CAUSAL ANALYSIS GRAPH MODELING FOR STRATEGIC DECISIONS

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ABSTRACT

The use of causal analysis graphs for developing and evaluating strategies in complex problems is illustrated through two case studies: agricultural production in Gambella, Ethiopia and the crisis in the South China Sea. A Timed Influence net tool called Pythia is used to analyze and evaluate possible courses of action for each case.

INTRODUCTION

Causal modeling, planning, and forecasting activities support analysts trying to understand and answer questions relevant to national and global security. Reasoning over complex causal graphs and quantitative models could be dramatically improved by automated systems that help analysts configure scenarios of interest and focus on the most uncertain parts of the model. Ideally, Natural Language Processing can be used over a variety of data and narrative sources to construct the basic causal analysis graph. Once the graph has been defined, parameters that designate the influence of a cause on an effect are specified, usually by Subject Matter Experts, and time delays added to reflect the sojourn or processing time at a node and the propagation delay between nodes. The resulting graph, called a Timed Influence Net, can then be used to (a) assess the effect of a selected set of actions, or Course of Action (COA), on the outcomes, (b) to develop optimal COAs, and (c) analyze the sensitivity of the results to the individual actions and to the influence parameters. A tool called Pythia has been used to model and analyze a wide diversity of strategic problems. The workings of the tool are described in the next section. In the subsequent two sections two very different examples are presented: reducing famine in Ethiopia and avoiding conflict in the South China Sea.

PYTHIA: A TIMED INFLUENCE NET TOOL

Pythia provides an environment to build graph-based probabilistic cause-and-effect models and to perform several analyses on them. It was developed by the System Architectures Laboratory at George Mason University to aid decision making and Course of Action development and evaluation in complex situations. (Haider and Levis, 2008; Levis, 2014, Wagenhals and Levis, 2007) The process embodied in ***Pythia*** consists of four steps. The first step is the determination of the desired effects: the effects that are of interest whether they are desirable outcomes to be achieved or undesirable outcomes to be avoided. To determine how these effects can be accomplished and what could inhibit their accomplishment, an influence net model is constructed in which complex probabilistic influences between causes and effects and between effects and actions are indicated. The process for constructing the Influence Net starts with the effects on the right and works backwards toward the left. The process continues until the nodes that would influence the outcomes (or effects) are events that are controllable or scenario dependent. These large actions can then be decomposed further to the left until they become specific tasks or, in the terminology of Influence Nets, actionable events. If time is introduced, it is possible to indicate the time phasing of the actions and observe the probability of achieving the desired effects change over time. The various influences (links) in the Influence Net have processing delays associated with them; an event can take place at time t but its influence may not be felt until $t + \delta t$. Also, the actionable events (the root nodes of the Influence Net) may not all take place at the same time, but at different times. ***Pythia*** provides for entering delays in the influence links and delays in the actionable events. This creates a Timed Influence Net that produces, when executed, not just the final probabilities but probability profiles over time. This enables the creation and evaluation of Courses of Action in which the various actions can be distributed on the timeline so that the best probability profiles can be achieved. The influence net model is then used to carry out sensitivity analyses to determine which actionable events, alone and in combination, appear to produce the desired effects.

Graphical Interface Features

The main graphical interface features are: Actionable events (root nodes) drawn as rectangles (Fig.1, top left) while non-actionable events are drawn as rounded rectangles (top right) thus making them visually distinct. Different link styles are used in ***Pythia*** to distinguish between positive (blue with

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pointed arrow head; bottom left) and negative (red with round arrow head; bottom right) influences.

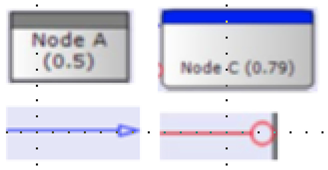


Fig. 1: Pythia symbols.

The underlying analytical framework for Influence Nets is Bayesian Nets. Consequently, Conditional Probability Tables (CPT) need to be constructed from the influence values. The Causal Strength (CAST) logic algorithm is used. (Haider, S., & Levis, A. H. 2008). The set of values for the influences is shown in Fig. 2.

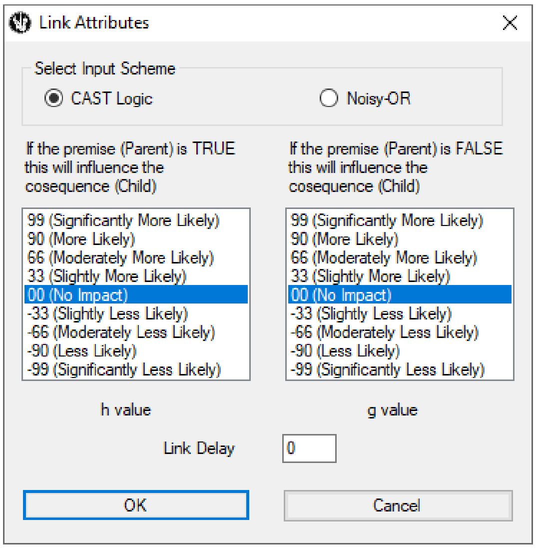


Figure 2: Link Properties Window.

A color-coding scheme for the nodes is used that assists a user in estimating the likelihood of occurrence of a particular event in an Influence Net. The coloring scheme for the nodes ranges from Darker Blue ($p > 0.88$) or Significantly More Likely to Darker Red. ($p < 0.11$) or Significantly Less Likely.

Once a Timed Influence Net is completely specified by a user, ***Pythia*** computes the marginal probabilities of all the events. When a COA is specified, ***Pythia*** generates probability profiles of selected events. A profile shows the likelihood of occurrences of events over a period of time. The period is determined from the COA and temporal information available in the form of link and node delays.

GAMBELLA, ETHIOPIA

To demonstrate the technical approach, a use case is presented based on the food security and migration situation in the Gambella region of Ethiopia (Fig. 3). This use case has many features that illustrate causal analysis graph modeling, including temporal dynamics with seasonal variations based on the agricultural cycle, and several possible decision points for interventions. The model is based on data, (Dalal, et al., 2021) but it is a simplified representation of the actual conditions in Gambella. It focuses on the temporal effects of weather/rainfall and the impact of various interventions, including:

(1) Increase in food imports (current purchases)
(2) Long-term infrastructure investments (roads, irrigation, storage, processing facilities, etc.)
(3) Investment in cropland development
(4) Investment in better seeds (current purchases)
(5) Investment in chemical fertilizers (current purchases)

The following source nodes represent the scenario: (1) Weather; (2) Increases in Agricultural Labor; (3) Displaced Persons in camps;(4) Direct Food Aid

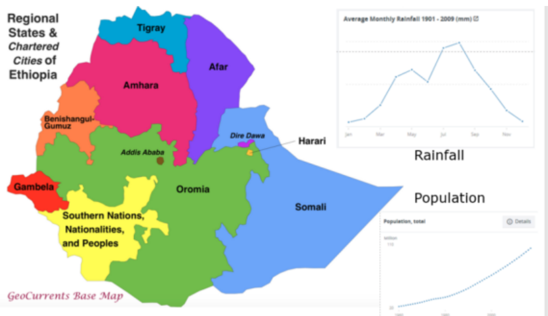


Fig. 3: On Ethiopia and Gambella. Rapid population growth: 51M (1993) to 108M (2018)

The model captures external events in a timeline (monthly) modeled on historical and scientific observations. Exogenous decisions are included in the timeline based on reasonable expectations, given a humanitarian goal. A textbook Solow-Swan model was used to construct parts of the scenario.

The model is shown in Fig. 4, which contains the model parameters (i.e., the influence parameters) described in the CAST format indicating the conditional influence of the parent nodes on their children. The crop season scenario over 12 months is shown in Fig. 5. External events and decisions (e.g., policy interventions) are applied to the model as observations (evidence), and are represented as tables indicating the state of each event in each month. The model calculates posterior marginals for crop yield increase, crop production increase, adequate urban food, and adequate rural food using a Bayesian Net algorithm.

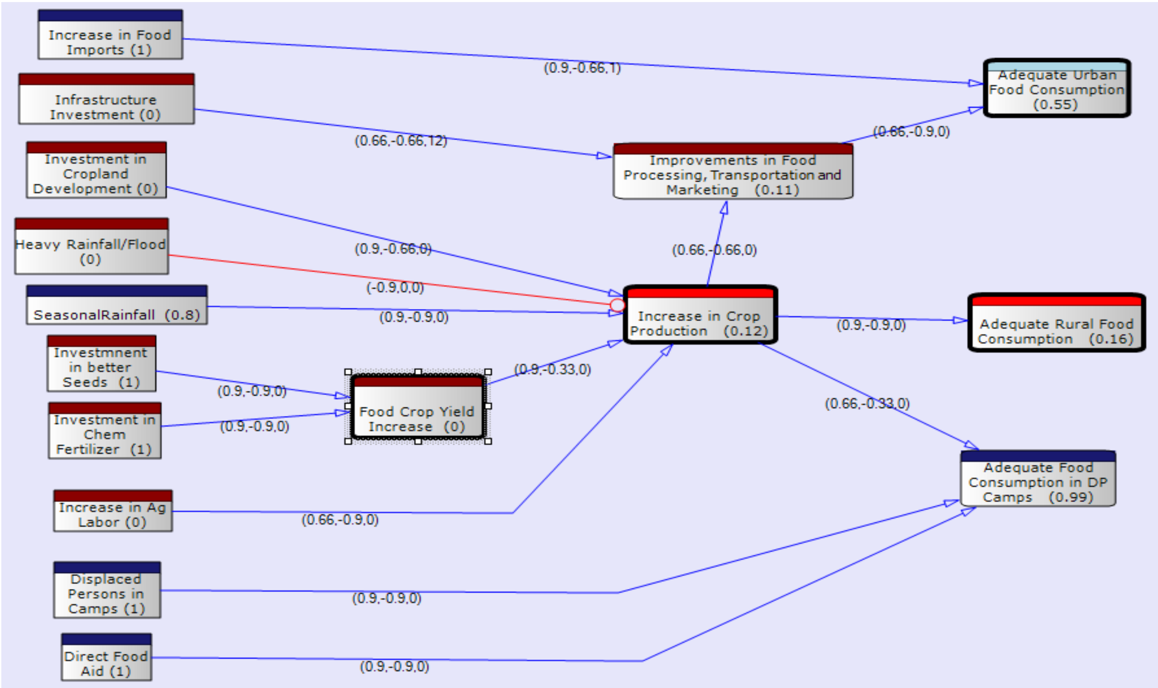


Fig. 4: Causal Analysis Graph (Influence net) for Gambella, Ethiopia test case

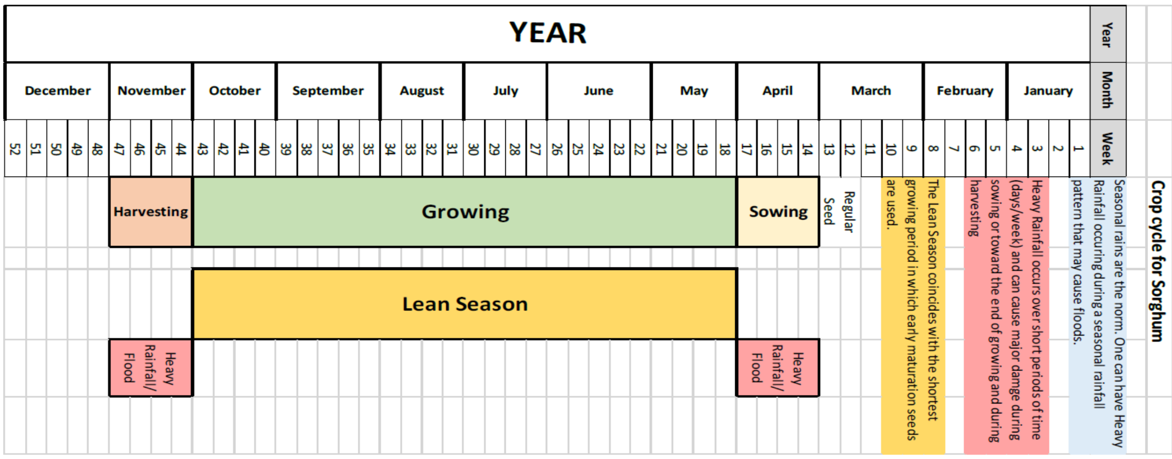


Fig. 5: Crop season scenario for Gambella test case

In this scenario, there is heavy rainfall during both the harvesting and sowing period. Using Pythia analytic algorithms, the objective is to predict the distributions over model variables over time and assess the stability of possible interventions under different conditions. Figure 6 shows the trajectories of certain model variables of interest over time. For example, in month 4, an increase in the probability that food yield will rise is observed (this is during the growing season), whereas this value drops in month 11 when flooding impacts potential crop yields.

To illustrate the behavior of the demonstration model, the scenario shown in Fig. 7 was developed. Here, the policy being explored is the impact of increasing food imports and investment in seeds, while the scenario includes heavier than average rainfall.

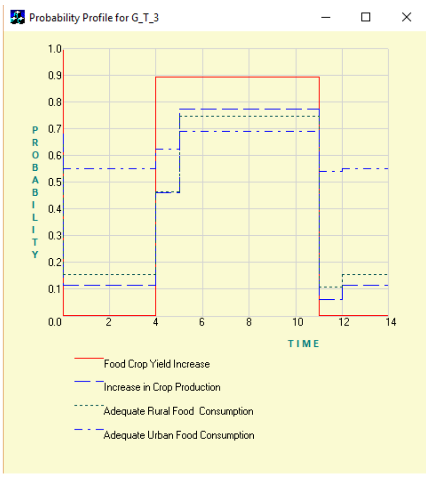


Fig. 6: Probability profiles of the bold nodes in the Gambella model. The probabilities shown on the model graph are the final probabilities

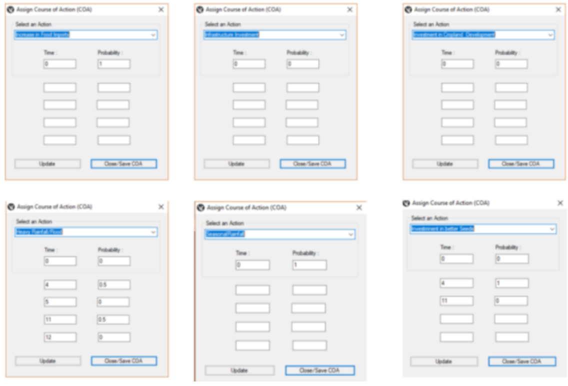


Fig. 7: Evaluation Scenario

Table 1 contains the results from running the Gambella model on the above scenario over a 12-month prediction period. What is shown is not only the seasonal variation, but the way in which the model is responding to the different weather conditions at different times of the year (i.e., heavy rainfall only matters if it disrupts the sowing or harvest).

Table 1: Runtime results for Gambella demonstration model.

Month	p(Crop Yield Increase)	p(Crop Production Increase)	[(Adequate Urban Food)	p(Adequate Rural Food)
0	0.01	0.12	0.55	0.16
1	0.01	0.12	0.55	0.16
2	0.01	0.12	0.55	0.16
3	0.01	0.12	0.55	0.16
4	0.9	0.4	0.61	0.41
5	0.9	0.78	0.69	0.75
6	0.9	0.78	0.69	0.75
7	0.9	0.78	0.69	0.75
8	0.9	0.78	0.69	0.75
9	0.9	0.78	0.69	0.75
10	0.9	0.78	0.69	0.75
11	0.01	0.12	0.55	0.16
12	0.01	0.12	0.55	0.16

Multiple scenarios were executed (a) covering a 12-month period and (b) a ten-year period. The ten-year period was used to analyze the impact of long-term investments in land reclamation, population changes and policy changes such as the one in which refugees were allowed to leave the camps and be employed. Key drivers in the Gambella case (and in Ethiopia in general) are the population increase, urbanization, the need to put more cropland into agricultural production, improvement in the productivity of the agricultural sector, and investment in food processing, transportation and markets to serve the urban population.

SOUTH CHINA SEA: THE SECOND THOMAS SHOAL CASE 2014

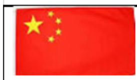
Background: The Second Thomas Shoal (2TS) is located south-east of Mischief Reef in the north-eastern part of the Spratly Islands. There are no settlements north or east of it. It is a tear-drop shaped atoll, 11 nautical miles (20 km; 13 mi) long North-South and fringed with coral reefs. The coral rim surrounds a lagoon which has depths of up to 27 meters (89 ft) and is accessible to small boats from the East.

A CNN report of April 22, 2020 stated that the Philippines has filed a diplomatic protest over China's creation of two new districts of Sansha City, the southernmost city of Hainan province, which cover features in the disputed South China Sea, including the Philippine-claimed Spratly Islands, Scarborough Shoal and Fiery Cross Reef.

Because over the years there have been many diverse crises in the Spratly Islands area, a different approach was taken in developing the Timed Influence Net (TIN) model. A generic model was created first that contained all identified actions and reactions of the three principal actors. These were determined from reviewing published reports as well as newspaper articles from the Philippines and the US reporting on the various crises. These included documents that were available from the Center for the Study of Terrorism and Responses to Terrorism at the University of Maryland (START) (Wilkenfeld and Ellis, 2021) and from the DoD Strategic Multilayer Assessments (SMA) Program. This generic Influence Net was very complex and was not operational. It was used as the basis from which specialized models were extracted to analyze specific Use Cases. The model is static (no time delays) and the strengths of the relationships are not inserted.

In this Influence Net model three Actors are considered: The Philippines (PH), the People's Republic of China (PRC), and the United States (US). Each actor has a set of available actions (See Table 2). What is interesting and challenging in is that many of these actions can be either initiating actions or responses to another actor's actions. The sequencing can be modeled using appropriate delays. For example, the Philippines may initiate the transport of building materials and the PRC then blocks access to the shoal by deploying Navy or Coast Guard assets. Conversely, the PRC may block access to the shoal by sea (through Navy or Coast Guard assets) thus forcing the Philippine Navy to resupply the Sierra Madre through air drops. This complexity is reflected in the many relationships that are represented by links in the model. However, only some of these relationships are active for any particular scenario.

Table 2: Possible Actions by the three Actors.

Actor	Actions
 Philippines (PH)	PH resupplies the Sierra Madre by Air drops
	PH resupplies the Sierra Madre by sea
	PH reinforces Sierra Madre military presence
	PH repairs the Sierra Madre
	PH brings in replacement ship
	PH brings in building materials
	PH sends message to PRC
	PH appelas to ASEAN
	PH requests US support
 China (PRC)	PRC Navy blocks access to Second Thomas Shoal (2TS)
	PRC Coast Guard blocks access to Second Thomas Shoal (2TS)
	PRC Coast Guard escort fishermen to 2TS area
	PRC endangers air rops to the Sierra Madre
 USA	US aids PH in Air drops
	US supports PH in ASEAN
	US conducts FON cruises in 2TS area

Technical Approach: Two objectives (outcomes) are considered for the two illustrative Use Cases that were analyzed: (a) The Philippines maintains military presence in the Second Thomas Shoal (2TS). (b) The PRC continues to take provocative actions.

The general technical approach consists of three steps. In this paper, only the first two steps are described. **Step 1:** Use Case development. Since there are many possible scenarios, a set of distinct Use Cases were developed. Each Use Case was expressed as a subset of the general model. This is accomplished primarily by setting the influences on the non-active links to 0 and by adding or subtracting some specialized nodes. **Step 2:** Static analysis. Consider the Use Cases developed in Step 1 and populate the model with the appropriate influence values on the active links for each scenario. Run the Static propagation algorithm to determine the marginal probabilities of the two final effects or outcomes. Conduct sensitivity analysis with respect to the initiating actions and with respect to influences. Run the SAF optimization algorithm (Haider and Levis, 2008)) to find the optimal Courses of Action. Document the results. **Step 3:** Dynamic analysis. Introduce time delays in the nodes to indicate when they become active to reflect each one of the two Use Cases. Add delays on the links to reflect times it takes for assets to execute their actions. Consider different time dependent courses of action and execute them to obtain the probability profiles of nodes of interest (i.e., p(t) vs. t). Investigate the effect of time delays in the courses of action on the probability profiles. Document the results.

Use Case 1 Narrative: Philippines resupplies Sierra Madre by sea. The Philippine Navy is attempting to resupply its base at the 2TS (the Sierra Madre) by sea. A nearby unit of the PRC Navy moves to intercept and block the resupply ship. PH appeals to ASEAN and requests US support. The US supports the PH complaint at ASEAN and directs a unit of the US Navy to conduct a Freedom of Navigation (FON) exercise near 2TS where the PRC Navy units are moving. The question that is posed is twofold: What is the probability as a result of this set of events that PH will maintain its presence in 2TS and the PRC continues to take provocative actions?

Goal in Context: Explore the effect of PRC reaction to PH action

Scope: US actions in this situation

Pre-Condition: PRC Navy is monitoring the situation at 2TS

Success End Condition: PH maintains presence in 2TS and PRC decreases provocative actions

Minimal Guarantees: Direct confrontation between US and PRC Navies is avoided

Primary Actor: The Philippines (PH)

Trigger Event: The Sierra Madre needs supplies

Main Success Scenario

Step	Entity	Action Description
1	PH	Initiates Resupply of 2TS by sea
2	PRC	Navy vessels move to block assess to 2TS
3	PH	Appeals to ASEAN
4	PH	Requests US support
5	US	Supports PH in ASEAN
6	US	Conducts FON in 2TS
7	PH	Provides supplies to 2TS

Scenario Variations

Step	Variable	Possible Variations
3	ASEAN	PH does not appeal to ASEAN
4	US Support	PH does not request US help
6	FON mission	US decides not to conduct FON mission

The model for the main success scenario of Use Case 1 is shown in Fig.8.

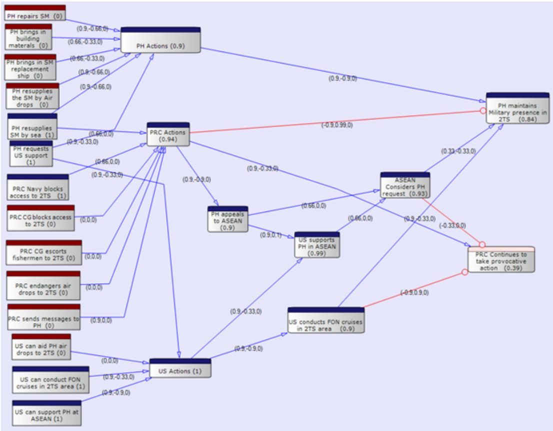


Fig. 8: Influence Net of Use Case 1 for the main success scenario. Results from Static analysis.

If the actions depicted as square nodes with dark blue stripes are taken, then the probability that the Philippines will maintain military presence in the Second Thomas Shoal (2TS) is 84% and the probability that the PRC will continue to take provocative actions drops to 39%.

Consider now the first variation: PH does not appeal to ASEAN and, consequently, the US does not support PH at ASEAN. In that case, the probability that the Philippines will maintain military presence in the Second Thomas Shoal (2TS) remains essentially the same (83%) but the probability that the PRC will continue to take provocative actions increases to 53%. In the second variation, the PH does not require support by the US and the US does not take any action. The only action taken by the Philippines is to appeal to ASEAN where the US supports the appeal. This changes drastically the results. The probability that the Philippines will maintain military presence in the Second Thomas Shoal drops to 16% but probability that the PRC will continue to take provocative actions increases to 89%.

To confirm the interpretation of these results one can conduct a sensitivity analysis of the outcomes with respect to the initiating actions. The results for the third variation are shown in Table 3. It is clear that none of the actions by PH and US with ASEAN have much impact on PRC's objectives. Conversely, sensitivity analysis of the PH objective to maintain military presence at 2TS is very much dependent on requesting US help. See Table 4.

Table 3: Sensitivity analysis of "PRC continues to take provocative actions" to active inputs.

Actions Name	Lower Probability	Upper Probability	Differenc
PH resupplies the SM by Air drops	0.889	0.889	0
PH resupplies SM by sea	0.814	0.889	0.075
PH repairs SM	0.889	0.889	0
PH brings in SM replacement ship	0.889	0.889	0
PH brings in building materals	0.889	0.889	0
PH requests US support	0.89	0.889	-0.001
PRC Navy blocks access to 2TS	0.814	0.889	0.075
PRC sends messages to PH	0.889	0.924	0.035
PRC CG blocks access to 2TS	0.889	0.889	0
PRC CG escorts fishermen to 2TS	0.889	0.889	0
PRC endangers air drops to 2TS	0.889	0.889	0
US can aid PH air drops to 2TS	0.889	0.889	0
US can conduct FON cruises in 2TS area	0.889	0.889	0
US can support PH at ASEAN	0.89	0.889	-0.001

Table 4: Sensitivity analysis of "PH maintains military presence on 2TS" to active inputs.

Actions Name	Lower Probability	Upper Probability	Difference
PH resupplies the SM by Air drops	0.602	0.657	0.056
PH resupplies SM by sea	0.216	0.602	0.386
PH repairs SM	0.602	0.657	0.056
PH brings in SM replacement ship	0.602	0.646	0.044
PH brings in building materals	0.602	0.646	0.044
PH requests US support	0.165	0.602	0.437
PRC Navy blocks access to 2TS	0.643	0.602	-0.042
PRC sends messages to PH	0.602	0.582	-0.019
PRC CG blocks access to 2TS	0.602	0.602	0
PRC CG escorts fishermen to 2TS	0.602	0.602	0
PRC endangers air drops to 2TS	0.602	0.602	0
US can aid PH air drops to 2TS	0.602	0.602	0
US can conduct FON cruises in 2TS area	0.602	0.602	0
US can support PH at ASEAN	0.599	0.602	0.003

Dynamic analysis: Introduction of sequencing of actions and delays (of the order of days) produced insignificant variations in the probability profiles of the objective nodes over time.

Use Case 2 Narrative: **The PRC takes provocative actions**. The PRC takes the initiative by sending fishermen to fish in 2TS waters. The fishing boats are escorted by the PRC Coast Guard. The Philippines react by sending a formal message to the PRC and making an appeal to ASEAN. To avoid direct confrontation with the PRC Coast Guard, the Philippines attempts to resupply the Sierra Madre at 2TS by air drops. The PRC however endangers the air drops by having helicopters from the Coast Guard interfere with the flights of the PH helicopters. PH asks for help from the US and the US supports the ASEAN appeal, conducts a FON mission and overflies the air drop zone to deter the PRC from interfering with the resupply. All parties try to avoid a direct military confrontation. Finally, the PRC fishermen depart.

Characteristic Information

Goal In Context: Explore the effect of PH reaction to PRC action

Scope: US actions in this situation

Pre-Condition: PRC Coast Guard is near 2TS

Success End Condition: PH maintains presence in 2TS and PRC decreases provocative actions

Minimal Guarantees: Direct confrontation between US and PRC Navies is avoided

Primary Actor: PRC

Trigger Event: PRC fishermen in 2TS waters

Main Success Scenario

Step	Entity	Action Description
1	PRC	Coast Guard cutters escort PRC fishermen
2	PH	Sends formal protest to PRC
3	PH	Resupplies the 2ts by Air Drops
4	PRC	Endangers air drops to 2TS
5	PH	Requests US support
6	PH	Appeals to ASEAN
7	US	Supports PH in ASEAN
8	US	Aids PH air drops to 2TS
9	US	Conducts FON missions in 2TS area
10	PRC	Fishermen complete mission and leave

Scenario Variations

Step	Variable	Possible Variations
3	PH	PH does not attempt to resupply 2TS through air drops
5	PH	PH does not request US support but US still supports PH in the ASEAN appeal but does not conduct a FON mission and does support the air drops.

The model for the main success scenario of Use Case 2 is shown in Fig. 9.

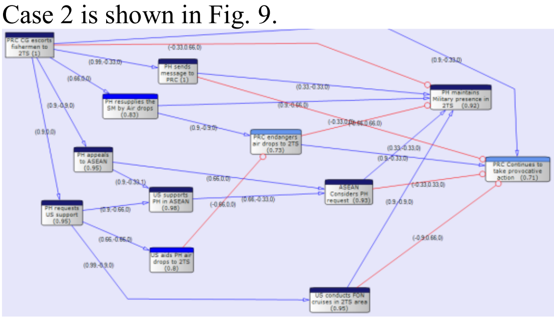


Fig. 9: Influence Net of Use Case 2 for the main success scenario. Results from Static analysis.

The influence net shows that the Philippines will send a message to PRC with probability 1, but the probability of initiating resupply by air drops is only 83%. The US supports the appeal to ASEAN with probability 98%, but the probability of aiding the air drops by sending aircraft in the area is only 80%, indicating that there is concern of an accident precipitating a crisis. The final outcome is that, as a result of all these actions, the Philippines will maintain its military presence in 2TS (at 92%) and the PRC will continue provocative actions (at 71%) since the fishermen completed their actions without major incident.

An interesting result is obtained from sensitivity analysis. There is a single initiating action: PRC CG escorts fishermen to 2TS. If this action is taken, the PRC is emboldened to continue provocative actions (probability 71%). But if this action is not taken, then the probability of continuing provocative actions drops to 42%. (Table 5)

Table 5: Sensitivity analysis of "PRC continues to take provocative actions" to "PRC CG escorting fishermen to 2TS".

PRC Continues to take provocative action

Actions Name	Lower Probability	Upper Probability	Difference
PRC CG escorts fishermen to 2TS	0.423	0.71	0.286

In the first variation the Philippines does not attempt to resupply 2TS by air drops but takes all the other actions and so does the US. The results are somewhat surprising. The probability that PH will maintain military presence in 2TS is 72% but the probability of the PRC continuing to take provocative action drops to 39%. One possible interpretation is that the fact that PH does not resupply 2TS may mean that the military presence appears to be well established and not threatened by the presence of the PRC Coast Guard and the fishermen. On the other hand, the immediate US Navy Freedom of Navigation mission has a strong deterrence effect.

The second variation is a kind of worst-case scenario. The Philippines only send a message to the PRC and appeal to ASEAN. The US supports the appeal but takes no other action since PH has not requested help. The result is clear. The PRC is emboldened by the fact that neither PH nor the US take any serious action (No FON mission, no resupply) and the probability of continuing to carry out provocative actions to make PH abandon the 2TS goes to 95%. The probability that PH will maintain its military presence drops to 7%.

Both models (each a subset of a more general causal model) shows that if PH and the US do not take strong highly visible actions such as resupplying the military presence in the 2TS and the US Navy conducting FON missions in the area, the ability of PH to maintain a military presence in 2TS becomes very problematic. An emboldened PRC can increase the pressure if it perceives that there is no serious reaction.

CONCLUSION

Causal Analysis Graphs and their implementation as a Timed Influence Net provide a useful and rapid approach to examining complex strategic situations and determining the consequences of alternative courses of action.

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