ACQUISITION PATH ANALYSIS MODELING USING THE JOINT COMPREHENSIVE PLAN OF ACTION AS A CASE STUDY

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ABSTRACT
A systems-based approach to acquisition path analysis was developed under a request by the International Atomic Energy Agency Member State Support Program. The model evaluates a given state’s Physical Model to determine the optimal inspection strategy by first applying graph theory for the determination of the technically feasible acquisition paths by the state and then applying game theory for the evaluation of inspection and proliferation strategies. To satisfy the requirements of the request, the Physical Model was constructed as a directed graph such that edges represent processes leading to the nodes, which are material forms. In previous papers presented at the INMM annual meetings and elsewhere, the model was demonstrated by using two hypothetical states as examples. In 2015, the Joint Comprehensive Plan of Action (JCPOA) was signed by Iran, the E3+3 and the European Union. Earlier this year, following the agreement’s schedule, Iran applied the Additional Protocol and modified Code 3.1 to its agreement with the International Atomic Energy Agency. This paper uses details within the JCPOA and its annexes along with open source information about the agreement to evaluate the utility of this systems-based approach to determine inspection strategies. By using the JCPOA as a data input, the model is demonstrated to be useful for acquisition path analysis. The results are critically evaluated and potential improvements to the acquisition path analysis model are detailed.

INTRODUCTION
The International Atomic Energy Agency (IAEA) has implemented the State Level Concept (SLC) in order to treat each state ‘as a whole’ rather than its previous strategies of using stricter criteria-based evaluations at each nuclear facility within a country [1]. Acquisition path analysis is defined by the IAEA as “the analysis of all plausible acquisition paths or acquisition strategies for a state to acquire nuclear material usable for the manufacture of a nuclear explosive device” and is a major step in the state evaluation process which now guides the inspection strategies for the IAEA’s Department of Safeguards [2].

Beginning in 2011, the IAEA, through the Member State Support Programme extra-budgetary contribution, requested the German Member State Support programme to assist in the development of a software implementation for acquisition path analysis. To satisfy the request by the IAEA and demonstrate a standardized method for modeling acquisition path analysis, a model employing
directed graph theory and game theory was developed. The International Safeguards Working Group of the Forschungszentrum Jülich constructed a three step approach to modeling the acquisition path analysis (Listner, Canty et al. 2012). As noted in previous papers [3-6], this acquisition path analysis (APA) modeling strategy permits the Department of Safeguards to apply the SLC’s non-discriminatory mandate to each state by establishing a systems-based approach to APA. This paper will demonstrate the model using the Joint Comprehensive Plan of Action (JCPOA) as a case study. Details within the JCPOA and its annexes, published information from the IAEA about their inspection strategy in Iran along with publicly available information about the agreement are used to evaluate the utility of this systems-based acquisition path analysis approach to determine inspection strategies. By applying the APA to the JCPOA, the model is demonstrated to be useful for acquisition path analysis. The results are evaluated, potential improvements to the acquisition path analysis model are detailed and a outlook and future studies section provides comments for future research.

JCPOA AND CHANGES TO IRAN’S NUCLEAR FUEL CYCLE

In July 2015, the Joint Comprehensive Plan of Action (JCPOA) was signed by Iran, the E3+3 and the European Union [7]. This plan of action was built upon earlier agreements and intense negotiations between the signatories. The agreement “will ensure that Iran’s nuclear programme will be exclusively peaceful” [7] by setting out the nuclear technologies, including research and design, permitted in the Republic of Iran for at least the next 10 years. The IAEA is “requested to monitor and verify the voluntary nuclear-related measures as detailed” in the JCPOA. The JCPOA contain five annexes that describe the nuclear related measures. By signing the JCPOA, Iran committed to ratifying the Additional Protocol (AP) to their Comprehensive Safeguards Agreement as well as further transparency and confidence building measures beyond the scope of the AP.

The nuclear fuel cycle in Iran has been directly impacted by the signing of the JCPOA in several ways and is detailed in the JCPOA and annexes. Heavy water production is restricted in the Arak heavy water production facility and will be monitored by the IAEA (Annex I, section C). Heavy water production is important to many natural uranium fuel reactors and was therefore a major agenda item during the negotiations. The Arak reactor (IR-40) will be re-built as a light water reactor and use low-enriched fuel to be used on research and radioisotope production. The redesign of IR-40 was a major point of contention within the talks preceding the final JCPOA agreement. With the assistance of the E3+3 and the IAEA, the Arak reactor will be redesigned (Annex I, section C). The previous Arak reactor design, using heavy water as the moderator, could produce weapons-grade plutonium but the redesign will mitigate this concern. With the new design, plutonium extraction is much more difficult due to the change in reactor design and configuration. Additionally, Iran agreed to abstain from any spent fuel reprocessing, whether as research and development tasks or for production activities. The Natanz facility will restrict enrichment to 3.67% and permit daily access to enrichment facilities by IAEA while the Fordow facility will “refrain from any uranium enrichment and uranium enrichment R&D.” The existing stores of enriched
uranium will be down-blended or used in the Tehran research reactor. The milling facilities will now have surveillance and containment strategies implemented by the IAEA.

The IAEA described the JCPOA and its activities related to it in the document “Verification and Monitoring in the Islamic Republic of Iran in light of United Nations Security Council Resolution 2231.” The Department of Safeguards estimates that annual inspection costs for these activities in Iran will cost 9.2 million Euro (with Iran’s nuclear related commitment estimated at 6.2 million and the 3 million Euro for the AP) annually [8].

MODELING THE JCPOA

The 3 step approach to acquisition path analysis in this model follows a logical sequence of:

1. Network modeling to determine the plausible acquisition paths using an adapted version of the IAEA’s Physical Model
2. Network analysis to determine the attractiveness of each of the paths determined by inputs from the first step, and finally
3. Strategic assessment of the most plausible paths using a two-person, non-cooperative game model to determine the Nash equilibra.

Step 3 requires, inter alia, the assignment of detection probabilities and the associated inspection costs to each of the edges in the network graph. A justification of the game theoretical approach and calculations are given in [9] and the assignment of detection probabilities is discussed in [4]. The second step requires the IAEA physical model to be adapted such that the edges are processes and the nodes are materials. Reorganizing the Physical Model in this way permits it to be used as a mathematical directed graph. The directed graphs use three variables as inputs to weight the attractiveness of each of the edges and include technical difficulty, proliferation time and proliferation cost [10]. As noted later in this paper, these three input parameters require expert judgment and have a large impact on the final outcome of the model. The requirement of expert judgment is critical to note since the model was designed for use by IAEA staff with in-depth understanding of the given state’s nuclear fuel cycle. The IAEA annual budget is used to determine the inspectorate activity costs for the model.
The model’s outcome relies on assumptions derived from the researchers’ point of view based on open-source information available about the IAEA budget related to the JCPOA and the JCPOA documents. Thus, the input parameters of technical difficulty, proliferation cost and proliferation time are gleaned from open source reports about the capability of each part of Iran’s fuel cycle with the JCPOA in mind. For each of the three input parameters, the analyst running the model is given the opportunity to rate each process based on a scale from 0 (very attractive) to 3 (very unattractive). For example, the diversion edge for indirect use enrichment product is weighted with a technical difficulty of 2, proliferation cost of 2 and proliferation time of 1. These ratings were given because Iran has two enrichment facilities with a high level of sophistication. Since the IAEA has access to nuclear related declarations from Iran, the parameters would necessarily be adjusted according to state provided information as well as inspection reports. Although the JCPOA details how Iran will reduce their enrichment production, the technical difficulty for enrichment is still very low. In this example, declared information gives the IAEA the possibility to accurately determine the separative work at each enrichment plant and therefore may more accurately estimate the inputs to the model. Another important piece of information in the modeling is the exact costs related to inspection activities for each part of the inspection strategy. The model was created for such input but since these activities are confidential, only estimations were possible for this study.

MODEL RESULTS AND ANALYSIS
The initial step of the APA model determines the network model by critically evaluating the fuel cycle within Iran and then weights the path edges based on user input for the proliferation cost, proliferation time and technical difficulty of each edge. The initial graph is constructed such that a clandestine edge is always present between the nodes even if the state has not declared any facilities
The network modeling, the first step in the model, was found to be useful for determining the plausible pathways for Iran given the input information. This step is easily reproducible and may be adjusted if there are changes to the fuel cycle e.g. closing of an enrichment facility or if analysts have reason to change the evaluation for the proliferation cost, proliferation time or technical difficulty. The resulting graphic in this step is useful for collaboration and acts as a valuable piece of information for knowledge management because it summarizes the acquisition paths for a given period of time. Figure 1 shows the fuel cycle used for this study. The graph analysis, the second step in the modeling, resulted in 741 possible paths (740 acquisition paths + legal behavior). Figure 2 shows the most attractive and least attractive paths based on the attractiveness of each edge in the graph. Accordingly, the most attractive strategy for Iran would be to import direct use enrichment material. In contrast, the least attractive path involves many clandestine activities. Such graph analysis stands to reason since each additional clandestine activity adds more chance for detection and more difficulty for proliferation.

![Physical Model graphics of the second stage of the APA model, network analysis.](image)

Each graph is exported to JPEG graphics which can be used during the state evaluation process and as illustrations during reporting phases. Given the large number of paths, in this case more than 700, it is clear that such a computation would be painstaking for an analyst to conduct without the assistance of an automated directed graph theory model.

The strategic assessment, step 3, was calculated for several different detection probabilities of clandestine activities and at different inspection budgets. In previous papers e.g. [6, 9] clandestine activities in states were dependent on the type of agreement held between the state and the IAEA. For example, a state with an Additional Protocol in force with the broader conclusion met should have a much higher probability of detection than a state with only a Comprehensive Safeguard Agreement in place. Figure 3 shows the clandestine detection probability, DP(cland), equal to four different values in order to illustrate the model’s sensitivity to such changes. Listner et al., in a 2013 study [6] demonstrate the model for Iran, mentioned in the paper as ‘State B’. The 2013 study...
considered Iran without signing the AP and therefore established the detection probability of clandestine to be low (20%). Determining the detection probability is an on-going research topic so the values for 70% and 80% are provided here to simply show changes in the model when clandestine detection probabilities change. With the information from steps 1 and 2, it is then possible to calculate an inspectorate strategy which leads to a Nash equilibrium in which the state’s strategy is legal behavior. Nash equilibrium is interpreted as being one hundred percent effective. The results in Figure 3 show the inspector’s budget requirements in order to meet this definition of full effectiveness or deterrence from illegal behavior. The model allows iteration through different values of the inspectorate’s overall budget. Each value will lead to a possibly different Nash equilibrium for inspectorate and state. If the state’s equilibrium strategy is illegal (i.e. if it makes use of an acquisition path) then the effectiveness is essentially determined by the associated overall detection probability at a given inspection cost. If the budget is sufficient to induce legal behavior at equilibrium, the effectiveness is assured. The graph shows the effectiveness plotted as a function of inspection budget for different values of clandestine detection probabilities.

Figure 3: Inspectorate strategy modeled iteratively with increased inspection budget. Each line represents the model output if the detection probability (DP) for clandestine activities is set to 90%, 80%, 70% or 20% respectively.

While iteration through different budgets shown in Figure 3 might be valuable for research purposes, State Evaluation Groups (SEG) at the IAEA would most likely input the budget for
annual inspections in order to determine the best strategy for the acquisition path analysis and subsequent state-level approach to the implementations of safeguards and omit the iteration.

The strategic acquisition path analysis approach presented here using the JCPOA information as a case study demonstrates the flexibility and robustness of the model. The model is constructed in three modules which may be used in succession to form an acquisition path analysis. By using proliferation time, proliferation cost and technical difficulty of each edge in the network, the model may be uniquely adjusted to each state’s nuclear fuel cycle. The detection probabilities sensitively influence the model predictions and in particular the inspectorate strategy. The detection probabilities may be altered for the types of agreements between the state and inspectorate or based on state specific factors.

OUTLOOK AND FUTURE STUDIES
Acquisition path analysis must consider the state as a whole with all existing facilities. Therefore, the initial assessment of the facilities in a given state needs to be streamlined and a standardized methodology for assessment should be designed. Such an assessment would provide consistent input parameters for the technical difficulty, proliferation time and proliferation costs associated with each stage of the nuclear fuel cycle. When the Department of Safeguard’s SEGs conducts their initial evaluation or subsequent review, they should be able to easily access the assessment performed by previous SEGs. Currently, each SEG must document their APA results in the same format, but this does not address the myriad ways that the APA can be performed. A list of all the facilities in the country needs to be associated with the NFC related activities which are used for this model.

The timeliness aspect is implicit in the model since it is given for the annual budget and in each edge of the network analysis as proliferation time. For example, in a MOX facility if the timeliness goal for detection of diversion of one SQ of direct use material is two weeks, then the model assumes that, within the allotted budget, inspection frequencies are chosen accordingly. The technical cost and technical difficulty are also very important factors to consider during acquisition path analysis. The model presented here can isolate proliferation time for weighting path edges. Such flexibility, while valuable for analysis, comes with the caveat that each parameter must be well understood and critically considered during the acquisition path analysis.

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1 Annex I, Section L specifically mentions Modified code 3.1, which directs the state to declare information on facilities and nuclear materials outside facilities.
REFERENCES


