Project Report
20656 - Methods and Data Analytics for Risk Assessment
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Barb David Loredan Carli Federico Ferrazzano Andrea Saveri Leonardo

Zamboni Isabella

Abstract

In this report, we will present our project with Agena Risk. The aim is to build a Bayesian Network to model the route and duration of the trip of a ship that comes from India and has to reach Italy. In the network, we created a set of nodes to model the decision to either take the Suez Canal or sail under Africa; this decision depends on a series of tests that the shipping company can either perform or not. After choosing the route, we decided to model four different risks associated to the route chosen and not. These risks are associated to the speed, the delay caused by the Suez Canal being closed, and the terrorists and the cyber attacks. We compute the delay that can be caused by all these factors and then estimate the time it would take the boat to reach its destination.

1. Introduction

The aim of the project is to estimate the time a shipping boat would take to reach Italy from India. To do so, we model the risks and the scenarios using the Agena Risk software.
We want to answer the question: *"How long would a ship take to reach Italy from India? How would different conditions, such as weather or cyber-attacks, delay the trip?"*

The project's focus on estimating the duration of a ship's trip holds significant relevance in the realm of maritime logistics and risk management. By modeling the route, considering the various factors, the project aims to address critical concerns in the shipping industry.

Bayesian Networks can address this by providing a chance to model:

- **Uncertainty Management:** Bayesian networks allow modeling uncertain events like weather conditions, canal closures, and cyber-attacks, providing a probabilistic framework to assess their impact on trip duration accurately.

- **Dependency Modeling:** By capturing dependencies between decisions (e.g., route selection) and test outcomes, Bayesian networks help in understanding how different choices influence the overall trip duration.

- **Risk Assessment:** Incorporating nodes for risks like speed variations, Suez canal closures, and cyber-attacks enables comprehensive risk assessment within the model. Bayesian inference techniques can estimate the likelihood and impact of these risks on trip duration.

- **Scenario Analysis:** Bayesian networks facilitate scenario analysis, allowing simulation of various conditions (e.g., different weather scenarios, test outcomes) to observe their effects on trip duration. This capability aids in evaluating strategies and contingencies for the ship's journey.

1.1. Data

The data will be later explained in details in Section 2. Our strategy was to find official statistics wherever possible. About the weather, the number of days of closure of the Suez Canal, the number of boats, the number of terrorist's attacks and of cyber attacks. We looked for the average length of the trip and tried to find information about the possible delays. When it was not possible to find official data, we estimated the appropriate distributions for the nodes using similar statistics and reasoned assumptions.

1.2. Sketch of the model

You can find the structure of the model in Appendix A, and the model used at this GitHub repository[1].
The model contains 3 main sections:

- **The Decision Modelling** section which is used to choose which route to take. This contains two different checks (that add a penalty to the overall time if done) that can be performed to choose the best route: Checking for Sandstorms in the Suez Canal, and checking if the Suez Canal is closed or open.
- **Houthi Attack** section, which is used to model the probability of getting attacked, as well as the outcome of such attack depending on the military situation of the ship and the political motivation.
- **Cybersecurity** section, which is used to model the probability of failing to a cyber attack, depending on the software situation of the boat and on the business continuity strategy they implemented.

These sections then are used to estimate the delay and the speed which are, in the end, used to estimate the overall time.

2. The Model

2.1. Assumptions

Environmental and Security Concerns:

- *Sandstorms:* Sandstorms are exclusive to the Suez route.
- *Political Safety:* Ships flagged under China or Russia are generally safe from attacks, with rare exceptions.

Operational Continuity:

- *Military Defense:* Ensures the ship sustains no damage; however, without it, an attacked ship will not complete its delivery.
- *Business Continuity:* Guarantees control is maintained over operations.
- *Cyber Threats:* May cause delays but won't halt the ship.

Geographical and Economic Simplifications:

- *Suez Canal Passage:* Assumed feasible for all vessels.
- *Route Speed:* Africa's transit is consistently slower.
- *Economic Factors:* Oil prices and canal fees are not considered in the decision-making process.
- *Houthi Attack:* can happen only if the Suez route is taken, as the usual place of attack is that route. No other attacks are considered as we could only find data about the Houthi attacks.

Utility and Decision Nodes:

- *Utility of Decision:* The penalties for taking the tests are incorporated into the "Day for Test" node.
- *Total Utility:* This is encapsulated within the probabilities of the "Decision Route Node."
- *Test Suez Closed:* When we perform the test, and we get that that Suez is closed, it means that the canal will be closed for more days than it would take the ship to use the Africa route.

Assumption on time:

- Base Route:
  - 19 days for base Suez (found 3 weeks)
  - 50 days for base Africa (found + 26 days)
  - Plus 1 day if either test is performed
  - Plus 2 days if both tests are performed
  - If the test returns that the Suez canal is closed, we assume that the Canal is closed indefenitely.
- Delay Suez and Speed:
  - Plus 5 for Slow Speed
  - Plus 10 for Very Slow Speed
  - Plus 2 for Short Wait
  - Plus 7 for Long Wait
- Delay attacks:
  - Plus 5 for some damage
  - Plus 100 (never delivers) for Delivery Cancelled
  - Plus 1 for Loss of Control

2.2. Variables and Probabilities

2.2.1 Decision Section

Decision Check Sandstorm: This node represents the decision to check for sandstorms in the Suez Canal. The base probability is 50% since we can freely choose to test or not. If we test, we can know for sure whether there is a sandstorm, but since the probability of having one is very low, checking with the test adds another day to the route.

[1] https://github.com/leonardosaveri/Methods_Spring2024

Check Sandstorm: This observable node has probabilities for having a sandstorm, not having one, or not taking the test, which depend on the parents. It changes based on the unobservable. If we test and set the Sandstorm Suez, we get either "Yes" or "No" storm. If we don't test, the node will take the "No test" status.

Sandstorm Suez: This node shows the probability of having a sandstorm in the Suez Canal. Based on data, we assign a probability of $\frac{1}{365}$ as there was only one sandstorm event in 2023[2].

Speed: This node depends on whether there is a sandstorm and the route chosen. It has three states:

- Very Slow: Happens if we have a sandstorm and take the Suez route with a 90% probability. It adds 10 days to the overall route.
- Slow: Happens if we have a sandstorm and take the Suez route with a 10% probability. It adds 5 days to the overall route.
- Normal: The speed when there is no sandstorm or when choosing the Africa route. It doesn't add any extra days.

Decision Check Suez: The decision to check if the Suez Canal is closed or not before departing. This affects the utility of the decision. The base probability is 50% since we can freely choose to test or not. If we test, we can know for sure whether the Suez Canal is closed or open, but since the probability of having it closed is very low, checking will add another day to the route.

Suez Test: This observable node has probabilities for having Suez Close, Suez Open, or not taking the test that depend on the parents. It changes based on the unobservable. If we test and set the Suez, we get either "Open" or "Close" canal. If we don't test, the node will take the "No test" status.

Suez: This node represents real statistics about the closure of the Suez Canal in the past 24 years. It has only been closed for 11 days due to cargo blockages, not political or natural reasons.[3].

Wait Time: a labelled node. If the Suez Canal is open, there is "No Wait". If closed and taking the Africa route, there is a "Short Wait". Otherwise, waiting at the canal results in a "Long Wait".

Days for Tests Node this is a Discrete Real type node, which Unique Identifier is Day. The possible node states are respectively 0.0, 1.0, and 2.0.
The probability for each state depends on two nodes:

1. *Decision Check Suez* that respectively has states: No Test, and Yes Test
2. *Decision Check Sandstorm* that respectively has states: No Test, and Yes Test

In the case where no test is taken the probability of 0.0 days for test is exactly equal to 100% since no penalty must be applied. Instead, when either one of the two tests are executed the node takes state 1.0 (*a penalty of one day*) with probability 100%. Lastly, when both the tests are executed the node takes state 2.0 (*a penalty of two days*) with probability 100%.

Decision Route Node this is a Labelled type node, which has as Unique Identifier Route. The possible node states are respectively Suez and Africa, since we assumed that there are no others possible routes to take into consideration. The probability for each route depends on several nodes' states:

1. *Check Sandstorm Suez* that respectively has states: Yes Sandstorm, and No Sandstorm
2. *Suez Test* that respectively has states: Suez Close, Suez Open, and No Test
3. *Decision Check Suez* that respectively has states: No Test, and Yes Test
4. *Decision Check Sandstorm* that respectively has states: No Test, and Yes Test

The first case we considered has no test performed: *Decision Check Suez == No Test* and *Decision Check Sandstorm == No Test*. For this reason, the nodes *Check Sandstorm Suez* and *Suez Test* are not relevant.
If no test are done, the probability navigate the *Suez Route* is at *0.95*, whereas the probability to undertake the *Africa Route* is *0.05*. We assigned this 95-5 split to balance, on one hand, the faster route, and, on the other hand, the low risk of delay due to a closure of the Suez Canal. Also, as no tests are performed, there is no penalty on the Utility.

Then, we considered the case where *Decision Check Sandstorm == Yes Test*, *Check Sandstorm Suez == Yes Sandstorm, Decision Check Suez == No Test*. Since the Decision Check Suez has not been implemented, the state of *Suez Test* is irrelevant. In this case the probability to undertake Suez Canal drops to 0.2 while the probability to undertake Africa Route increases to 0.8, that's because when a Sandstorm occurs in the Suez Canal, the speed of the ship undertaking the route changes from Normal to Very Slow (with a probability of 0.9) or to Slow (with a probability of 0.1). This will affect the decision on the preferred route to choose. The 0.2 probability of taking the Suez Canal route serves the purpose of taking into consideration the risk of delay in the Africa Route, caused by a congestion.

[2] looking at online news about sandstorms
[3] from various online sources

Thirdly, we considered the case where *Decision Check Suez == Yes Test, Suez Test == Suez Close, Decision Check Sandstorm == No Test*, so irrespective of the state of *Check Sandstorm Suez* (because the Decision Check Sandstorm has not been implemented).
In this case, the probability to undertake Suez Canal drop to 0.001 while the probability to undertake Africa Route goes up to 0.999, that's because when Suez Canal is closed no ships can undertake this route. The 0.001 is kept for AgenaRisk software purposes, as when we first assigned 1, we noticed some inconsistencies with how Utility was handled. At the same time, it could also be argued that the possibility to take the impeded route should still be granted.

After that, we considered the case where *Decision Check Suez == Yes Test, Suez Test == Suez Open, Decision Check Sandstorm == No Test,* so irrespective of the state of *Check Sandstorm Suez* (because the Decision Check Sandstorm has not been implemented).
In this case, the probability to undertake Suez Canal goes up to 0.97, as the faster route becomes 'safer', with no risk of canal closure. The probability to undertake Africa Route drops to 0.03.

Later, we considered the case where *Decision Check Suez == Yes Test, Suez Test == Suez Open, Decision Check Sandstorm == Yes Test, and Check Sandstorm Suez == Yes Sandstorm*
In this case the probability to undertake Suez Canal drop down to 0.3 while the probability to undertake Africa Route goes up to 0.7, that's because when a Sandstorm occurs in the Suez Canal the speed of the ship undertaking the route change from normal to Very Slow (with a probability of 0.9) or to Slow (with a probability of 0.1). This will affect the decision on the preferred route to choose. The 0.3 probability of Suez Canal wants to take into consideration that there is a risk of delay in the Africa Route, in fact the latter can experience congestion, leading to delays, this probability is higher than in the previous case of Sandstorm (probability to undertake Suez Canal sets at 0.2) because in this case we know for sure that the Canal is open, that increase the probability of a ship to undertake the Suez Route.

Lastly, we considered the scenarios where *Decision Check Suez == No Test, Decision Check Sandstorm == Yes Test, and Check Sandstorm Suez == No Sandstorm,* so irrespective of the state of *Suez Test* (because the Decision Check Suez has not been implemented).
In this case, the probability to undertake Suez Canal goes up to 0.98 while the probability to undertake Africa Route drop down to 0.02. Here, the probability increase more than the previous case because since the probability of the occurrence of a Sandstorm is higher than the probability of the closure of the Canal, the removal of a risk that is bigger leads to a bigger increase in the probability.
These probabilities were chosen to reflect the utility each route has depending on the various situations.

2.2.2 Houthi Attack Section

Find in Appendix B the data found for this section to compute the probabilities.

Political Motivation: is a Boolean node which models the terrorist's political motivation on whether to attack a ship or not. It is widely assumed that some countries, Russia and China, may have struck deals with pirates not be attacked. The probabilities we assigned are a very broad estimation, as there were no official data about country flags of origin of the vessels. We assumed that there is no political motivation in 70% of the cases.

Houthi Attack: a Boolean node that depends on "Political Motivation" and "Decision Route" nodes. If the ship goes around Africa, we assumed vessels can't be attacked by the Houthi, thus a probability of 100% for the *False* state. If the vessel takes the Suez route, we used the data found and reported in Appendix B and computed that 43 ships form November 2023 to April 2024 were attacked successfully. On average, 50 ships per day go through the Suez Canal, so we put the probability of getting an attack as $\frac{43}{50 \cdot 30 \cdot 6} = 0.00477$.

Military Defence: We found that only 7 ships out of the 50 attacked intercepted the attack, so we assumed that the probability of having military defense is $\frac{7}{50} = 0.14$. We also assumed that if there is military defence, the attack is intercepted and does not affect the ship.

Ship Destroyed: is a labeled node with the following possible states:

- *No Damage:* having probability 100% if Houthis don't attack and probability 48.88% if Houthi attack and there is military defence
- *Some Damage:* having probability 0.5112 if the Houthi attack and there is military defence
- *Delivery Cancelled:* having probability 1 if the Houthi attack and there is no military defence (our assumption)

2.2.3 Cyber Attack Section

Outdated Software: is a Boolean node that assumes state *True* with 25% probability[4]. That figure is taken from a survey done by the firm BitSight.

Threat Intelligence: is a Boolean node which assumes *True* state with 21.5% probability (From BCI Report of 2023). Threat Intelligence (TI) is a proactive security measure that aims to understand the possible threat actors that may target the firm's important assets (e.g. vessel navigation system) and know in advance the technique they use to prevent breaches. TI also reduces the response times, as it helps detect breaches early. This is supported by the evidence that shows that companies with TI, are mature and have on average a 4x faster response time.

Cyber Attack is a Boolean node that depend on the parent nodes "Outdated Software" *(Cause)* and "Threat Intelligence" *(Mitigant)*. From this blog[5], we could find that, without mitigantion measures, the probability of breaches when a firm uses old software is of 65%, while with up-to-date software, the probability of getting breached drops to 29%.
Then, starting from this McKinsey Study[6] which identifies 7 important capabilities, we assume that Threat Intelligence accounts for $\frac{1}{7}$, or 14%, reduction in probability of a breach.

Business Continuity: is a Boolean node that assume state *True* with probability 49% (From Mercer via Economic Times).

Loss of Control: is a Boolean node that depends on the parent nodes "Business Continuity" and "Cyber Attack". From the BCI Report of 2018, we found that 87% of firms implementing Business Continuity found a faster recovery time. We assume that employing a Business Continuity Plan reduces the probability of a complete loss of control, specifically, we assume a 87% reduction.

2.3. Delays and Estimation

Base Route: is a discrete real node which take values depending on the parents "Decision Route" and "Day for Tests." It uses formulas to add the amount of days extra needed for the tests to the base route time of 19 days for Suez and 50 days for Africa.

Delay Suez and Speed: this is a Discrete Real type node, which Unique Identifier is Delay2. The possible node states are respectively 0.0, 2.0, 5.0, 7.0, 10.0, 12.0, and 17.0. The probability for each state depends on two nodes:

- Wait time that respectively has states: No Wait (add 0 days), Short Wait (add 2 days), and Long Wait (add 7 days)
- Speed that respectively has states: Very Slow (add 10 days), Slow (add 5 days), and Normal (add 0 days)

Long Wait is the longest period for which the Suez Canal has been closed, with one extra day added because we considered that there is the needed of that day to restore standard operational conditions. The others have been logically estimated by us and should be reasonably updated by the company that will use the model accordingly with their available data.

Delay attacks: this is a Discrete Real type node, which Unique Identifier is Delay. The possible node states are respectively 0.0, 1.0, 5.0, 6.0, and 100.0.
The probability for each state depends on two nodes:

1. *Ship destroyed* that respectively has states: No Damage (add 0 days), Some Damage (add 5 days), and Delivery Cancelled (add 100 days)
2. *Loss of Control* that respectively has states: True (add 1 day), and False (add 0 days)

For the case in which the ship is destroyed, we add a a figurative 100 days which will be evaluated in the end to "never arrives." For the *True* state of Loss of Control, 1 days is added as we have found that usually this type of problem would delay the ship of half a day[7].

Time Expected: a "simple" Labelled node which uses the following formula to decide which label to assign based on the sum of the values of the 3 parents ("Base Route", "Delay Attacks" and "Delay Suez and Speed").
This is the formula used:
$if(Delay >= 100.0, "never\ arrives",$
$if(Delay + Delay2 + BRoute < 20.0, " < 20\ days",$
$if(Delay + Delay2 + BRoute <= 30.0, "20\ to\ 30 days",$
$if(Delay + Delay2 + BRoute <= 40.0, "31\ to\ 40 days",$
$if(Delay + Delay2 + BRoute <= 50.0, "41\ to\ 50 days",$
$if(Delay + Delay2 + BRoute <= 60.0, "51\ to\ 60 days",$
$" > 60\ days"))))))$

Given the very low probabilities of getting longer routes or attacks, we get that the the most probable time is *"20 to 30 days"* as we set that it is very probable to take either

[4] https://www.digitalguardian.com/blog/behind-breaches-lots-outdated-software

[5] https://www.kaspersky.com/blog/it-security-economics-2020-part-2/?utm_source=press-release&utm_medium=partner&utm_campaign=gl_economics-report_kk0084&utm_content=link&utm_term=gl_press-release_organic_nepblhe84a87xs6

[6] https://www.mckinsey.com/capabilities/risk-and-resilience/our-insights/organizational-cyber-maturity-a-survey-of-industries

[7] https://maritimecybersecurity.nl/incident/P8voLnDmnW

of the tests and adding at least 1 day. It is not very likely to reach more than 50 days as it is very unlikely to ever choose the Africa Route.

3. Simulations

Base Route: As can be seen in Appendix C, in the base case scenario there is a very low probability of choosing the Africa Route or encountering Houthi or Cyber Attacks. This leads to have a very high probability of either having an estimated time of "$<$ 20 days" (22.933%) or "20 to 30 days" (74.248%). This is because we have set the probabilities of taking the tests as 50% for both the test for the Sandstorms or for the closure of the Suez Canal. As it is quite likely to take at least one test, it is very probable to reach the "20 to 30 days" estimated time.
There is also a small chance (2.679%) of having "50 to 60 days" in case we choose to take the Africa route.

Cyber Attack without Business Continuity: This case shows the consequences of a cyberattack (*Cyberattack = True*), if business continuity is not implemented (*Business Continuity = False*). In real life, this case could represent an old western vessel.

Compared to the base case, there's an increase in the probability of a loss of control, from about 3% to 14%. More generally, the distribution of probabilities of the expected time of delivery shows an important shift (an increase of 2.605%) towards the 20 to 30 days range.

Both Attacks happen with Mitigating Measures: This case considers both attacks taking place (*Houthi Attack = True, Cyberattack = True*), but mitigation measures are present (*Military Defense = True, Business Continuity = True*). In real life, this case could represent a new western vessel, which is protected by its Navy and implements the newest Business Continuity Technologies.

Compared to the base case, there's a decrease of 1,12% in the probability of a loss of control, showing how important having Business Continuity is, and a considerable increase that the ship is damaged but not destroyed by the Houthi attack (now at 51.12% instead of being negligent). More generally, the distribution of probabilities of the expected time of delivery shows a significant shift (0.13968 increase of probability) towards the 20 to 30 days range.

Both Attacks happen with no Mitigations: This case is designed to show how the estimated time would change if both attack happens (*Houthi Attack = True, Cyberattack = True*) and no mitigating measures are implemented (*Military Defense = False, Business Continuity = False*).

In this case, we'll have 100% probability of the ship never arriving as, as we stated in the assumptions, a ship which is attacked and has no military defense will never deliver the package.

Attacks may happen with no Prevention or Mitigations This case is designed to understand how Causes (*Political Motivations = True, Outdated Software = True*) without Preventive or Mitigative measures (*Military Defense = False, Business Continuity = False, Threat Intelligence = False*) influence both the attacks' probabilities and the overall expected time.

Compared to the base case, there's a 0.32 increase in the probability of a Houthi Attack and a 0.0616 increase in the probability of a Cyberattack. More generally, the distribution of probabilities of the expected time of delivery shows a really minor shift (0.01185 increase of probability) towards the 20 to 30 days range.

Check Suez, No Check Sandstorm, Suez Open, with Sandstorm: We take the test to check if the Suez Canal is closed, and it's open, and don't check for sandstorms. The unobservable is set as "Yes Sandstorm." The expected time is, with around 94% probability "20 to 30 days" but we see an increment to 2.572% of the "30 to 40 days."

Check Suez, No Check Sandtorm, Suez Closed, yes Sandstorm: We take the test to check if the Suez Canal is closed, and it's closed, and don't check for sandstorms. The unobservable is set as "Yes Sandstorm." The expected time is, with around 99% probability "50 to 60 days" as, with the Suez Canal closed, we assume it is closed indefenitely and would prefer to take the Africa Route.

Other scenarios: More scenarios can be found in the agena risk file[8], showing more possibilities and the change in probabilities given some risks, decisions and events.

4. Sensitivity Analysis

We are providing the sensitivity analysis only for some nodes, the table and tornado charts can be found in appendix D. We wanted to check how much would a change in some selected nodes impact the probability of the different "Expected Time."

- *Political Motivation:* This was the most interesting to look at, as it has been the node for which we could find less information about the probabilities. We are happy to see that the node has very small impact on the probability of the time expected, meaning that even if we change the initial condition of the node, the impact on the overall network would be extremely small.

- *Decision Check Sandstorm* and *Decision Check Suez:* we can see that choosing to take the test impact much on the probability of having longer time, as expected. This also means that, if instead of giving it a probability of 50% to either take it or not we would put something different, the probabilities of the expected time would change a lot.

[8] https://github.com/leonardosaveri/Methods_Spring2024/blob/main/agena_model.cmpx

- *Decision Route:* we can see that deciding a different route, as expected, changes a lot the expected time.

5. Future Considerations

To enhance the model developed, we should consider addressing the limitations and biases introduced by the model's current assumptions. First, the model currently only factors as weather issues the Sandstorm, whereas in practice other weather factors are present (examples: Extremely High Winds, Heavy Rains, Ice and Cold Weather). Moreover, the weather condition in the Cape Route has not been taken into consideration, which could be added to have more comprehensive view of the natural perspective in the scenarios.
Secondly, political motivations are assumed, making a realistic approximation of how many ships are Chinese, Russian, or other types would benefit the network. Also, integrating not publicly available data and incident reports could help understanding how political dynamics influence route safety and security, beyond the simplistic nationality-based assumptions.
The economics of shipping has also not been taken into consideration. Integrating economic data such as fluctuating oil prices, and fees could help in modeling more realistic scenarios where cost considerations might dictate route preference. For example, nodes that account for oil prices and canal entrance fees could influence the decision and lead to choosing the Cape Route when oil prices are extremely low and Suez fees high. Another possible improvement relates to cyberattacks. Maritime companies do not disclose data on every cyberattack their ships suffer. Integrating that private data would enable a more precise outlook of how cyberattacks affect shippings.

In conclusion, enhancing the model by incorporating a wider range of environmental, political, and economic factors will provide a more comprehensive and realistic assessment of maritime route selection. Addressing the limitations of current assumptions will improve the model's accuracy and adaptability, better aligning it with the complexities of global maritime logistics. This enriched approach ensures more informed and strategic decision-making in navigating the challenges of maritime operations.

Example of nodes that could enhance the model:

- Nodes linked to SUEZ node that help to explain the possible causes of its closure:
  - Accidents (i.e. Collisions, Groundings., ecc.)
  - Political Tensions (i.e. Arab Spring, tension in the Middle East, ecc.)
  - Maintenance (Yes, No)
  - Technical Failures (Malfunctioning, breakdown, ecc.)
- Economic-linked nodes:
  - Oil Prices
  - Suez Fees
- Weather:
  - Wind
  - Rain
  - Cold Weather

6. Conclusion

Our Bayesian network model offers a comprehensive framework for assessing risks and optimizing logistical decisions in maritime operations. Through a combination of empirical data, industry reports, expert insights, and logical assumptions, we've created a structured approach to understanding key factors such as cyber attacks, delays, route selection, and decision pathways.

One of our key findings underscores the critical importance of cyber attack mitigation measures, including threat intelligence and updated software. These measures not only reduce the probability of breaches but also lead to faster response times and enhanced security postures. Similarly, our analysis highlights the significant role of business continuity strategies in minimizing disruptions and ensuring timely deliveries, particularly in the face of unforeseen events like cyber attacks.

However, our study also acknowledges certain limitations and areas for improvement. Limited data availability for nodes such as political motivations and the decision route necessitated the use of assumptions, which may not fully capture the intricacies of real-world scenarios. While we considered factors like sandstorms in route selection, broader environmental considerations and economic variables were not explicitly integrated into our model.

Moving forward, future iterations of the model could benefit from incorporating more comprehensive and updated data sources, expanding the scope to include environmental and economic factors, and refining decision pathways to reflect a wider range of scenarios. Dynamic updates and ongoing stakeholder engagement will be crucial in ensuring that the model remains relevant and effective in supporting decision-making processes within the maritime industry.

In essence, while our model provides valuable insights into risk management and operational optimization, continued refinement and data enhancements are imperative to address key weaknesses and provide robust decision support capabilities for navigating the complexities of global maritime logistics.

A. The Model

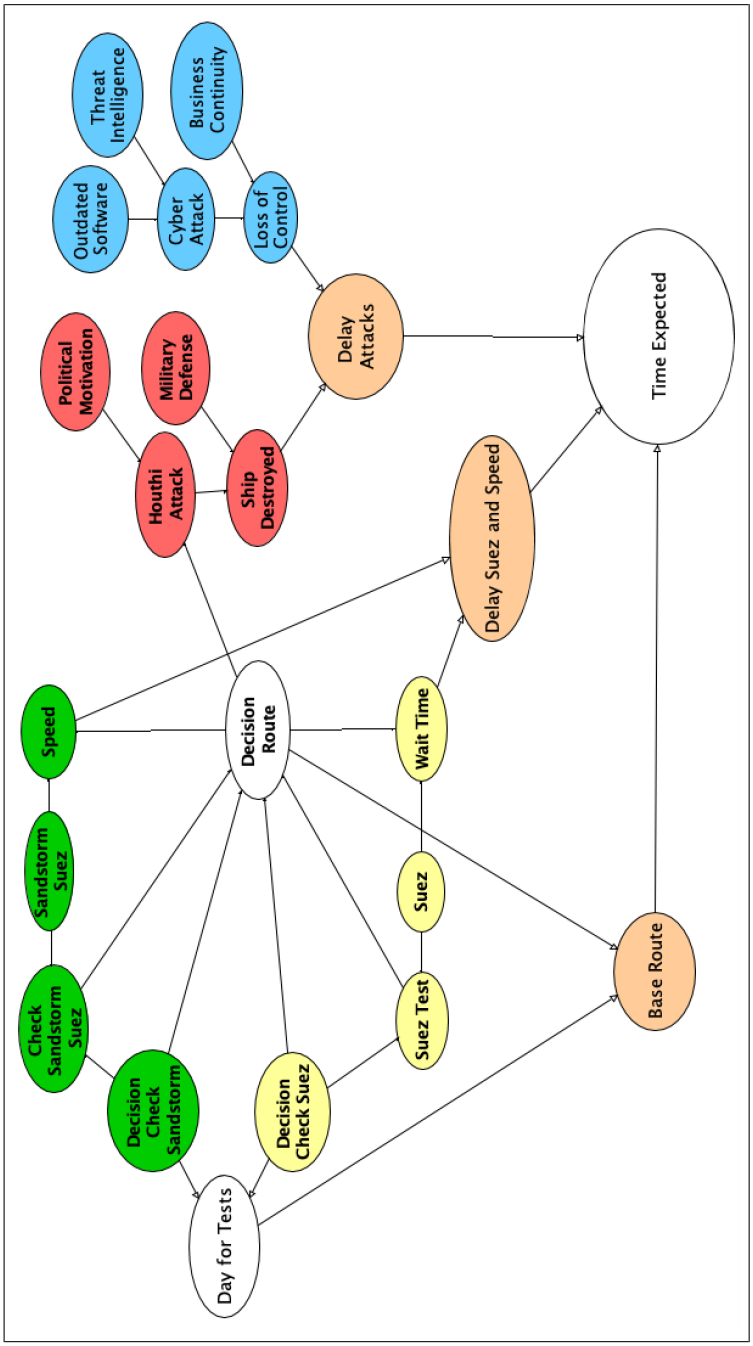


Figure 1. Bayesian Network

B. Data for Houthi Attack Section

Recap of Attacks Leading to Delays

From Lloyd List [9]
Attacks on Commercial Ships: 50
Intercepted: 7
Level of Destructions:

- Delivery not impacted nor damage received: 27 (0.54)
- Delivery impacted or damage received: 18 (0.36)
- Delivery cancelled: 5 (0.1)

Data: NOT IMPACTED NOR DAMAGED

- 2 missed on 10.12.23
- 1 missed on 14.12.23
- 1 missed on 18.12.23
- 1 missed on 2.01.24 (but mentions 3 explosions, counted as 1 attack or 3?)
- 1 intercepted on 09.01.24
- 1 missed on 11.01.24
- 1 struck but no damage on 15.01.24
- 1 struck but no damage on 16.01.24
- 1 struck but no damage on 17.01.24
- 1 missed on 18.01.24
- 1 missed on 24.01.24
- 1 intercepted on 24.01.24
- 1 missed on 01.02.24
- 1 missed on 02.02.24
- 2 missed on 06.02.24
- 1 intercepted on 06.02.24
- 1 no damage on 12.02.24
- 1 missed on 15.02.24
- 1 intercepted on 24.02.24
- 1 missed on 08.03.24
- 1 missed on 11.03.24
- 1 no damage on 14.03.24
- 1 no damage on 15.03.24
- 1 missed on 17.03.24
- 1 missed and intercepted on 06/07.04.24

Total NOT IMPACTED: 27
IMPACTED

- 3 on 3.12.23
- 1 on 11.12.23
- 1 intercepted on 13.12.23
- 1 on 15.12.23
- 1 on 18.12.23
- 1 on 23.12.23
- 1 possibly on 26.12.23 (crew unharmed but vessel under evaluation)
- 2 intercepted on 30.12.23
- 1 on 26.01.24 (crew unharmed, no mention of cargo)
- 1 on 16.02.24
- 2 on 19.02.24
- 1 on 22.02.24
- 1 on 04.03.24
- 1 on 23.03.24

Total IMPACTED: 18
Recap of Specific Attacks:[10]

- 19/11/23 - Galaxy Leader: Delivery Cancelled. Crew hijacked, vessel and crew held in Yemen.
- 03/12/23 events: 4 attacks, one heavily damaged (delivery cancelled)[11].
- 15/12/23 - Al Jasrah, MSC Palatium III: Delivery Cancelled (one of two ships).
- 18/2/24 - Rubymar: Delivery Cancelled. Master initially reported explosions near the vessel. Vessel and crew reported safe.
- 6/03/24 - True Confidence: Delivery Cancelled. Two Houthi missiles hit the vessel, resulting in casualties and abandonment of the vessel.

[9] https://lloydslist.com/hot-topics/red-sea-risk/map-and-list-of-attacks

[10] https://lloydslist.com/hot-topics/red-sea-risk/map-and-list-of-attacks

[11] https://www.reuters.com/world/britains-maritime-agency-reports-potential-explosion-red-sea-20

C. Base Case

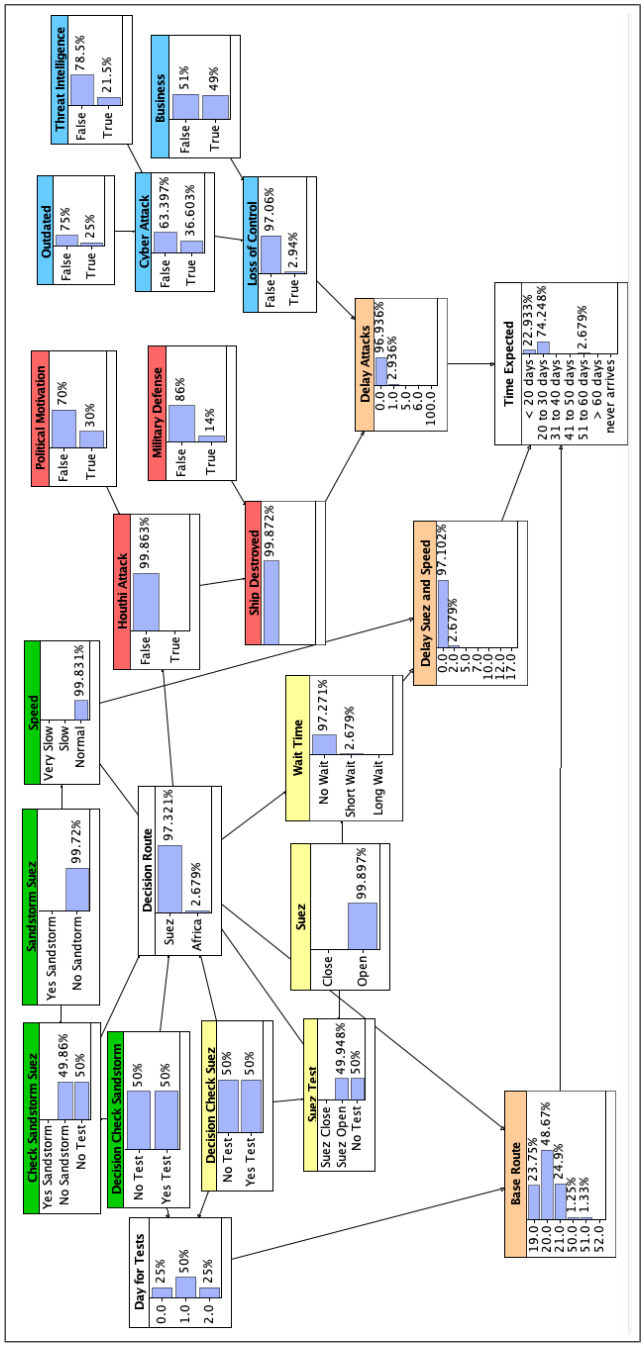


Figure 2. Base Scenario

D. Sensitivity Analysis

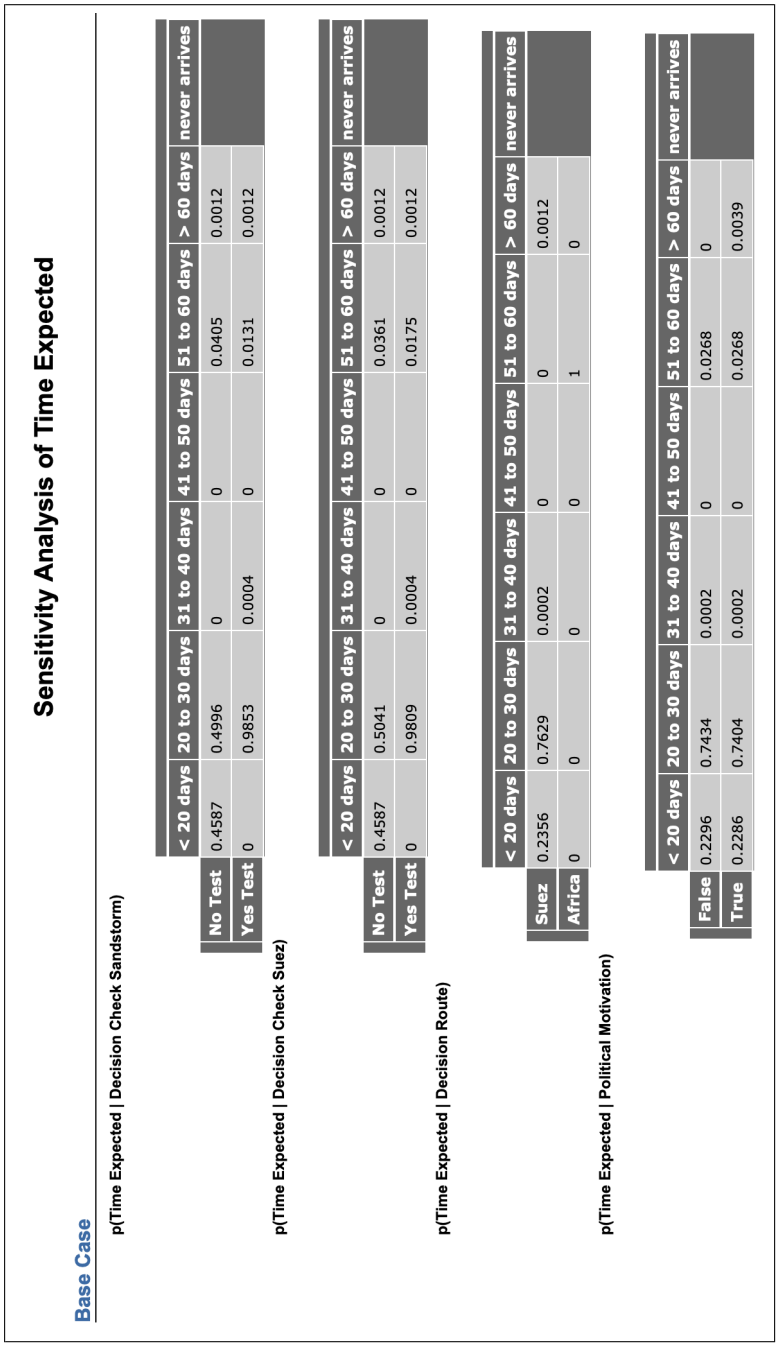
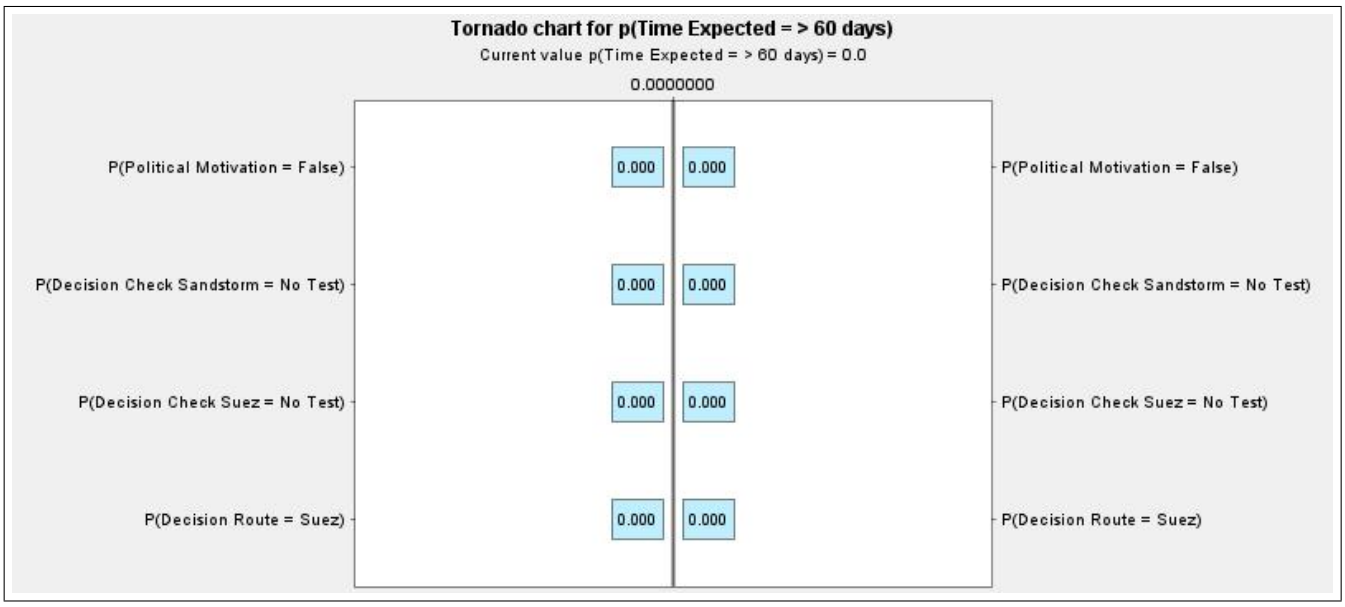
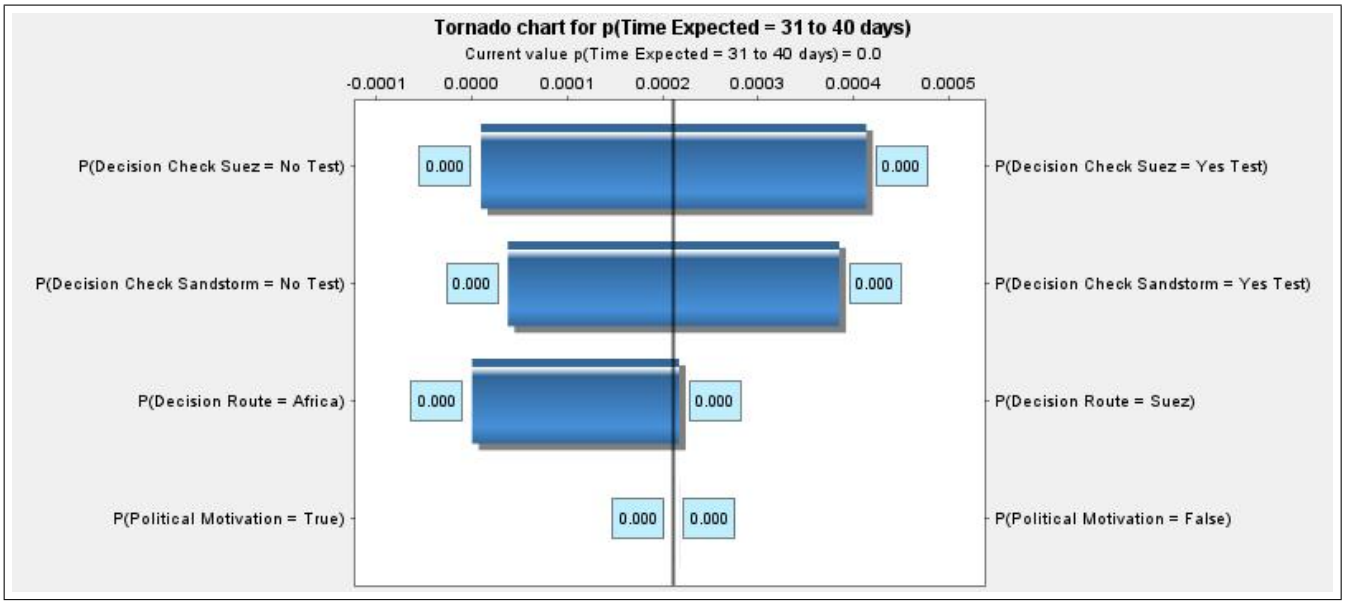
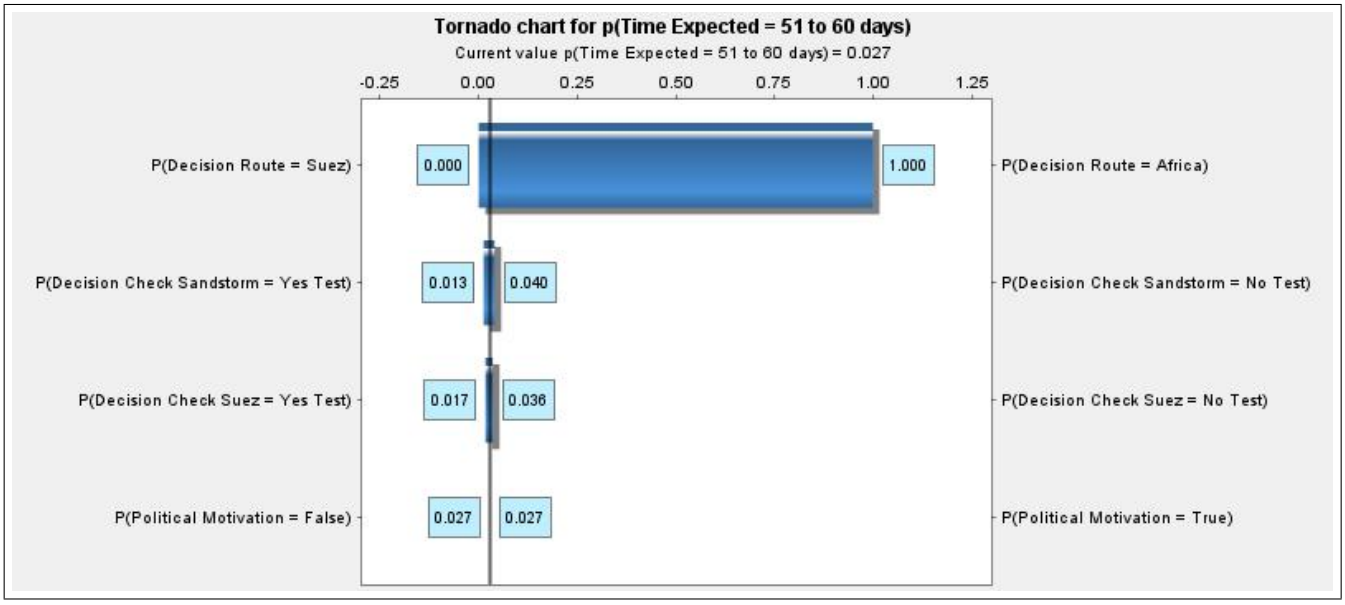
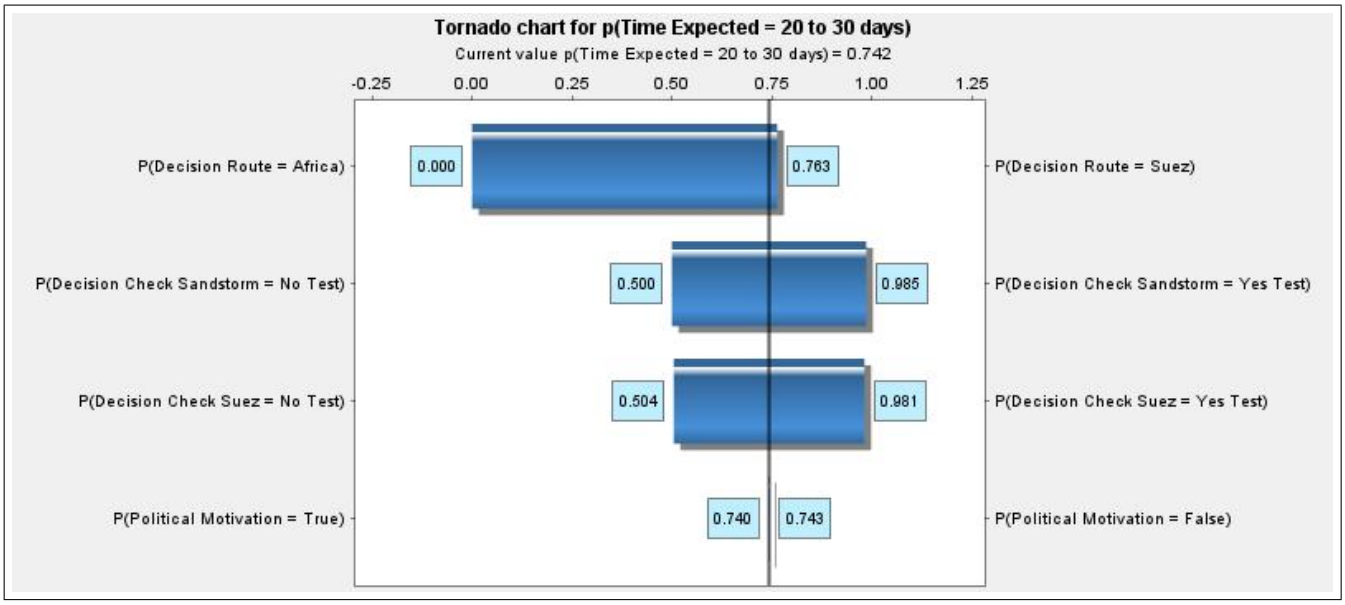


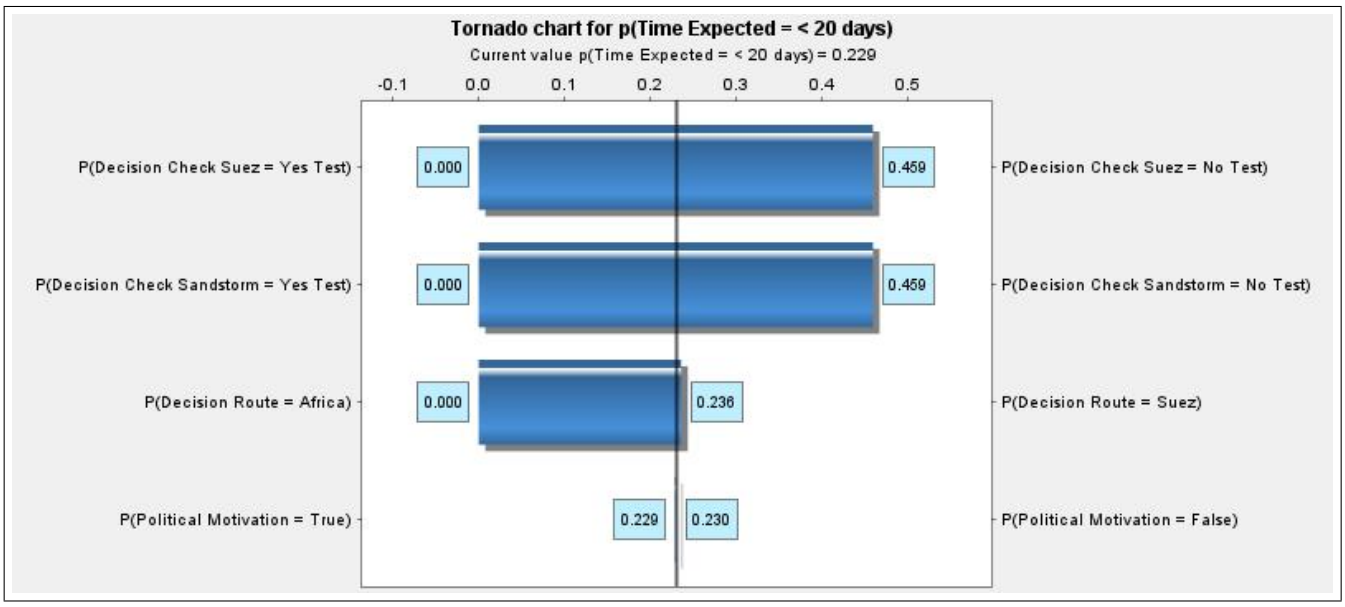
Figure 3. Sensitivity analysis table

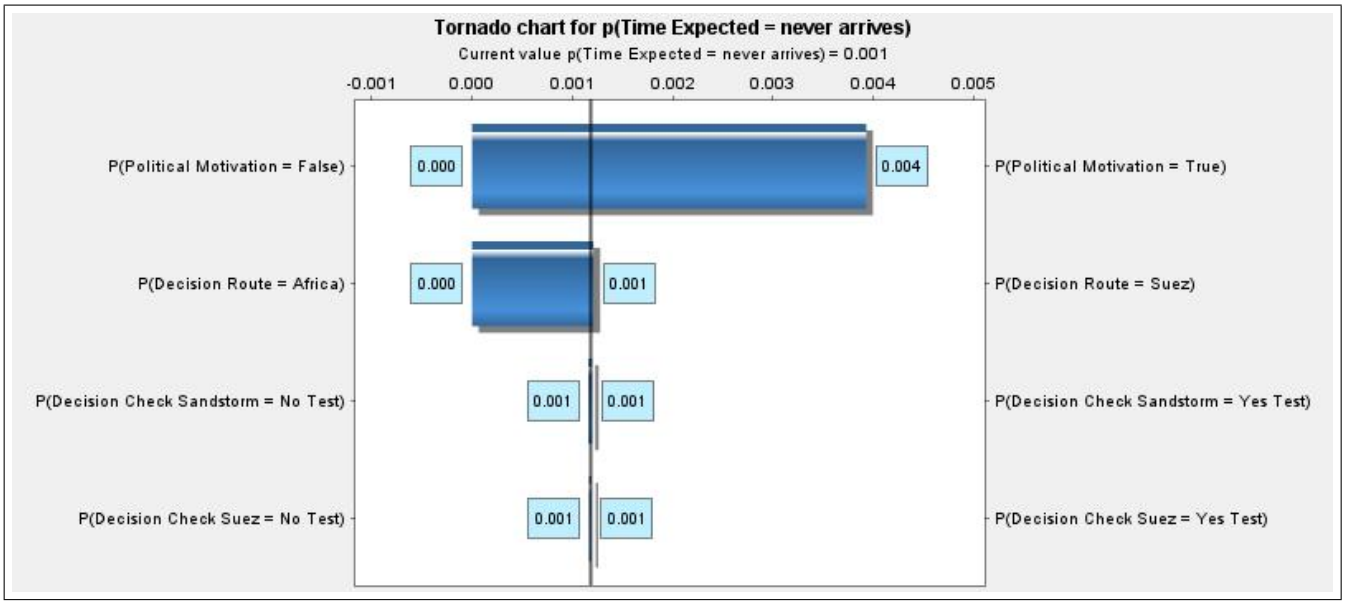

Tornado chart for p(Time Expected = > 60 days)
Current value p(Time Expected = > 60 days) = 0.0
0.0000000
P(Political Motivation = False)
P(Decision Check Sandstorm = No Test)
P(Decision Check Suez = No Test)
P(Decision Route = Suez)
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
P(Political Motivation = False)
P(Decision Check Sandstorm = No Test)
P(Decision Check Suez = No Test)
P(Decision Route = Suez)

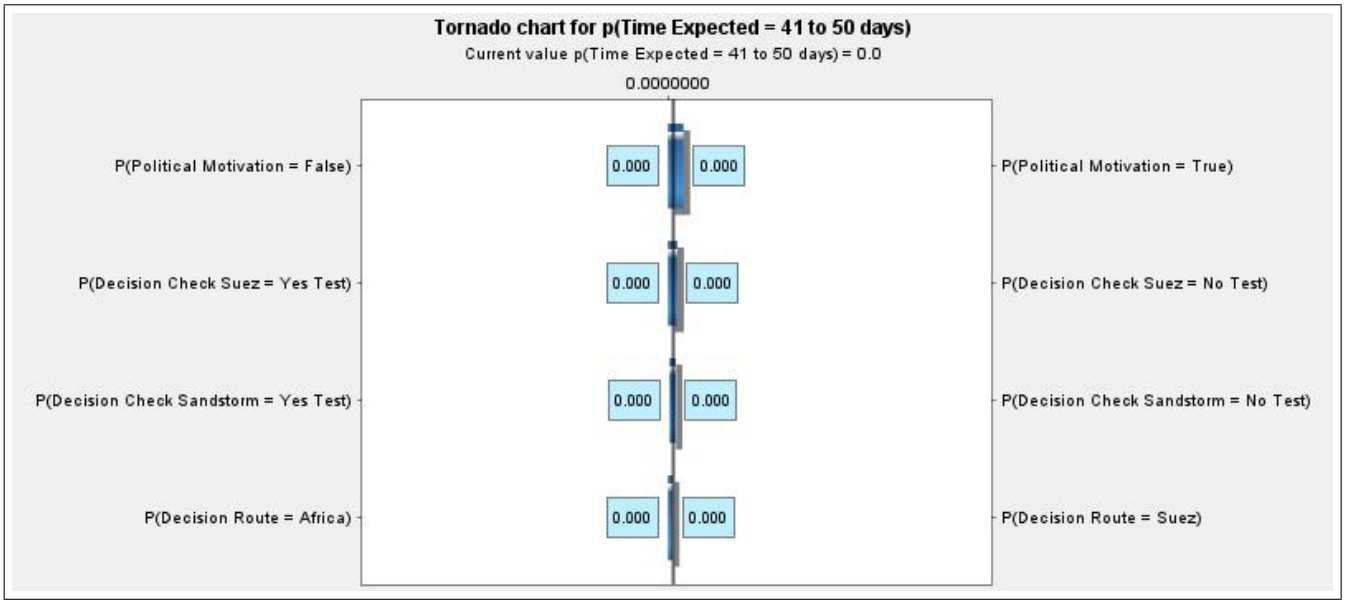

Tornado chart for p(Time Expected = 31 to 40 days)
Current value p(Time Expected = 31 to 40 days) = 0.0
-0.0001
0.0000
0.0001
0.0002
0.0003
0.0004
0.0005
P(Decision Check Suez = No Test)
P(Decision Check Sandstorm = No Test)
P(Decision Route = Africa)
P(Political Motivation = True)
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
P(Decision Check Suez = Yes Test)
P(Decision Check Sandstorm = Yes Test)
P(Decision Route = Suez)
P(Political Motivation = False)


Tornado chart for p(Time Expected = 51 to 60 days)
Current value p(Time Expected = 51 to 60 days) = 0.027
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
P(Decision Route = Suez)
0.000
1.000
P(Decision Route = Africa)
P(Decision Check Sandstorm = Yes Test)
0.013
0.040
P(Decision Check Sandstorm = No Test)
P(Decision Check Suez = Yes Test)
0.017
0.036
P(Decision Check Suez = No Test)
P(Political Motivation = False)
0.027
0.027
P(Political Motivation = True)


Tornado chart for p(Time Expected = 20 to 30 days)
Current value p(Time Expected = 20 to 30 days) = 0.742
-0.25
0.00
0.25
0.50
0.75
1.00
1.25
P(Decision Route = Africa)
0.000
0.763
P(Decision Route = Suez)
P(Decision Check Sandstorm = No Test)
0.500
0.985
P(Decision Check Sandstorm = Yes Test)
P(Decision Check Suez = No Test)
0.504
0.981
P(Decision Check Suez = Yes Test)
P(Political Motivation = True)
0.740
0.743
P(Political Motivation = False)


Tornado chart for p(Time Expected = < 20 days)
Current value p(Time Expected = < 20 days) = 0.229
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
P(Decision Check Suez = Yes Test)
0.000
0.459
P(Decision Check Suez = No Test)
P(Decision Check Sandstorm = Yes Test)
0.000
0.459
P(Decision Check Sandstorm = No Test)
P(Decision Route = Africa)
0.000
0.236
P(Decision Route = Suez)
P(Political Motivation = True)
0.229
0.230
P(Political Motivation = False)


Tornado chart for p(Time Expected = never arrives)
Current value p(Time Expected = never arrives) = 0.001
-0.001
0.000
0.001
0.002
0.003
0.004
0.005
P(Political Motivation = False)
0.000
0.004
P(Political Motivation = True)
P(Decision Route = Africa)
0.000
0.001
P(Decision Route = Suez)
P(Decision Check Sandstorm = No Test)
0.001
0.001
P(Decision Check Sandstorm = Yes Test)
P(Decision Check Suez = No Test)
0.001
0.001
P(Decision Check Suez = Yes Test)


Tornado chart for p(Time Expected = 41 to 50 days)
Current value p(Time Expected = 41 to 50 days) = 0.0
0.0000000
P(Political Motivation = False)
0.000
0.000
P(Political Motivation = True)
P(Decision Check Suez = Yes Test)
0.000
0.000
P(Decision Check Suez = No Test)
P(Decision Check Sandstorm = Yes Test)
0.000
0.000
P(Decision Check Sandstorm = No Test)
P(Decision Route = Africa)
0.000
0.000
P(Decision Route = Suez)