Cyclus, an agent-based fuel cycle simulator

Brief Overview

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May 21, 2018

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Outline

Agent-based Framework

- Cyclus is agent-based, which means it's very modular
- User can develop / plug in facilities
    - User can 'design' their own fuel cycle
    - Highly customizable

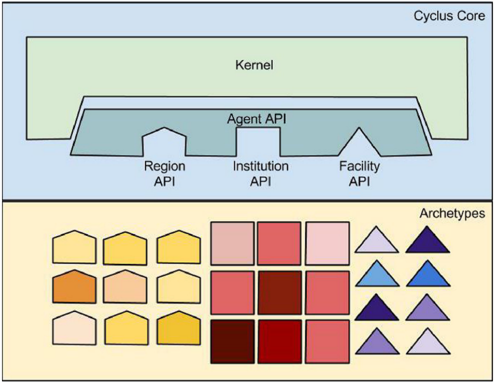
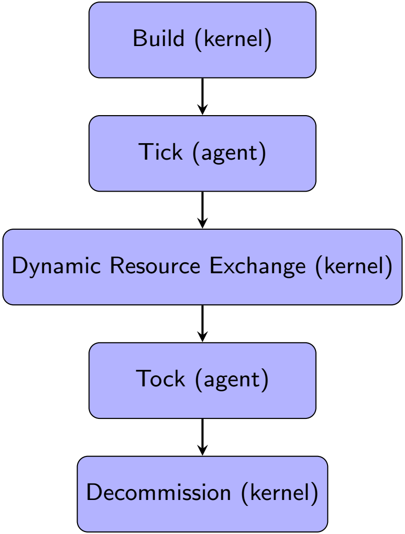


Figure 1: Modular Design of Cyclus

Timestep Execution

A simplified explanation: Each timestep:



General Info

- Written in: C++, Python
- Input file: xml, json, python
- Output file: .sqlite, .hdf5

Terminology

- Archetypes: A collection of logic and behavior which can be configured into a prototype which can then be instantiated in simulation as a agent. Archetypes are represented as C++ classes that inherit from the base cyclus::Agent class. (e.g. Reactor module, Sink module)
- Prototypes: Archetype + parameters (e.g. Reactor with input-defined `name`, `cycle time`, `assembly size`, `core size etc`)
- Agents: Every single 'entity' in play during simulation (Region, Institution, Facility)

Terminology

- Region: The group agent that is a collection of institutions (Can manage / control regions)
- Institution: Agent that manages facilities (Can deploy, decommission facilities)
- Facility: The agent that 'trades' and does calculations (Trades material and transmutes, separates)

Extensions - Archetypes

Since Cyclus is an extensible framework, anyone can develop a new archetype and plug-and-play. (Institution, region, facility otherwise.)

- Cycamore: Sink, Storage, Recipe Reactor, Fuelfab, Enrichment, Source, DeployInst, Mixer, Separations, GrowthRegion
- d3ploy: Demand-driven deployment Institution (NEUP 16-10512)
- CYBORG: Reactor depletion analysis tool using ORIGEN
- CYDER: A CYclus Disposal Environment and Repository object.
- CORRM: Continuous On-line Reprocessing Reactor Module.
- Pyre: Pyroprocessing module with non-proliferation metrics
- And more..

Extensions - Analysis / Drivers

There are other tools to help visualization / output data analysis of Cyclus.

- RICKSHAW: Automated stochastic driver for Cyclus
- Cymetric: Extracts important fuel cycle metrics
- Analysis: Collection of functions to extract metrics (e.g. natU usage, trade between two facilities, etc.)
- Cymap(?): GIS visualization tool for Cyclus
- Cyclist: GUI for Cyclus (DEPRACATED)

Installation - Binary

Better, more thorough explanations are in `fuelcycle.org`

- Windows: N/A
- MacOS: `conda install -c conda-forge cyclus cycamore`
- Linux: `conda install cyclus cycamore`

Installation - Build from Source

All source files are open-source, and available on Github.
`github.com/cyclus/cyclus` and `github.com/cycamore/cycamore` has the source files, and guides

1. Clone repository (`git clone [url]`)
2. Install dependency (see github guide README)
3. `python install.py`

Look for your error message or make a new post in the following Cyclus communities:

1. Github Issue in `github.com/cyclus/cyclus`
2. Cyclus google user group
3. Email jbae11@illinois.edu (me)

Outline

Structure

1. `Control`: Simulation Definition
2. `Archetypes`: List of available archetypes
3. `Facility`: Facility prototypes - define parameters of archetypes
4. `Region`: Region agents
5. `Institution`: Institution agents (inside Region definition)
6. `Recipe`: recipe definitions

Control

```
<control>
  <duration>2280</duration>
  <startmonth>1</startmonth>
  <startyear>1970</startyear>
  <decay>manual</decay>
</control>
```

Archetypes

```xml
<archetypes>
  <spec>
    <lib>cycamore</lib>
    <name>Source</name>
  </spec>
  <spec>
    <lib>cycamore</lib>
    <name>Sink</name>
  </spec>
  <spec>
      <lib>cycamore</lib>
      <name>Reactor</name>
  </spec>
  <spec>
    <lib>agents</lib>
    <name>NullRegion</name>
  </spec>
  <spec>
    <lib>agents</lib>
    <name>NullInst</name>
  </spec>
  <spec>
    <lib>cycamore</lib>
    <name>DeployInst</name>
  </spec>
  <spec>
    <lib>cycamore</lib>
    <name>Separations</name>
  </spec>
</archetypes>
```

Facility - Cycamore::Separations

```xml
<!-- La Hague Model from Schneider & Marignac -->
<!-- Since 1976 -->
  <facility>
    <name>LA_HAGUE</name>
    <config>
      <Separations>
         <feed_commods>   <val>cooled_french_uox_waste</val> </feed_commods>
         <feed_commod_prefs> <val>20.0</val> </feed_commod_prefs>
         <feedbuf_size>91600</feedbuf_size>
         <!-- 1100 tons/year 91.6 tons/timestep -->
         <throughput>91600</throughput>
         <leftover_commod>lahague_raffinate</leftover_commod>
         <leftoverbuf_size>91600</leftoverbuf_size>
         <streams>
          <item>
            <commod>french_uox_Pu</commod>
            <info>
              <buf_size>91600</buf_size>
              <efficiencies>
                <item>
                  <comp>Pu</comp> <eff>.998</eff>
                </item>
                </efficiencies>
            </info>
          </item>
          <item>
            <commod>uox_U</commod>
            <info>
              <buf_size>91600</buf_size>
              <efficiencies>
                <item>
                  <comp>U</comp> <eff>.998</eff>
                </item>
                </efficiencies>
            </info>
          </item>
        </streams>
      </Separations>
    </config>
  </facility>
```

Facility - Cycamore::Reactor

```xml
<facility>
  <!-- France -->
  <!-- PWR -->
  <name>FLAMANVILLE-1</name>
  <config>
    <Reactor>
      <fuel_inrecipes>  <val>uox_fuel_recipe</val>       <val>mox_fuel_recipe</val>       </fuel_inrecipes>
      <fuel_outrecipes> <val>uox_used_fuel_recipe</val>  <val>mox_used_fuel_recipe</val>  </fuel_outrecipes>
      <fuel_incommods>  <val>uox</val>                   <val>mox</val>                   </fuel_incommods>
      <fuel_outcommods> <val>french_uox_waste</val>             <val>mox_waste</val>             </fuel_outcommods>
      <fuel_prefs>      <val>1.0</val>                   <val>3.0</val>                   </fuel_prefs>
      <cycle_time>18</cycle_time>
      <refuel_time>2</refuel_time>
      <assem_size>446</assem_size>
      <n_assem_core>257</n_assem_core>
      <n_assem_batch>86</n_assem_batch>
      <power_cap>1330</power_cap>
    </Reactor>
  </config>
</facility>
```

Region

```xml
<region>
  <name>Poland</name>
  <config>
    <NullRegion/>
  </config>
  <institution>
    <name>Poland_government</name>
    <config>
      <DeployInst>

        <prototypes>
          <val>CHOCZEWO</val>
          <val>NONAME</val>
        </prototypes>

        <build_times>
          <val>708</val>
          <val>780</val>
        </build_times>

        <n_build>
          <val>1</val>
          <val>1</val>
        </n_build>

        <lifetimes>
          <val>720</val>
          <val>720</val>
        </lifetimes>

      </DeployInst>
    </config>
  </institution>
</region>
```

```xml
<recipe>
  <name>natl_u_recipe</name>
  <basis>mass</basis>
  <nuclide>
    <id>U235</id>
    <comp>0.711</comp>
  </nuclide>
  <nuclide>
    <id>U238</id>
    <comp>99.289</comp>
  </nuclide>
</recipe>
```

Benefits

1. Generate input file from database
    - Reactor specifications from database
    - Recipe from database
    - Sensitivity study using external driver (e.g. RAVEN)
2. Simple automation / modification of input file

Outline

Output

Cyclus records all transactions between `Facilities` and other metrics unique to each archetype, such as:

- Cycamore::Reactor - Power generation per timestep
- Cycamore::Enrichment - SWU per timestep

Example Workflow

This workflow was used in the paper `Synergistic Spent Nuclear Fuel Dynamics Within the European Union` (in ANS 2017 Winter meeting, journal publication pending).

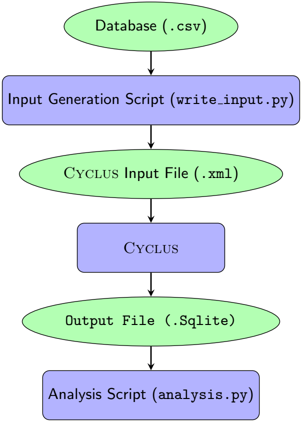


Figure 2: Green circles and blue boxes represent files and software processes, respectively, in the computational workflow.

CSV to Cyclus input file

1. Python script to parse through CSV file (reactor name, start / decom date, power output, etc)
2. Use Jinja template to construct input file (Python script fills curly brackets)

```
<facility>
   <!-- {{ country }} -->
   <!-- {{   type  }} -->
   <name>{{ reactor_name }}</name>
   <config>
     <Reactor>
       <fuel_inrecipes>  <val>uox_fuel_recipe</val>       </fuel_inrecipes>
       <fuel_outrecipes> <val>uox_used_fuel_recipe</val>  </fuel_outrecipes>
       <fuel_incommods>  <val>uox</val>                   </fuel_incommods>
       <fuel_outcommods> <val>uox_waste</val>             </fuel_outcommods>
       <fuel_prefs>      <val>1.0</val>                   </fuel_prefs>
       <cycle_time>18</cycle_time>
       <refuel_time>2</refuel_time>
       <assem_size>{{assem_size}}</assem_size>
       <n_assem_core>{{ n_assem_core}}</n_assem_core>
       <n_assem_batch>{{n_assem_batch}}</n_assem_batch>
       <power_cap>{{capacity}}</power_cap>
     </Reactor>
   </config>
 </facility>
```

Output analysis

- Python script to query and process output data
- Use Jupyter notebook to organize / visualize output

Output - regional analysis

- The user can separate analysis by regions
- Concept of children-parent: each `facility` has a parent `Institution`, and each `Institution` has a parent `Region`.

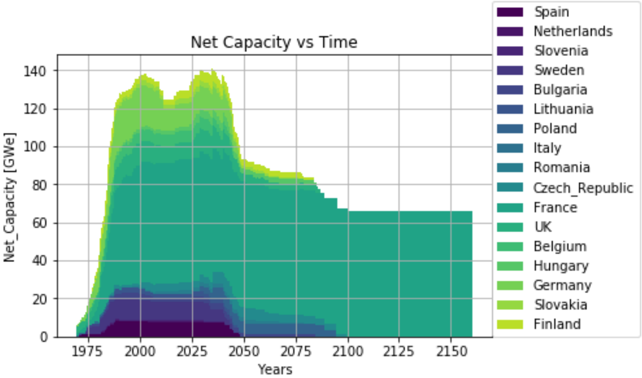


Figure 3: Power generation is separated by region.

Output - regional analysis

- The user can separate analysis by regions
- Concept of children-parent: each `facility` has a parent `Institution`, and each `Institution` has a parent `Region`.

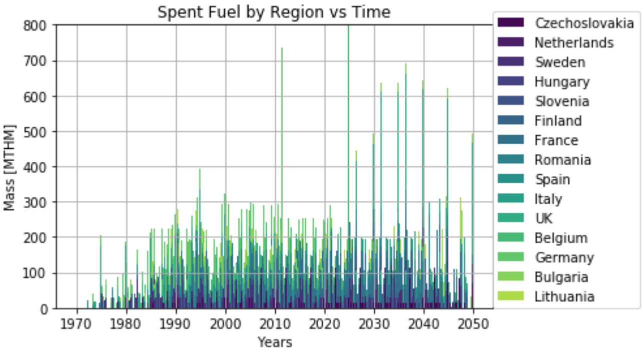


Figure 4: Waste output mass is separated by their origin region.

Output - Prototype analysis

- The user can separate analysis by prototype
- User can see how much `power` is from SFRs compared to PWRs.

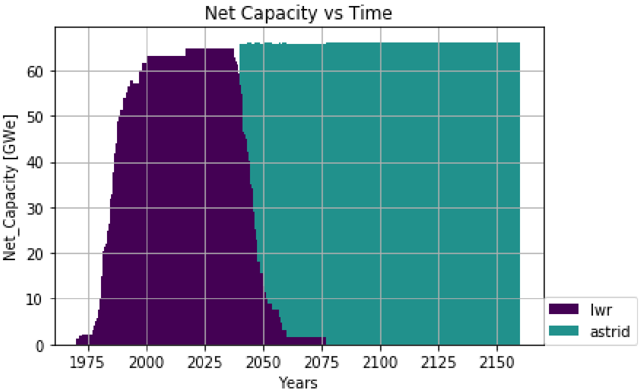


Figure 5: Power generation is separated by prototype (SFR, PWR).

Output - Prototype analysis

- The user can separate analysis by prototype
- User can see how much fuel is from which facility.

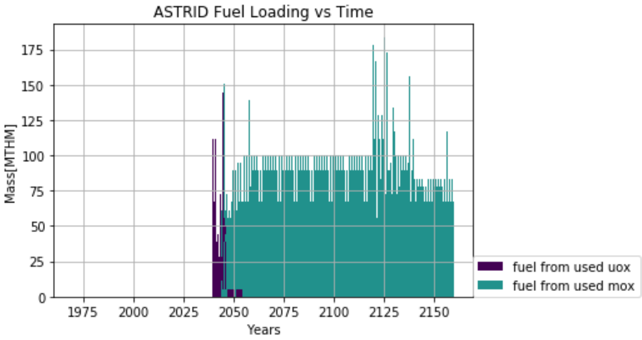


Figure 6: Fuel production is separated by production facility.

Sensitivity Study

Breeding ratio sensitivity study can be done by simply changing the SFR output fuel recipe in the input file.

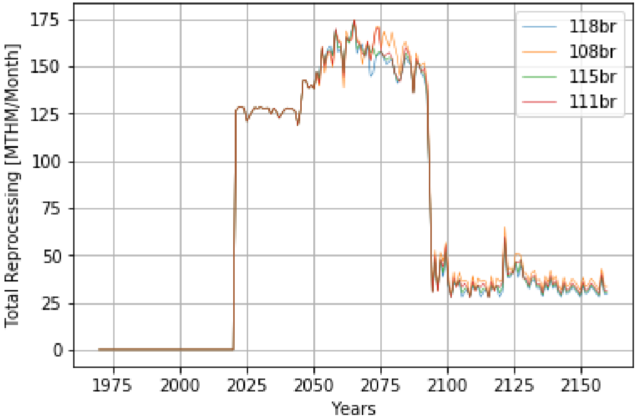


Figure 7: Breeding Ratio affect on total reprocessing.

Lifetime extension sensitivity study can be done by adding the lifetime of the pwrs and adjusting SFR deployment accordingly.

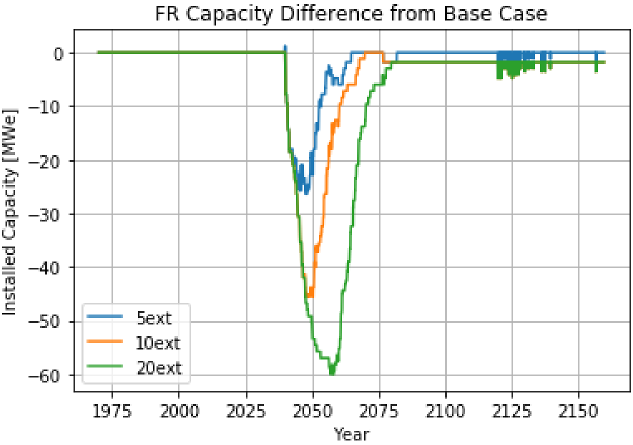


Figure 8: PWR lifetime extension affect on FR installed capacity.

References I