Modeling Material Diversion with the Cyclus Nuclear Fuel Cycle Simulator

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Abstract

Already the dominant source of clean energy, nuclear power is growing at a rapid pace. While beneficial to a world confronting climate change, the nuclear security and non-proliferation impacts of expanding nuclear power will become more consequential. As a result, it is imperative to develop credible methods to verify compliance with treaties that control fissile material production, such as the Non-Proliferation Treaty or a potential Fissile Material Cutoff Treaty. As part of the Consortium for Verification Technology, the Cyclus fuel cycle simulator is being used to model current and next-generation nuclear fuel cycles to inform treaty verification. Cyclus is an agent-based, systems-level simulator that tracks discrete material flow through the entire fuel cycle, from mining through burnup in reactors to a repository, or alternatively through one or more iterations of reprocessing. Cyclus includes social-behavior models of individual actors, facilitating the study of clandestine material diversion from declared fuel cycles. Cyclus also features a region/institution/facility hierarchy that can incorporate the effects of tariffs and sanctions in regional or global contexts. This paper presents initial Cyclus simulations of highly enriched uranium diversion from a declared once-through fuel cycle. Material flow signals are analyzed using anomaly detection techniques to identify diversion.

1 Introduction

In the 70 years since nuclear bombs were dropped on Hiroshima and Nagasaki, the knowledge and technology required to make these weapons has proliferated around the globe. There are now nine states that have developed their own nuclear weapons, as well as many others who have the capability to do so[1]. Moreover, this knowledge will continue to spread as climate change change further tilts the scales such that the benefits of nuclear power outweigh the risks [2]. China is already investing heavily in nuclear power, planning to triple its generating capacity from 19GWe to 58GWe by 2020 [3]. As climate change increasingly dominates discussions of national security, the perception of the risks inherent to nuclear energy is decreasing and states are embracing nuclear energy as a reliable large-scale source of carbon-neutral energy. However, the expansion of nuclear power increases concerns with respect to nuclear security, because the same technologies used to produce nuclear fuel can also be exploited in the pursuit of nuclear weapons.

1.1 Sensitive Parts of the Nuclear Fuel Cycle

Two nuclear technologies are of of particular concern for proliferation, uranium enrichment and plutonium reprocessing. Uranium enrichment is required for the once-through fuel cycles that are dominant around the world today, and used exclusively in the US. A once-through fuel cycle includes a source of natural uranium such as a mine, and is comprised of non-fissile 99.3% ^{238}U and only 0.7% fissile ^{235}U. Concentrations of 4-20% fissile ^{235}U are required to fuel a nuclear reactor. Enrichment facilities are used to increase the concentration of ^{235}U to the desired amount. Fuel is then burned in a nuclear reactor and the remaining material, which includes the original ^{238}U, short- and long-lived fission products, as well as $\tilde{1}$% ^{239}Pu and ^{240}Pu, is then stored as waste. The enrichment facility is notable because it can be used to increase the concentration of ^{235}U up to the 80-90% required to make a nuclear weapon[4].

Several countries are developing nuclear reactors that can accomodate recycled fuel [5]. Recycled fuel is plutonium-based rather than uranium-based, and is made by separating the components of spent uranium fuel and increasing the concentration of fissile ^{239}Pu up to 80%. This material can then be used as fuel or blended with uranium to make mixed oxide (MOX). As with the enrichment process however, separations facilities can increase the concentration beyone that required for fuel to generate weapons-grade plutonium (WGP) (up to 93% ^{239}Pu). However, fuel cycles with the capability to burn MOX fuel are advangteous because WGP from decommissioned nuclear weapons can be blended into MOX, which reduces the amount of special nuclear material (SNM) that must be safeguarded. In part due to the large stockpile of WGP in the United States (US), reprocessessing has been considered at several times over the past half-century. However, a host of political, economic, environmental and strategic concerns have cpushed the issue of reprocessing out of the technical realm and it has become a contentious political topic, and currently the US is pursuing only basic science research in this field [6, 7].

1.2 Use of Treaties to Minimize Proliferation

While it has not proven possible to prevent the spread of nuclear knowledge entirely, international treaties have been used in an attempt to control it. The Nuclear Nonproliferation Treaty (NPT), which has been signed by 190 states including the original 5 nuclear weapons states, has codified a set of rules and norms for allowing the peaceful pursuit of nuclear energy[8]. The NPT created an organization called International Atomic Energy Agency (IAEA), whose role is to verify compliance with the treaty by periodically inspecting facilities related to nuclear technology. Other notable treaties include Comprehensive Nuclear-Test-Ban Treaty (CTBT), which placed a moratorium on testing nuclear weapons, and the Strategic Arms Reduction Treaties (START) in which the US and Russia agreed on nuclear arms reductions.

These treaties seek to have done much to prevent the spread of nuclear weapons, but they do not address the production capabilities of states that already posess nuclear weapons. A potential Fissile Material Cutoff Treaty (FMCT) would place limits on the amount of SNM each weapons state could stockpile, possibly including current stockpiles in addition to future production. However, a major unresolved issue is the difficulty of developing verification techniques that can reliably confirm that nuclear material is not being produced [9]. Furthermore, making measurements of nuclear material for treaty verification is itself a sensitive issue, as even collecting the spectra of a material to confirm its authenticity can potentially expose sensitive information[10]. Particularly if non-weapons states are to contribute to treaty verification, it is important to prevent the further dissemination of nuclear knowledge.

An effective treaty verification regime must synthesize knowledge from the realmns of political science, international relations, nuclear physics and engineering, and even behavioral psychology. A nuclear fuel cycle simulator provides a framework in which to integrate these disparate components

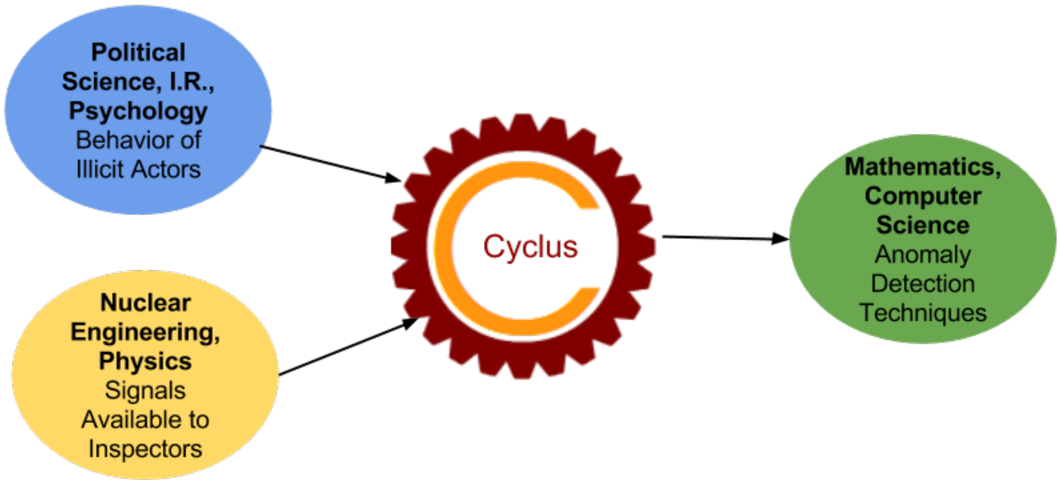

Fig. 1: The Cyclus nuclear fuel cycle simulator provides a testbed to integrate innovations in treaty verification across many disciplines.

into an effective strategy. As shown in Figure 1, a fuel cycle simulator can combine the technical specifications of innovative detection modalities, signal processing techniques, and models of the social-behavioral interactions between actors to provide insights into proposed verification approaches. At a systems level, a fuel cycle simulator can be used to frame test scenarios as responses to stimuli. That is, even if not all of the specific details are available, simulations can incorporate response behaviors to illucidate the strengths and weaknesses of various verification strategies.

2 The Cyclus Fuel Cycle Simulator

The Computational Nuclear Engineering Research Group (CNERG)[1] group at the University of Wisconsin has developed the Cyclus[2] nuclear fuel cycle simulator to model all aspects of the nuclear fuel cycle in a flexible way[11, 12, 13]. Cyclus tracks nuclear material as it flows through the entire fuel cycle in tracked time-steps. It has been designed to compare different types of technologies in the transition from current one-through cycles to alternative next-generation scenarios including potential technologies such as spent fuel recycling. Cyclus has three key features that make it suitable for non-proliferation studies: it is agent-based, it incorporates social and behavioral interaction models, and it tracks discrete materials.

2.1 Agent-Based

Cyclus is designed using an agent-based framework, meaning that each actor in a fuel cycle (such as a mine, a nuclear reactor, or other) is modeled as an independent agent[14, 15]. Each agent is self-contained and may include physics, economics, or behavioral components[16, 17, 18]. The agents interact with other agents in the fuel cycle through the dynamic resource exchange (DRE), which

[1] http://cnerg.github.io/
[2] http://fuelcycle.org/

facilitates the trading of resources and commodities[19]. At each time step, agents can choose to request resources. Resources are defined using both a quantity (1 metric ton), and a quality, such as having a compositions of 99.7% ^{238}U and 0.3% ^{235}U. The DRE then solicits bids from any facilities that are interested in offering those resources. Resources can be offered as bids even if they do not exactly match the requested material. For example, a reactor might request a commodity called "fuel", which it has defined as being uranium oxide (UOX). It may receive bids for "fuel" that are specified as UOX or MOX, having two distinct isotopic compositions. Therefore, after the bids are received, the requestor is able to apply a preference for one bid over another. Finally, once the preferences have been applied, the DRE calculates all potential trades across all agents, then executes a minimization to find the solution that does the best job of fulfilling all the requests. Once this solution is found, material is transferred across the facilities and the timestep is concluded.

2.2 Behavioral Modeling

The preference adjustment phase of the DRE allows for the introduction of interaction behaviors. Each agent can prioritize bids for resources in any way it chooses. A specific agent might have preferences based on material composition, physical proximity between facilities, or allowed and disallowed trading partners. In particular, CYCLUS has a region-institution-facility hierarchy that facilitates economic modeling[20]. Individual facilities can be managed by insistutions, such as multinational corporations, utilities, government agencies, etc. Additionally, facilities and institutions can be ascribed to unique regions, which may represent geo-political entities or economic trading partners. These features allow CYCLUS to model tariffs, sanctions and other types of economic agreements. It is possible that as a result of the preference adjustments, no trades are executed for some facilities in a given time step. Agents may also make decisions about interacting at each timestep based on their own internal logic, for example, an illicit facility may not choose to trade at every timestep in an attempt to avoid detection.

2.3 Discrete Materials

CYCLUS also tracks discrete material flow through the simulation, which means that once a material enters the simulation, its location and quality is tracked at all remaining timepoints[21]. CYCLUS includes nuclear data from Pyne,[3] a computational nuclear science tool that enables calculation of decay, transmutation, diffusion and other nuclear physics[22]. As a result, CYCLUS can model decay of materials and track all decay products from a parent isotope, facilitating studies of heat loading, radiation exposure, and other derived fuel cycle metrics[23].

Because of the modular design of CYCLUS, individual agents can be swapped in otherwise identical fuel cycles for comparison. For example, a user could compare enrichment technologies by creating two different enrichment agents, one using gaseous diffusion and the other using centrifuge technology. Then two simulations can be run where the entire fuel cycle is identical except for the two different enrichment designs, and the results can therefore be directly compared.

[3] http://pyne.io/

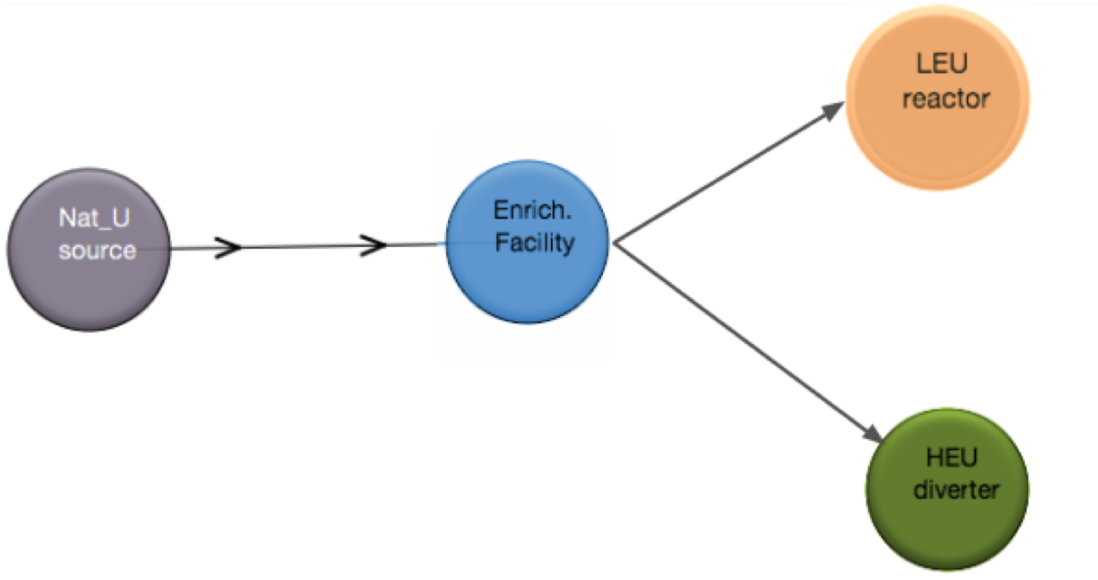

Fig. 2: Agent layout and material flow for a toy model of HEU diversion from a declared fuel cycle at the enrichment facility.

3 Diversion of Highly Enriched Uranium

As a part of the Consortium for Verification Technology (CVT)[4], Cyclus has been used to incorporate social-behavioral modeling into simulations of highly enriched uranium (HEU) diversion from a declared fuel cycle. In the simplest implementation, material is diverted at the enrichment facility. Figure 2 illustrates a toy model of this portion of the fuel cycle. A facility such as a mine supplies natural uranium (U) (0.7% ^{235}U) to an enrichment facility. The enrichment facility in turn receives requests for 4% enriched low enriched uranium (LEU) from a declared light-water reactor (ignoring the fuel fabrication facility for simplicity). The enrichment facility also receives requests for 90% enriched HEU from an undeclared actor seeking to build a nuclear weapon. Material flow, or throughput, out of each facility is is calculated once each month for a total of 100 months. This framework allows us to pose the following question: If an inspector only has access to the inventory records for LEU arriving at the declared reactor, can diversion of material be identified?

To make the scenario more realistic, three conditions are applied to the simulation:

- The enrichment facility is nominally operating near its separative work unit (SWU) limit
- The demand for LEU material has a time-varying amplitude
- The enrichment facility will always prioritize fulfilling requests for HEU

The SWU limit, a metric that incorporates power-consumption and maximum processing throughput, constrains the simulation so that if the enrichment facility chooses to produce HEU then its LEU output will necessarily decrease. As a result, if the LEU demand were constant then there would be a clear signature of diversion when HEU was produced and the simulation would be trivial. Moreover, the time-variation in LEU demand is more representative of real-life, where a single enrichment

[4] http://cvt.engin.umich.edu/

Gen. Sim.	Dur. (months)	100
	Nat. U % ^{235}U	0.7
	LEU % ^{235}U	4.0
	HEU % ^{235}U	90.0
Enrich. Fac.	SWU Capacity	180
	tails assay (%)	0.3
LEU Demand	Mean Qty (kg)	33.0
	σ (kg)	0.5
HEU Demand	Qty (kg)	0.03
	Avg Occur. (months)	1/5

Tab. 1: Simulation parameters for HEU diversion scenario.

facility provides fuel to many reactors, which may operate on different reloading schedules. It is also assumed that there will be variations in demand due to unanticipated reactor shutdowns, delays in receiving raw material, maintenance and repairs, etc. While these events are somewhat mitigated in real operations by the use of long-term contracts and material reserves, a small variation in nominal LEU demand is a reasonable assumption.

Two different behavioral models have been used for the behavior of the illicit actor who is requesting HEU. In one scenario, the illicit actor requests a small quantity of HEU at a regular interval. In the other scenario, the actor also asks for the same quantity of material in each request, but the requests do not have a constant frequency. Rather they are modeled as occurring 'randomly' with a Gaussian distribution that defines their average rate of occurrence. Table 1 lists the parameters used for the simulation presented here, where HEU is diverted using the 'random' model with an average occurrence rate of once per 5 months. Figure 3 shows the HEU demand from the illicit actor as a function of time.

Figure 4 illustrates the impact of this illicit material diversion on overall LEU production. The orange trace represents the amount of LEU material that would have been produced by the enrichment facility at each timestep if there had been no material diversion for HEU production. The blue trace represents the amount of LEU that was actually produced and shipped to the declared reactor during the diversion scenario.

If the inspector has access to only the blue time-series data, is it possible for them to identify whether or not material is being diverted from the system? A naive approach is to look at the distribution of the time-series. Figure 5 is a histogram of the declared LEU signal. The blue trace is a Gaussian fit to the declared data, while the orange trace is a Gaussian fit to the hypothetical variation in the LEU signal if there were no diversion. In this example, an inspector would need a sufficiently well-sampled dataset for the facility during a time when there was no diversion as a baseline to determine the expected type of distribution as well as a baseline for its quantitative features in order to draw conclusions about whether or not material diversion is occurring. An ongoing collaboration with researchers at the Michigan Institute for Data Science[5] seeks to apply innovative anomaly detection techniques and multi-modal data integration to these simulations to successfully identify material diversion with sparse data sets or low signal-to-noise ratios [**?**].

[5] http://midas.umich.edu/

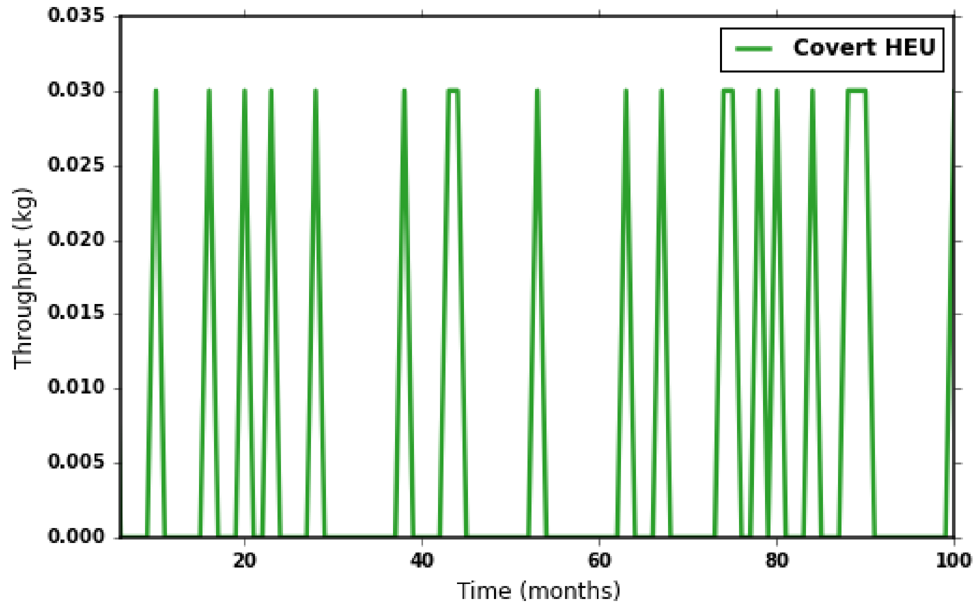

Fig. 3: An illicit actor request HEU from the enrichment facility at random timesteps with an average occurrence rate of 1 out of every 5 months

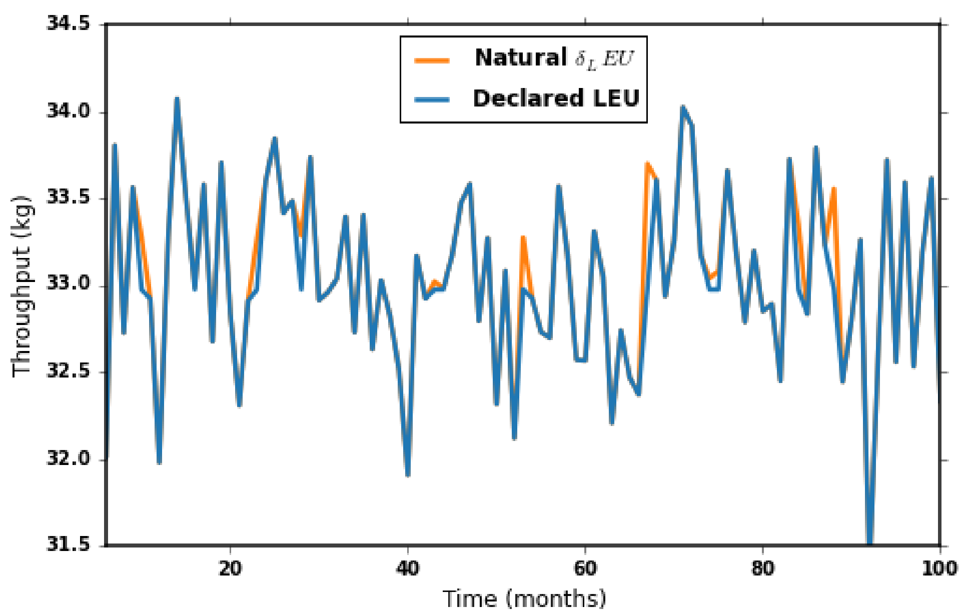

Fig. 4: Actual LEUThe natural variation of LEU demand in the absence of diversion is shown in orange, while the LEU actually produced in the diversion scenario is shown in blue. Amplitude of diverted material was chosen to displace the natural signal by 1-σ the natural variation.

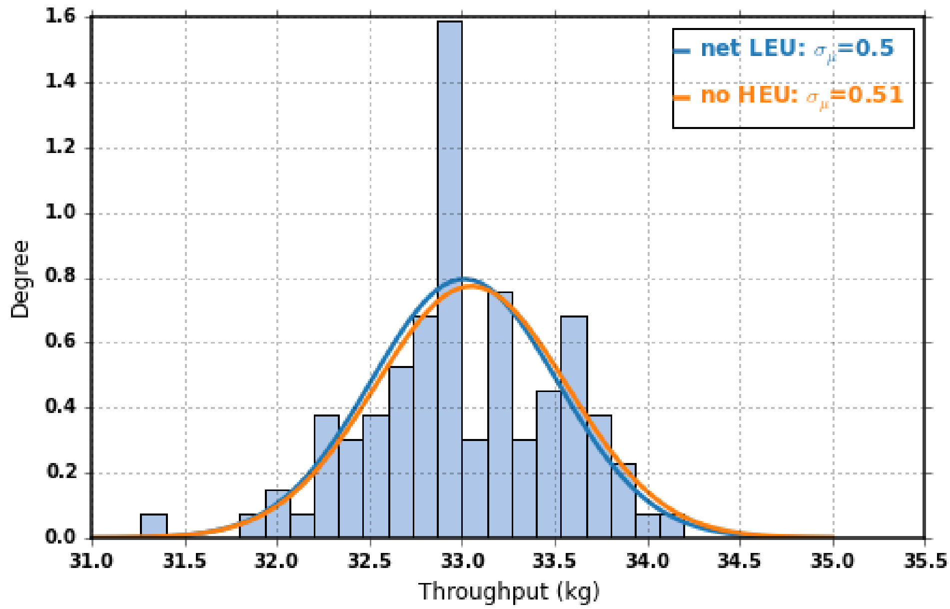

Fig. 5: The natural variation of LEU demand in the absence of diversion is shown in orange, while the LEU actually produced in the diversion scenario is shown in blue. Amplitude of diverted material was chosen to displace the natural signal by 1-σ the natural variation.

4 Discussion

The CYCLUS fuel cycle simulator can be used as a framework for combining techniques and knowledge from a variety of disciplines into a cohesive treaty verification scenario. This paper presents the diversion of HEU as a simple example of measuring facility throughput as a treaty verification strategy. The HEU simulation used a random time-base, constant amplitude model to describe the behavior of an illicit actor seeking to divert HEU from a declared enrichment facility. It applied a statistical anomaly detection technique to the data that would be available to an IAEA inspector, namely the LEU output of the enrichment facility to demonstrate that material diversion could be detected in this scenario.

This simulation is but one example of the capabilities of CYCLUS as a test bed for verification strategies. CYCLUS is also being used to model the geographical dissipation of ^{85}Kr emission from a covert separations facility processing WGP in the shadow of declared facilities. This feature can be used to assess the desired regional distribution of ^{85}Kr detectors to ensure detection of clandestine reprocessing programs. Additionally, CYCLUS has the capability to produce synthetic signals of inherent physical processes such as neutron spectra of various materials. As a result, CYCLUS simulations can provide theoretical signals to researchers developing experimental detectors in order to test sensitivity and detector response.

Moving forward, CYCLUS will be used to study more complex simulation scenarios. Probabilistic models for behavior based on risk-perception will be explored. Ongoing collaborations as part of the CVT will examine the mechanisms and limits of expanding anomaly detection algorithms to scenarios with diverse detection modalities and sparse datasets. Due to the inherently interdisciplinary nature of this work, external collaborations are sought in particular with experts in behavioral models of illicit actors. Innovative ideas on detection modalities and diversion detection techniques are also welcomed.

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