

# Integrating Acquisition Pathway Analysis Into The CYCLUS Fuel Cycle Simulator

Kathryn A. Mummah, Paul P.H. Wilson  
University of Wisconsin - Madison

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**WISCONSIN**  
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## Acquisition Pathway Analysis (APA)

Assess technically plausible steps a State could take to acquire material that could be used in a nuclear explosive device [1]

- Objective and reproducible analysis for any set of fuel cycle facilities and capabilities
- Bring experience in modeling nuclear material flows to the nonproliferation and safeguards community

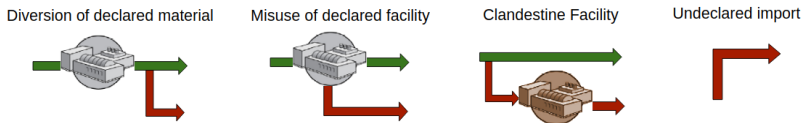
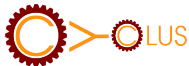


Figure: Four path steps to capture, based on [2]



- Open source modular fuel cycle simulator
- Market-based exchange of resources (commodities)
  - Nuclear materials
  - Knowledge, design information, experts
  - Economic units, money
- Discrete material tracking at the nuclide level
- Time-dependent

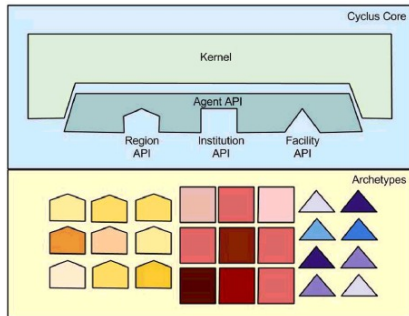
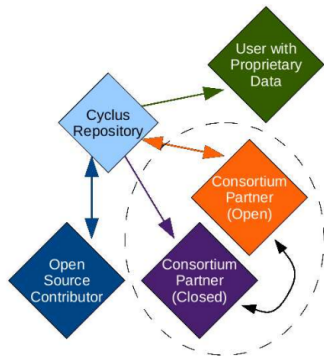


Figure: From [3]

- “Plug and play” with archetypes of varying fidelity
- CYCAMORE includes simple models of common fuel cycle facilities
- Developers have contributed higher fidelity models such as Bright-lite (Univ. of Texas), mbmore (Univ. of Wisconsin)
- Anyone can develop an archetype
  - Open source framework allows for open and closed contributors, models (archetypes), and users



**Figure:** CYCLUS architecture encourages open collaboration while allowing closed development and users with sensitive information, image from [3]

- TRAILMAP is a new Cyclus module to conduct APA

## Before running TRAILMAP

- User gathers State-specific factors and information
- Creates a CYCLUS input file with the set of existing facilities as well as technologically feasible undeclared activities and facilities

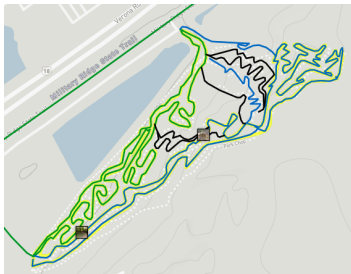


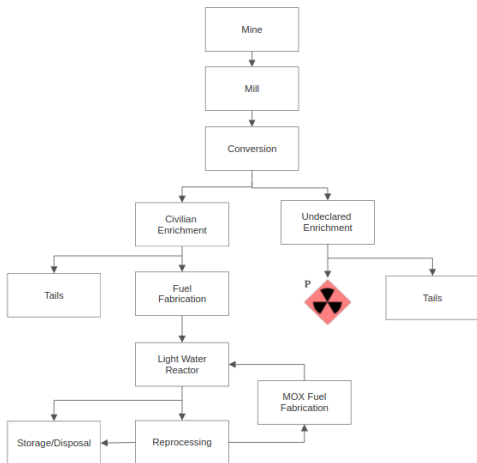
Figure: From MTB Project

- 1 Identify installed CYCLUS modules
- 2 Reads in CYCLUS input file, identifying agents and commodities
- 3 Builds a directed graph  $G = (V, E)$  of facilities and commodities using NetworkX
- 4 Depth-first search from all sources to all sinks
- 5 Visualize graph using Jupyter notebook
- 6 Filter and sort pathways using analysis tools

#### Future work

- 7 Run Cyclus for individual path or groups of paths
- 8 Further sorting and filtering of pathways
- 9 Test notional safeguards

# Example “Republic of Bundy”



- Small but well-developed fuel cycle
- Civilian declared enrichment and reprocessing
- Clandestine enrichment facility

Figure: Network flow of “ROB” fuel cycle



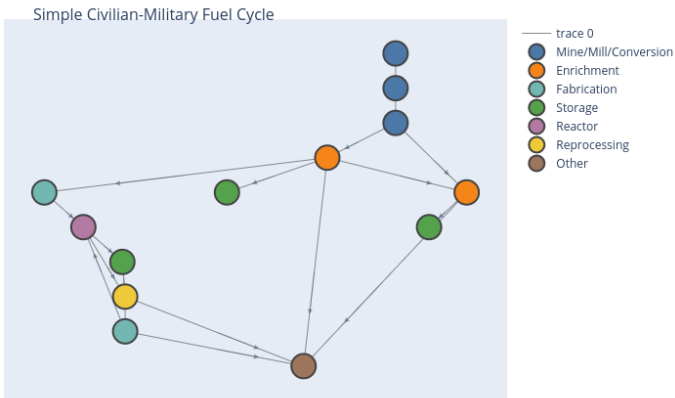
- Mine, Mill, Conversion, Declared Enrichment, Tails
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
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- Automated interactive visualization using Jupyter Notebooks and Plotly package
- Graphviz 'dot' to layout nodes
  - Good starting point, designed for trees
  - NFC are not quite trees, but almost



# Facility-specific pathways: reprocessing



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- Search over a given list of facilities
  - Pathways that contain *any* facilities in the list
  - Pathways that contain *all* facilities in the list
- Pathways that flow between a specific source and target node
  - Node disjoint paths
- Cyclical pathways
- Graph parameters
  - Graph semiconnectedness
  - Flow hierarchy

- TRAILMAP can conduct APA
- Next up: CYCLUS for individual pathways or groups of pathways to build flow network with **throughput**
  - Time to completion for paths of interest
- Capture time-dependent behavior
- Optimize visualization and interactive tools for users
- Add MBAs to existing CYCLUS facilities and build notional safeguards
  - Expand MBAs and signatures from recycle:Pyre archetype [4]
  - Expand inspector swipes from mbmore:RandomEnrich [5]

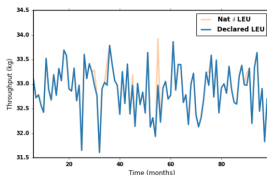






Figure: mbmore modeling of protracted diversion at an enrichment facility



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