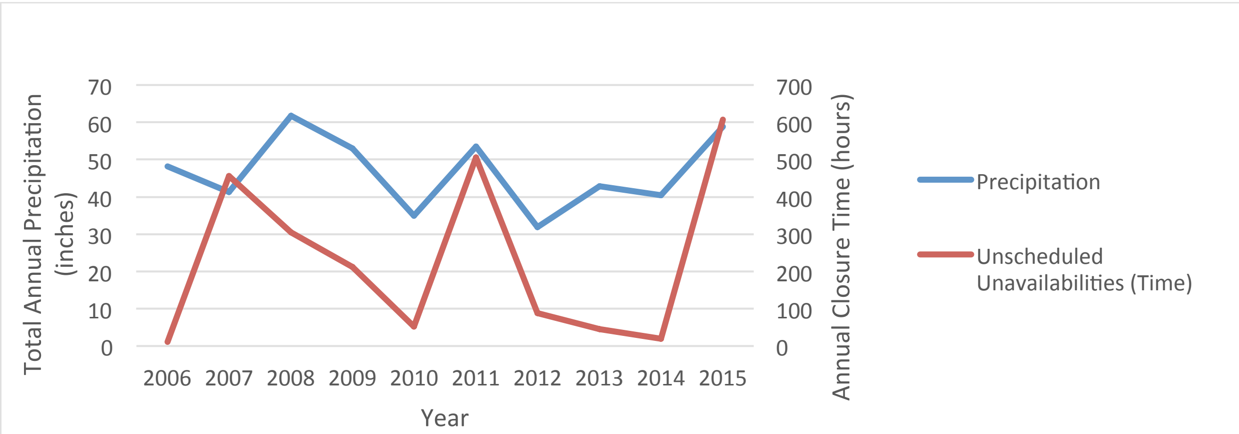


Figure 15. Unscheduled unavailabilities versus precipitation

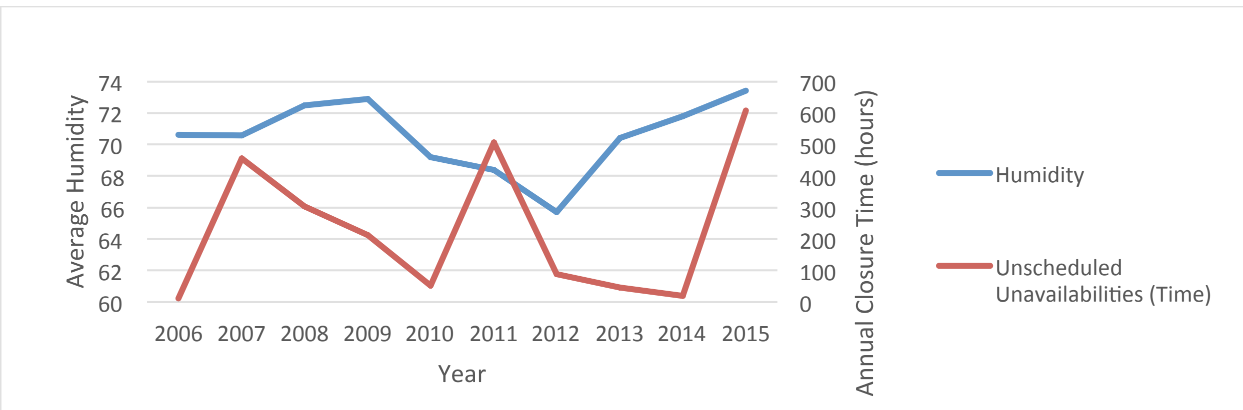


Figure 16. Unscheduled unavailabilities versus humidity

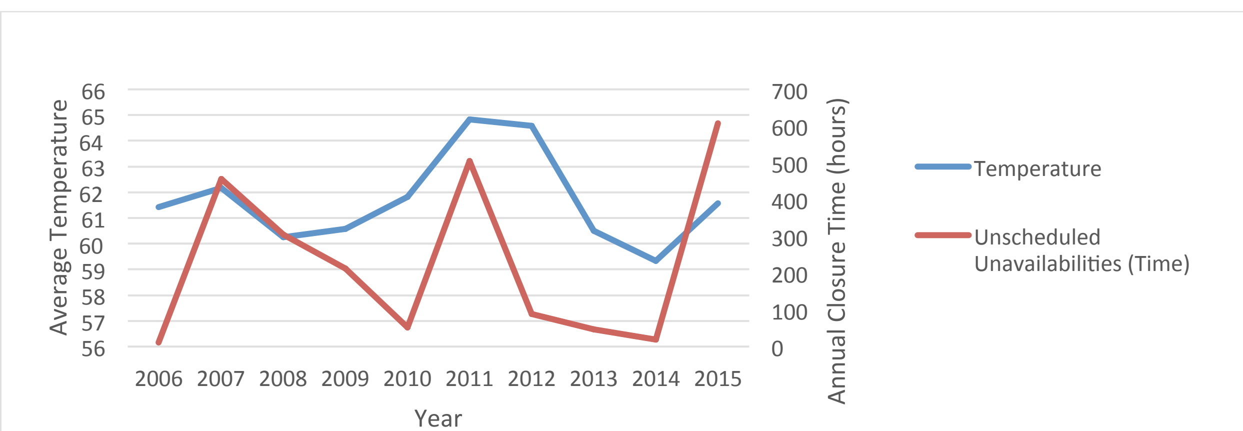


Figure 17. Unscheduled unavailabilities versus temperature

2.5. Decision making supporting tool

In our research, decision supporting tool is developed using Visual Basic Application (VBA) in Excel. It helps to calculate payoffs given current location and situation information. It consists of four modules: information management module, closure time forecasting module, cost calculation module, and output module. The following figure shows the composition of the supporting tool.

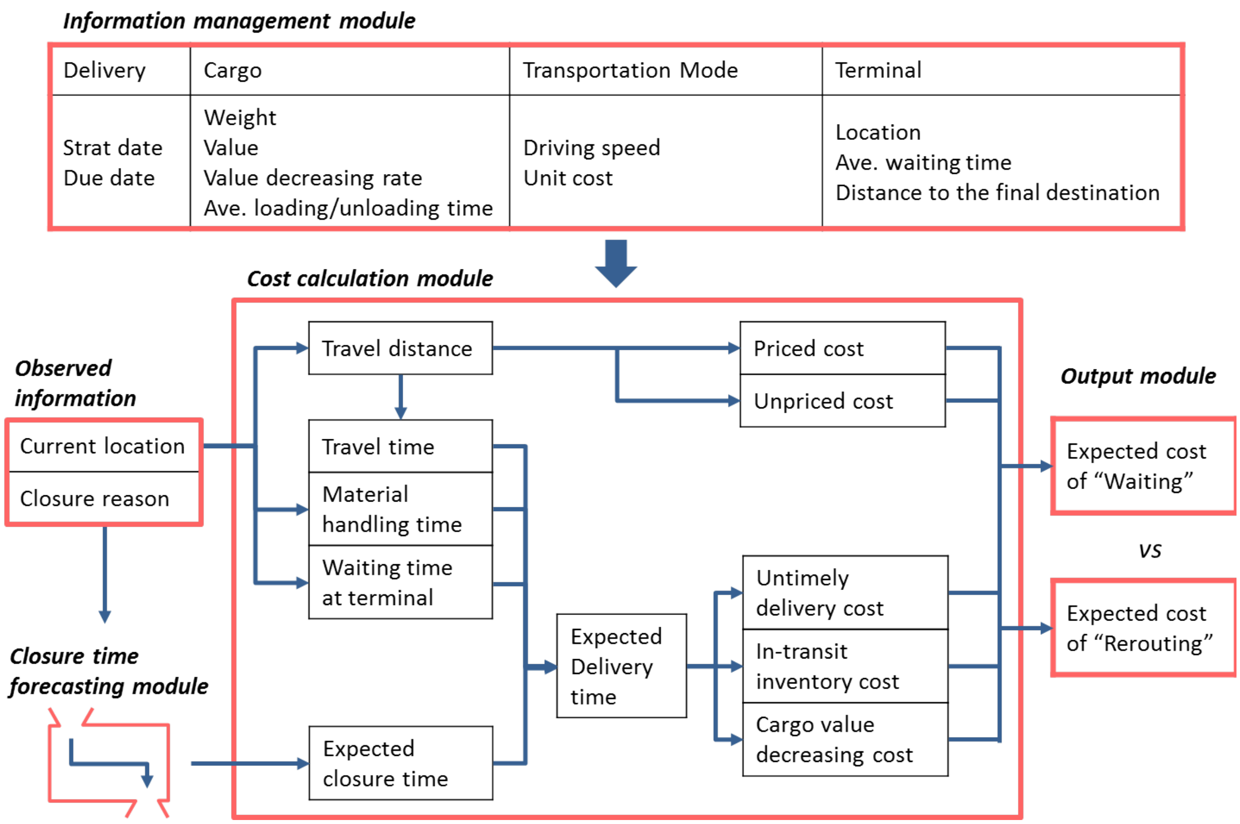


Figure 18. Structure of the decision making support tool

2.5.1. Information management module

To calculate delivery cost, required parameters need to be inputted in the system first. If there is no proper information at the corresponding cell, it causes error in running. This module exists as the form of table on spreadsheets. Thus, we can easily and intuitively input, change, and delete parameters which are required to calculate delivery cost.

Delivery information table simply stores start date and due date information as Figure 19. It is required to estimate expected days of delay.

	A	B
1	<Delivery>	
2	Start date	13-Nov
3	Today	15-Nov
4	Due date	17-Nov

Figure 19. Delivery information table

The cargo list table arranged according to the commodity class as Figure 20. The information of cargo currently transported is stored in this table.

		Commodity	Weight (ton)	Value		Average Loading/Unloading Time (min/ton)	Probability of Decreasing Rate												
				Unit ($/Ton)	Total		Ave	0	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010	Sum
5	1	Live animals/fish																	
6	2	Cereal grains	500	231.28	115640	0.15	0.07	0.4966	0.3476	0.1217	0.0284	0.005	0.0007						1
7	3	Other ag prods.																	
8	4	Animal feed																	
9	5	Meat/seafood																	
10	6	Milled grain prods.																	
11	7	Other foodstuffs																	
12	8	Alcoholic beverages																	
13	9	Tobacco prods.																	
14	10	Building stone																	
15	11	Natural sands																	
16	12	Gravel																	
17	13	Nonmetallic minerals																	
18	14	Metallic ores																	
19	15	Coal	1000	38.69	38690	0.1	0.03	0.7408	0.2222	0.0333	0.0033	0.0003	0.0001						1
20	16	Crude petroleum																	
21	17	Gasoline																	
22	18	Fuel oils																	
23	19	Coal-n.e.c.																	
24	20	Basic chemicals																	
25	21	Pharmaceuticals																	
26	22	Fertilizers																	
27	23	Chemical prods.																	
28	24	Plastics/rubber																	
29	25	Logs																	
30	26	Wood prods.																	
31	27	Newsprint/paper																	
32	28	Paper articles																	
33	29	Printed prods.																	
34	30	Textiles/leather																	
35	31	Nonmetal min. prods.																	
36	32	Base metals																	
37	33	Articles-base metal																	
38	34	Machinery																	
39	35	Electronics																	
40	36	Motorized vehicles																	
41	37	Transport equip.																	
42	38	Precision instruments																	
43	39	Furniture																	
44	40	Misc. mfg. prods.																	
45	41	Waste/scrap																	
46	42	Mixed freight																	
47	43	Unknown																	
48	44	Live animals/fish																	

Figure 20. Cargo list table

The transportation mode table manages the information related to each transportation mode such as general driving speed and priced and unpriced unit cost as Figure 21.

<Transportation mode>

	Driving speed	Unit cost ($/ton-mile)		
		Priced	Unpriced	Total
Waterway	8	0.0183	0.009	0.0273
Truck	50	0.1424	0.062	0.2044
Rail	25	0.0235	0.009	0.0325

Figure 21. Transportation mode table

The terminal information table involves location, average waiting time and distance to final destination from a terminal as Figure 22. Location is represented as the distance from the starting point on inland waterway. We assume that minimum cost path from a terminal is available and distance to final destination is measured along the path. If a transportation mode is not used, its distance is 0.

<Terminal>

	Location	Average waiting time	Distance to final destination	
			Truck	Rail
s	0	2.4	150	420
1	120	3.5	80	380
2	250	6.5	180	0
3	390	2.4	130	0
d	480	4.5	50	0

Figure 22. Terminal information table

2.5.2. Closure time forecasting module

This module calculates the expected closure duration based on received information such as reason of disruption, weather condition, age of a lock and a dam, waterway level, and so on. It returns the estimated expected closure duration to the cost calculation module.

2.5.3. Cost calculation module

This is the main module of the supporting tool. It receives the information of current location on inland waterway. It is also represented as the distance from the starting point. Using current location and terminal information, the nearest terminal is defined and expected travel distance is calculated. Expected closure duration is given from closure time forecasting module, and the expected waiting time on waterway is derived from this information. Then, travel time, material handling time, and waiting time at the terminal is calculated and the expected delivery time is defined in sequential order. Based on the travel distance and the delivery time, priced cost, unpriced cost, and private indirect cost is calculated. By summing these costs, expected delivery cost is given. Usually, this module is hidden under spreadsheet and not revealed on computer screen. Figure 23 shows a screenshot of the VBA code of cost calculation module.

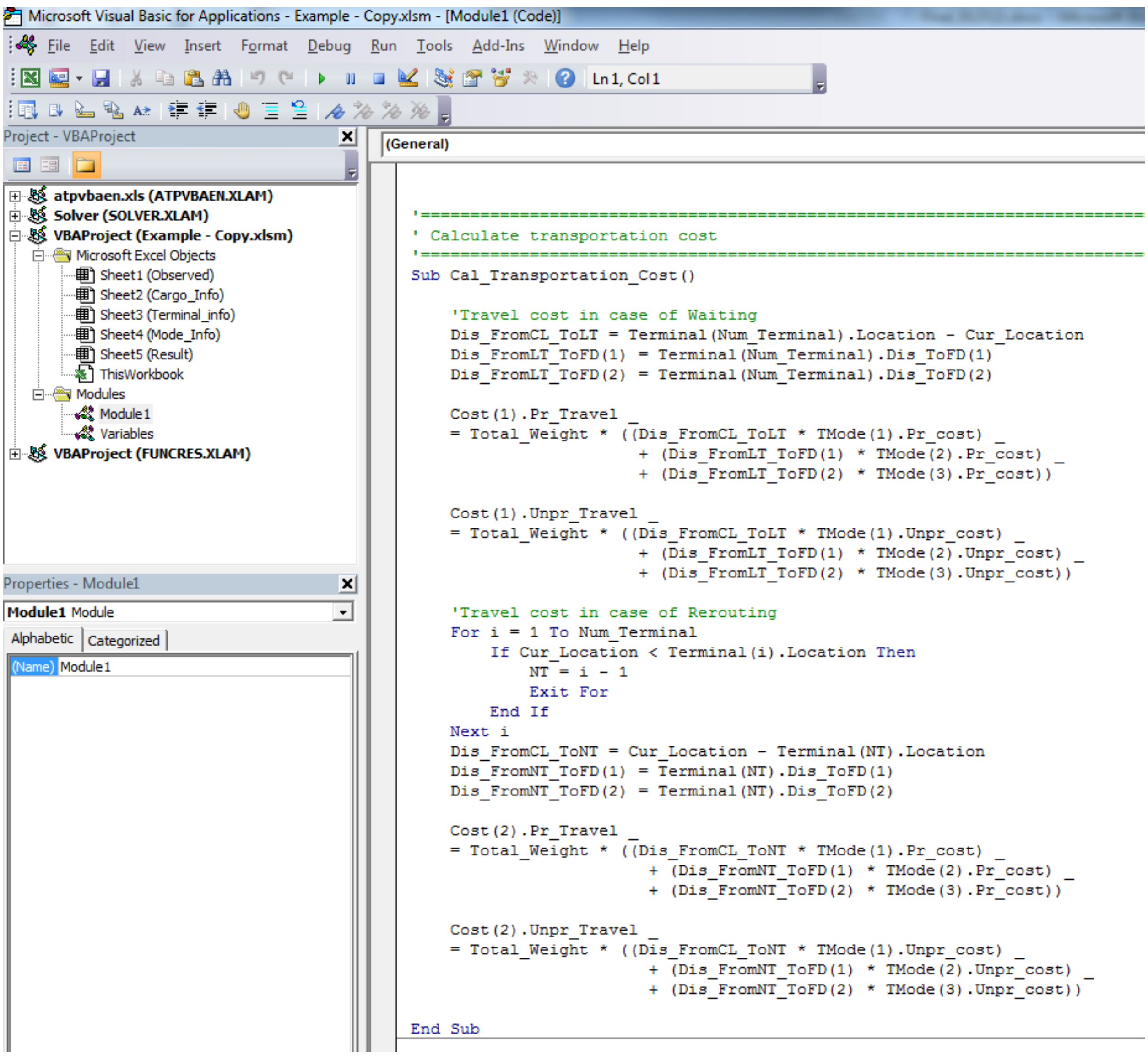


Figure 23. Cost calculation module

2.5.4. Output module

This module shows delivery cost of the waiting and the rerouting as Figure 24.

		Waiting	Rerouting	Difference
Transportation cost	Priced cost	16,170.00	39,271.50	23,101.50
	Unpriced cost	7,350.00	17,145.00	9,795.00
Secondary cost	Untimely delivery cost	15,433.00	0.00	-15,433.00
	In-transit inventory cost	45,240.00	0.00	-45,240.00
	Value decreasing cost	925.55	92.56	-833.00
Total cost		85,118.55	56,509.06	-28,609.50

Figure 24. Output module

2.6. Numerical example

2.6.1. Example

Look at the example illustrated in Figure 25.

Delivery information, current location, and closure information

This information is assumed.

Terminal information

All information is assumed. Location is represented as the distance from the starting point. Thus, Starting point's location is zero. From the starting point and the terminal 1 to the final destination, truck and rail are used together. From the terminal 2 and 3 and the last terminal to the final destination, only truck is used. As approach to the last terminal, the distance to the final destination decreases.

Cargo information

Cargo value information is derived from *Freight Analysis Framework Version 4*. For more details, refer to Appendix A. The total weight of cargo is set as 1500 ton considering capacity of one barge, 1750 ton. The other information is assumed.

Transportation mode information

Driving speed is based on real data.

Barge speed is retrieved from http://www.voanews.com/a/slow-going-barges-still-prosper-on-us-waterways-139356333/162802.html and http://www.recaap.org/Portals/0/docs/Tug%20Boats%20and%20Barges%20(TaB)%20Guide%20(Final).pdf.

Freight truck speed is retrieved from http://ops.fhwa.dot.gov/Freight/freight_analysis/nat_freight_stats/docs/10factsfigures/table3_8.htm.

Freight rail speed is retrieved from https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/transportation_statistics_annual_report/2010/html/chapter_02/table_04_33.html.

Unit cost is from the previous papers. For more detail, refer to Section 2.3.1.

< Observed Info. >

Delivery	
Start date	13-Nov
Today	15-Nov
Due date	17-Nov
Remaining	2 days
Location	
Current	280
Closure	
Reason	Weather related
Expected closure time	7.7

< Terminal Info. >

Terminal	Location	Average waiting time	Distance to the final destination	
			Truck	Rail
Start	0	-	80	420
1	120	3.5	50	300
2	250	6.5	180	0
3	390	2.4	130	0
Last	480	4.5	50	0

< Transportation model Info.>

Transportation Mode	Driving speed	Unit cost ($/ton-mile)		
		Priced	Unpriced	Total
Waterway	8	0.0183	0.009	0.0273
Truck	50	0.1424	0.062	0.2044
Rail	25	0.0235	0.009	0.0325

< Cargo Info. >

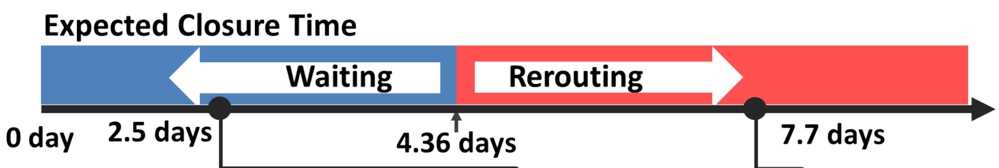
Commodity	Weight (Ton)	Value		Average Loading/Unloading Time (min/ton)	Average Decreasing Rate (%/day)
		Unit ($/Ton)	Total		
Cereal grains	500	231.28	115,640	0.15	0.07
Coal	1000	38.69	38,690	0.1	0.03

Figure 25. Numerical example of decision making under the disruption

2.6.2. Result

Figure 26 shows the result of the example. When the expected waiting time is give as 2.5 days, the waiting is better choice than the rerouting. On the other hand, when the given expected waiting time is 7.7 days, the rerouting overwhelms the waiting. Note that there is no change in the cost of the rerouting according to the different waiting times. It shows deterministic feature of the rerouting cost against uncertainty of the waiting time. In addition, the costs based on travel distance, priced direct cost and unpriced public and external cost, do not change. We can know that private indirect cost plays a key role in decision making.

The bar positioned at top of Figure 26 represents the threshold policy of the current instance. For this example, 4.36 days is given as the threshold value at which the optimal decision is divergent to the waiting or the rerouting.



Expected closure time		= 2.5 day		=7.7 day	
		Waiting	*Rerouting*	*Waiting*	*Rerouting*
Priced direct cost		16,170.00	39,271.50	16,170.00	39,271.50
Unpriced public and external cost		7,350.00	17,145.00	7,350.00	17,145.00
Private indirect cost	Penalty cost	4,629.90	0.00	15,433.00	0.00
	Holding cost	16,965.00	0.00	45,240.00	0.00
	Value decreasing cost	462.78	92.56	925.55	92.56
Total cost		**45,577.68**	56,509.06	85,118.55	**56,509.06**
Optimal Solution		***Waiting***		***Rerouting***	

Figure 26. Result of the example

3. Results/Findings

Through this research, four main results and findings are given as follows:

- Framework of the decision making process
- The threshold policy
- The feature of the cost model
- Certain factors affecting the closure

Framework of the decision making process

Our research problem is the decision making under uncertainty where ambiguity is inherent. Thus, it is significantly important to clearly and formally define the problem. In this type of problem, the framework of the decision making process plays a key role, providing the base of the research. It underlies the decision making supporting tool and shows structural justification of the decision making model and fundamental motivation of the development. The well-organized framework offers easy expandability and high probability of improvement. In addition, it can be used efficiently in explaining the decision making process to the user of supporting tool.

The threshold policy

Given the expected waiting time, we can simply find which alternative is a better choice. However, since the feature of the research problem having only two alternatives, we can construct the threshold policy and use it in decision making. The threshold policy can be established based on waiting time with fixed other factors. Once the threshold policy is developed, we do not need to calculate delivery cost. When the decision making situation is given with the same condition of the threshold policy, we can easily make reasonable decision by comparing waiting time and threshold value.

The feature of the cost model

In terms of private direct cost and private indirect cost, the waiting and the reroute have inverse relationship. In other words, comparing with each other, the waiting has a lower private direct cost due to lower unit cost and a higher private indirect cost because of longer delivery time. The rerouting has higher private direct cost due to high unit cost and lower private indirect cost because of shorter delivery time. Figure 27 shows this relationship.

Private direct cost	***Waiting*** (Lower unit cost)	<	***Rerouting*** (Higher unit cost)
Private indirect cost	***Waiting*** (Longer delivery time)	>	***Rerouting*** (Shorter delivery time)

Figure 27. Costs relationships in each alternative

Delivery cost of the rerouting is given as the deterministic value in terms of the waiting time. The changes in the waiting time affect private indirect cost of the waiting. Based on variation in this cost, the optimal decision is changed as the waiting time changes. Usually, low waiting time selects the waiting as the optimal choice.

Certain factors affecting the closure

In our research, we analyze the duration of the closure. From the historical data, we can find that the duration has wide range from 0 to 98 days. However, almost values are converged between 0 and 20 days. Thus, although the average duration of the disruption is about 15 days, we can expect the shorter duration than 15 days with quite high probability.

As limited by the available data, it is difficult to predict the closure length for an individual case. However, we can predict the annual closure length amount for locks based on weather information. It can be interpreted there exists certain relationship between the closure duration and weather conditions: precipitation, temperature, and humidity. In particular, precipitation and unscheduled disruption seem to follow a similar trend.

4. Impacts and benefits of implementation

Considering the objectives of our research, it helps the decision maker reduce the cost. Mainly, commercial companies using transportation service through the inland waterway system will receive pecuniary benefit by reduced cost. In addition, it will make positive impact on supply chain members by reducing untimely deliveries. Using the developed decision support tool will bring visible and invisible profits together.

Another impact of implementation is the changes in the decision maker's attitude. The expected value is usually used as the sole decision criterion because it is easy to calculate and to understand. However, to find at least reasonable result, we are required to use several approaches and tools together with the expected value. The framework helps persons understand decision making process under uncertainty and the developed tools reduce the required work for analysis. Consequently, it helps managers make decisions based on not intuition but analysis. Actually, the framework can be applied to any decision making problem accompanying uncertainty.

The last benefit of implementation is the improvement of the decision making supporting tool by date that would be accumulated continuously. The most important work in decision making under uncertainty is to make plausible probability distribution of the uncertainty and to anticipate the most likely outcome based on given information. To have high confidence on the prediction and the hypothesis concerning probability distribution, we require as much as data possible. It is only achieved through implementation in practice during a certain period. Thus, we can naturally expect the improvement of the support tool.

5. Recommendations and Conclusions

In our research, we developed the framework of the decision making process and devised the supporting tool for practitioner. The framework provides structural justification of the decision making model and fundamental motivation of the development. It shows the sequential procedure of decision making and elements of each stage including specific techniques and tools applied.

After the framework is constructed, the decision making support tool was devised and a prototype was developed using VBA in Excel. It reads and manages data through spreadsheets; calculates expected delivery cost; and gives several resources to support decision making.

We collected data for several districts concerning unavailabilities of the waterway over the years. We identified a strong relationship between the total closure time and yearly weather conditions (as characterized by temperature, humidity and precipitation). Based on this result, we believe it is possible to develop the forecasting module if sufficient data is given at individual location.

The numerical example also provides guidance for the future research. It reveals the significance of the private indirect cost in decision making and shows the existence of the threshold policy and how it can be used efficiently. For future research, we first recommend to develop the forecasting module. As mentioned above, it is an essential part of the decision making support tool. In addition, more sophisticate private indirect cost model is demanded. As can be seen above, it plays the key role in decision making. We can consider changing and adding elements of private indirect cost. Finally, we seek to continue improving the decision support tool upon implementation to allow more users to make real-time decisions upon inland waterway disruption.

Reference

American Society of Civil Engineers (2013, March). Inland waterways: Condition & Capacity, in *2013 Report Card for America's Infrastructure* (Inland Waterway). Retrieved from http://www.infrastructurereportcard.org/a/documents/2013-Report-Card.pdf

Anderson, D. R., Sweeney, D. J., and Williams, T. A. (2003). *An introduction to management science: quantitative approaches to decision making 10ed*, Cengage Learning. South-Western, Mason, OH.

Austin, D. (2015). *Pricing freight transport to account for external costs*. Congressional Budget Office, Washington, DC. Retrieved from http://www.cbo.gov/sites/default/files/114th-congress-2015-2016/workingpaper/50049-Freight_Transport_Working_Paper-2.pdf

Baroud, H., Ramirez-Marquez, J. E., Barker, K., and Rocco, C. M. (2014). Stochastic Measures of Network Resilience: Applications to Waterway Commodity Flows. *Risk Analysis*, 34(7), 1317–1335. https://doi.org/10.1111/risa.12175

Bergquist, M., Bernhardsson, V., and Rosklint, E. (2016). *Representation of the Swedish transport and logistics system in Samgods v. 1.1.* Swedish Transport Administration, Retrieved fromhttp://www.trafikverket.se/contentassets/ab220f9016154ef7a8478555560bb280/representation_report_20160919.pdf

Behdani, B., van Dam, K., and Lukszo, Z. (2011). Agent-based modeling for disruption management in industrial networks and supply chains. *Proceedings of 2011 International Conference on Networking, Sensing and Control*, April 11-13, Delft, Netherlands, 157–162. https://doi.org/10.1109/ICNSC.2011.5874947

Brown, A., and Badurdeen, F. (2014). Supply Chain Disruption Management : Review of Issues and Research Directions. *Proceedings of the 2014 Industrial and Systems Engineering Research Conference*, Y. Guan and H. Liao, eds. May 31 – Jun 3, Montreal, Canada, 3022-3029, http://0-search.proquest.com.library.uark.edu/docview/1622308818?accountid=8361

Bureau of Transportation Statistics (2016, April updated). Table 1-1 – System Mileage within the United States, *National Transportation Statistics*. Retrieved from https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_01.html

Caldwell, H., Quinn, K., Meunier, J., Suhrbier, J., and Grenzeback, L. (2002). *Potential impacts of climate change on freight transport*. Us Dot, 1–14. Retrieved from http://climate.dot.gov/documents/workshop1002/caldwell.pdf

Clark, C., Henrickson K. E., and Thoma, P. (2005). *An overview of the U.S. inland waterway system*. IWR Report 05_NETS-R-12. Institute for Water Resources, U.S. Army Corps of Engineers. Retrieved from http://www.corpsnets.us/docs/other/05-nets-r-12.pdf

Clarke, J., Solak, S., and Chang, Y. (2009). Air traffic flow management in the presence of uncertainty. *USA/Europe Air Traffic Management Research and Development Seminar (ATM2009).* Retrieved from http://www.atmseminar.org/seminarContent/seminar8/papers/p_147_NSTFO.pdf

Di Francesco, M., Lai, M., and Zuddas, P. (2013). Maritime repositioning of empty containers under uncertain port disruptions. *Computers and Industrial Engineering*, 64(3), 827–837. https://doi.org/10.1016/j.cie.2012.12.014

Figliozzi, M. A., and Zhang, Z. (2009). A Study of Transportation Disruption Causes and Costs in containerized maritime transportation. No 207815, *Transportation Research Forum*, 50th Annual Transportation Research Forum, Portland, Oregon, March 16-18, 2009.Retrieved from http://ageconsearch.umn.edu/bitstream/207815/2/2009_93_TransportationDisruption_paper.pdf

Gong, Q., Miao, Q., Wang, B. X., and Adams T. M. (2012). *Assessing Public Benefits and Costs of Freight Transportation Projects: Measuring Shipper's Value of Delay on the Freight System*. Technical report by University Transportation Center for Mobility (UTCM) and National Center for Freight and Infrastructure Research and Education (CFIRE). Retrieved from http://utcm.tamu.edu/publications/final_reports/Wang_11-00-65.pdf

Government Accountability Office (2011). *SURFACE FREICHTE TRANSPROTATION: A Comparison of the Costs of Road, Rail, and Waterways Freight Shipments That Are Not Passed on to Consumers,* GAO-11-134. Retrieved from http://www.gao.gov/new.items/d11134.pdf

Grout, J. R. (1998). Influencing a supplier using delivery windows: its effect on the variance of flow time and on-time delivery. *Decision Sciences*, 29(3), 747-764

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.

Guiffrida, A. L. and Nagi, R. (2006). Cost characterizations of supply chain delivery performance. *International Journal of Production Economics*, 102(1), 22-36.

Gurning, S., Cahoon, S., Dragovic, B., and Nguyen, H. O. (2013). Modelling of multi-mitigation strategies for maritime disruptions in the wheat supply chain. *Strojniski Vestnik/Journal of Mechanical Engineering*, 59(9), 499–510. https://doi.org/10.5545/sv-jme.2012.941

Hanssen, T. E. S., Mathisen, T. A., and Jørgensen, F. (2012). Generalized transport costs in intermodal freight transport. *Procedia-Social and Behavioral Sciences*, 54, 189-200.

Jackson, S. (2009, July), *Shipper and Carrier Response to the June-July 2008 Upper Mississippi River Flood Emergency Closure of Locks 12-25*, U.S. Army Corps of Engineers, Retrieved from https://planning.erdc.dren.mil/toolbox/library/IWRServer/09-NETS-R-01.pdf

Janic, M. (2007). Modelling the full costs of an intermodal and road freight transport network. *Transportation Research Part D: Transport and Environment*, 12(1), 33-44.

Johnson, J. G., and Busemeyer, J. R. (2010). Decision making under risk and uncertainty. *Wiley Interdisciplinary Reviews: Cognitive Science*, *1*(5), 736-749.

Koetse, M. J., and Rietveld, P. (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D: Transport and Environment*, 14(3), 205–221. https://doi.org/10.1016/j.trd.2008.12.004

Krajewski, L. J., Ritzman, L. P., and Malhotra, M. K. (2007). *Operations management: processes and value chains 8ed*, Pearson Prentice Hall, Upper Saddle River, NJ.

Kreis, D., Sturgill, R. E., Howell, B. K., Dyke, C. V., and Voss, D. S. (2014). *Inland Waterway Operational Model & Simulation Along the Ohio River*. Kentucky Transportation Center. Retrieved from http://uknowledge.uky.edu/cgi/viewcontent.cgi?article=2464&context=ktc_researchreports

Lewis, B., Erera, A., and White, C. (2006). Impact of temporary seaport closures on freight supply chain costs. *Transportation Research Record: Journal of the Transportation Research Board* (1963), 64–70. https://doi.org/10.3141/1963-09

Litman, T. A. and Doherty, E. (2009), *Transportation Cost and Benefit Analysis: Techniques, Estimates and Implications 2ed* (2. Transportation Cost Literature Review). Victoria Transport Policy Institute. Retrieved from http://www.vtpi.org/tca/tca02.pdf

Liu, T., and Lam, J. S. L. (2012). Impact of port disruption on transportation network. Fas.Nus.Edu.Sg. Retrieved from http://www.fas.nus.edu.sg/ecs/events/pe2012/Lam_paper.pdf

MacKenzie, C. A., Barker, K., and Grant, F. H. (2012). Evaluating the consequences of an inland waterway port closure with a dynamic multiregional interdependence model. *IEEE Transactions on Systems, Man, and Cybernetics Part A: Systems and Humans*, 42(2), 359–370. https://doi.org/10.1109/TSMCA.2011.2164065

Mails, R. M. (2002). *Beyond Expected Value: Making Decisions under Risk and Uncertainty*, Institute for Water Resources, U. S. Army Corps of Engineers. Retrieved from http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/02r4bey_exp_val.pdf

Meijeren, J., Groen, T., and Noordegraaf, D. (2011). *Impact of Climate Change on the Competitive Position of Inland Waterways Transport and Logistic Solutions*, Retrieved from http://abstracts.aetransport.org/paper/download/id/3766

Nachtmann, H. and Oztanriseven, F (2014), *Economic Evaluation of Arkansas Inland Waterways and Potential Disruption Impacts.* Technical report, Mack-Blackwell Rural Transportation Center. Retrieved from http://mack-blackwell.uark.edu/Research/mbtc-3029.pdf

Nilim, A., El Ghaoui, L., and Duong, V. (2002). Robust dynamic routing of aircraft under uncertainty. *Proceedings of The 21st Digital Avionics Systems Conference,* October 27-31, Irvine, CA, vol.1, 1A5-1A13. Retrieved from http://ieeexplore.ieee.org/document/1067888/

Pant, R., Barker, K., Ramirez-Marquez, J. E., and Rocco, C. M. (2014). Stochastic measures of resilience and their application to container terminals. *Computers and Industrial Engineering*, 70(1), 183–194. https://doi.org/10.1016/j.cie.2014.01.017

Parnell, G. S., Bresnick, T. A., Tani, S. N., and Johnson, E. R. (2013), *Handbook of Decision Analysis*, John Wiley & Sons, Inc., Hoboken, NJ

Planning Center of Expertise for Inland Navigation (2005, February), *Shipper and Carrier Response to the September-October 2003 Greenup Main Lock Closure*, U.S. Army Corps of Engineers, Retrieved from http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/05-NETS-R-02.pdf

Rose, A., and Wei, D. (2013). Estimating the Economic Consequences of a Port Shutdown: the Special Role of Resilience. *Economic Systems Research*, 25(2), 212–232. https://doi.org/10.1080/09535314.2012.731379

Shin, H., Benton, W. C., and Jun, M. (2009). Quantifying suppliers' product quality and delivery performance: A sourcing policy decision model. *Computers & Operations Research*, 36(8), 2462-2471.

Sumalee, A., Uchida, K., and Lam, W. H. K. (2011). Stochastic multi-modal transport network under demand uncertainties and adverse weather condition. *Transportation Research Part C: Emerging Technologies*, 19(2), 338–350. https://doi.org/10.1016/j.trc.2010.05.018

Thompson, T. (2005, September). Management accounting--decision management: what effect do risk and uncertainty have on decision-making? Tim Thompson considers some of the techniques that can be used to evaluate an opportunity. *Financial Management* [UK], 44+, 44-49, Retrieved from http://0-bi.galegroup.com.library.uark.edu/essentials/article/GALE%7CA146497984/cded13e4f0bfd41393c7279c95c4bb77?u=faye28748

Tong, Jingjing (2014), *Disruption Response Support for Inland Waterway Transportation* (Doctoral dissertation). Retrieved from ProQuest Digital Dissertations, http://0-search.proquest.com.library.uark.edu/docview/1564760889/fulltextPDF/CB5A91FA52C14BCCPQ/1?accountid=8361

Tong, J., Nachtmann, H., and Pohl, E. A. (2015). Value-focused assessment of cargo value decreasing rates. *Engineering Management Journal*, 27(2), 73-84.

Transport Canada (2008). *Estimates of the Full Cost of Transportation in Canada*. Synthesis report. Retrieved from http://publications.gc.ca/collections/collection_2009/tc/T22-165-2008E.pdf

Transportation Research Board (2015), *Funding and Managing the U.S. Inland Waterway System: What Policy Makers Need to Know.* Retrieved from http://onlinepubs.trb.org/onlinepubs/sr/sr315.pdf

U.S. Army Corps of Engineers (n.d.). Navigation: Did you know? [Webpage of U.S. Army Corps of Engineers]. Retrieved from http://www.usace.army.mil/Missions/Civil-Works/Navigation/

U.S. Army Corps of Engineers (2009). *Inland Waterway Navigation: Value to the Nation*. Retrieved from http://www.mvk.usace.army.mil/Portals/58/docs/PP/ValueToTheNation/VTNInlandNav.pdf

U.S. Army Corps of Engineers (2016). *The U.S. Waterway System: 2015 Transportation Fact & Information*. Retrieved from http://www.navigationdatacenter.us/factcard/FactCard2016-d.pdf

U.S. House Committee on Transportation and Infrastructure (2013, October). *Improving the Nation's Freight Transportation System: Findings and Recommendations of the Special Panel on 21st Century Freight Transportatio*. Retrieved from https://transportation.house.gov/uploadedfiles/freightreportsmall.pdf

Waterways Council, Inc. (n.d.). Media: Factoids [Webpage of Waterways Council, Inc]. Retrieved from http://waterwayscouncil.org/media/

Winston, W. L. and Albright, S. C. (2009). *Practical Management Science revised 3ed,* South-Western Cengage Learning, Mason, OH.

Gurning, S., & Cahoon, S. (2011). Analysis of multi-mitigation scenarios on maritime disruptions. Maritime Policy & Management, 38(3), 251–268. https://doi.org/10.1080/03088839.2011.572701

Zhou, Y., Wan, Y., Roy, S., Taylor, C., and Wanke, C. (2011). A stochastic modeling and analysis approach to strategic traffic flow management under weather uncertainty. *Proceedings of AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, August 8-11, Portland, OR, 1–18. https://doi.org/10.2514/6.2011-6514

Appendix A. Unit Cargo Value

It is calculated as follows:

$$\text{Unit Cargo Value} = \frac{\text{Yearly total value by commodity}}{\text{Yearly total weight by commodity}}$$

This data is from Freight Analysis Framework Version 4 (http://faf.ornl.gov/fafweb/Extraction2.aspx); and of 2015.

Value: $ Millions

Weight: Kilo Tones

Unit Cost: $/ton

Commodity	Total value	Total weight	Unit Value
Live animals/fish	163,695.59	99,888.14	1638.79
Cereal grains	231,570.94	1,001,238.71	231.28
Other ag prods.	287,413.38	462,550.22	621.37
Animal feed	121,747.16	301,343.85	404.01
Meat/seafood	304,474.85	89,061.76	3418.69
Milled grain prods.	157,315.94	117,884.04	1334.50
Other foodstuffs	635,589.52	652,373.12	974.27
Alcoholic beverages	178,940.32	100,788.45	1775.40
Tobacco prods.	59,164.65	2,756.80	21461.36
Building stone	10,960.87	35,471.46	309.01
Natural sands	8,262.54	551,592.62	14.98
Gravel	18,938.13	1,799,166.33	10.53
Nonmetallic minerals	14,752.23	169,580.21	86.99
Metallic ores	20,765.43	72,803.23	285.23
Coal	33,680.43	870,613.57	38.69
Crude petroleum	321,089.39	479,223.63	670.02
Gasoline	1,051,787.88	1,139,597.41	922.95
Fuel oils	712,202.61	848,909.86	838.96
Coal-n.e.c.	923,658.85	2,561,467.64	360.60
Basic chemicals	287,984.04	335,496.64	858.38

Pharmaceuticals	787,077.21	16,445.08	47860.97
Fertilizers	83,852.92	189,406.22	442.71
Chemical prods.	346,569.05	109,710.64	3158.94
Plastics/rubber	544,336.36	189,306.77	2875.42
Logs	12,174.40	305,960.88	39.79
Wood prods.	180,720.30	398,757.73	453.21
Newsprint/paper	89,820.64	86,808.49	1034.70
Paper articles	125,190.92	76,001.22	1647.22
Printed prods.	148,887.72	36,084.05	4126.14
Textiles/leather	467,897.78	42,253.11	11073.69
Nonmetal min. prods.	215,418.81	1,035,447.83	208.04
Base metals	444,426.91	305,098.58	1456.67
Articles-base metal	359,977.38	116,333.90	3094.35
Machinery	740,790.51	88,367.56	8383.06
Electronics	1,002,952.60	54,937.38	18256.29
Motorized vehicles	1,064,404.78	139,856.50	7610.69
Transport equip.	249,625.22	8,273.70	30170.92
Precision instruments	310,085.88	8,029.17	38619.90
Furniture	322,055.84	65,377.75	4926.08
Misc. mfg. prods.	565,834.10	96,455.51	5866.27
Waste/scrap	77,032.31	601,864.96	127.99
Mixed freight	1,388,073.09	381,159.34	3641.71
Unknown	374.47	1,339.32	279.59
Live animals/fish	163,695.59	99,888.14	1638.79