5th TECHNICAL WORKSHOP ON NUCLEAR FUEL CYCLE SIMULATION

APPLICATION OF SENSITIVITY ANALYSIS IN DYMOND/DAKOTA TO FUEL CYCLE TRANSITION SCENARIOS

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Virtual Meeting via Zoom

CONTENT

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  - DYMOND Model
  - Higher fidelity modeling
  - Dakota coupling
- **Example Fuel Cycle Transition Scenario**
  - Technologies deployment
  - Advanced reactor and facility deployment
  - Study parameters and responses
- **Sensitivity Analysis Results**
  - Failure space and solutions
  - Main and synergistic parameter effect

NUCLEAR FUEL CYCLE SIMULATOR

DYMOND FUEL CYCLE TRANSITION ANALYSIS CODE

- Nuclear Fuel Cycle Simulator (NFCS) for fleet deployments and transitions
- First developed at Argonne National Laboratory in 2001
- Released version 6 in 2019 having been rebuilt as a multi-paradigm model using the AnyLogic modeling platform

DYMOND 6

Dynamic Model for Nuclear Development

Version 6.0

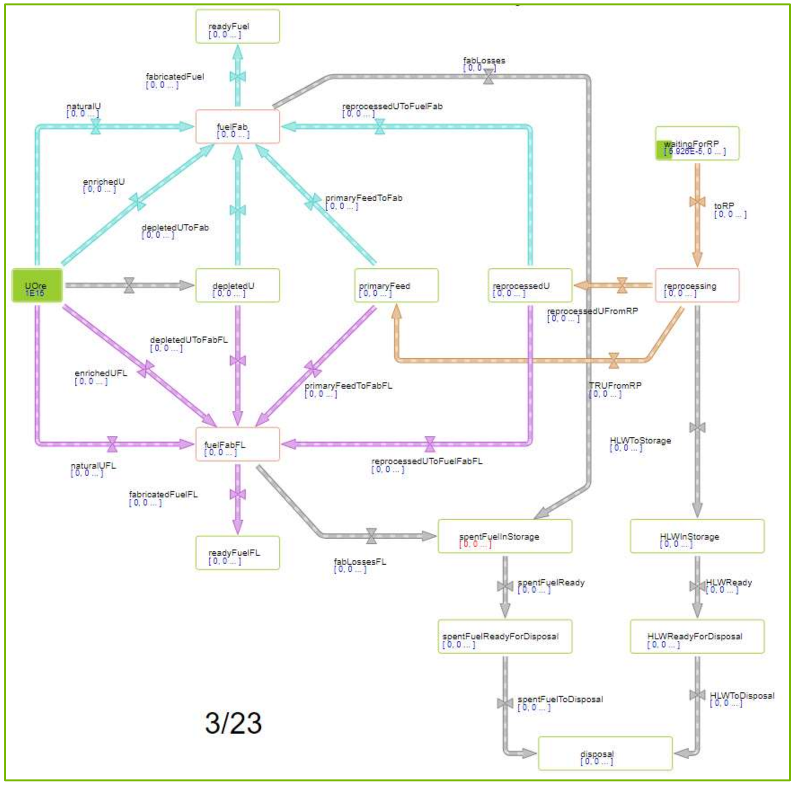
Input file selection (default: Input.xlsx)

input
File name Input.xlsx

outputDatabase
File name Output database.x...

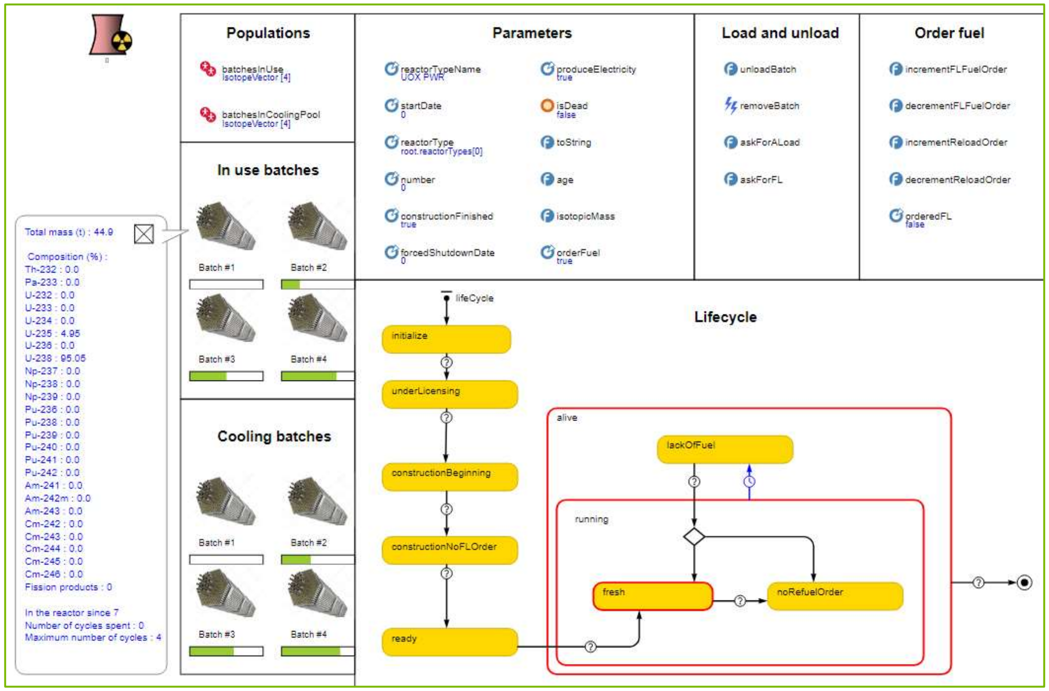
DYMOND FUEL CYCLE TRANSITION ANALYSIS CODE

- System Dynamics modeled material flows, transport, and head-end processes
- Dynamic material compositions and fuel loading
- Fuel loading can be
  - Recipe
  - Pu239 Equivalence
  - EOC criticality search
- Depletion, decay, and criticality search performed using ORIGEN



DYMOND FUEL CYCLE TRANSITION ANALYSIS CODE

- Agent-based facility models control system dynamics flow rates
- Discrete event-based facility lifecycle and batched material movements
- 25 Nuclides explicitly tracked in material agents with compositions updated by event



reactorTypeName
UOX PWR

startDate
0

reactorType
root.reactorTypes[0]

number
0

constructionFinished
true

forcedShutdownDate
0

produceElectricity
true

isDead
false

toString

age

isotopicMass

orderFuel
true

orderedFL
false

Total mass (t) : 44.9

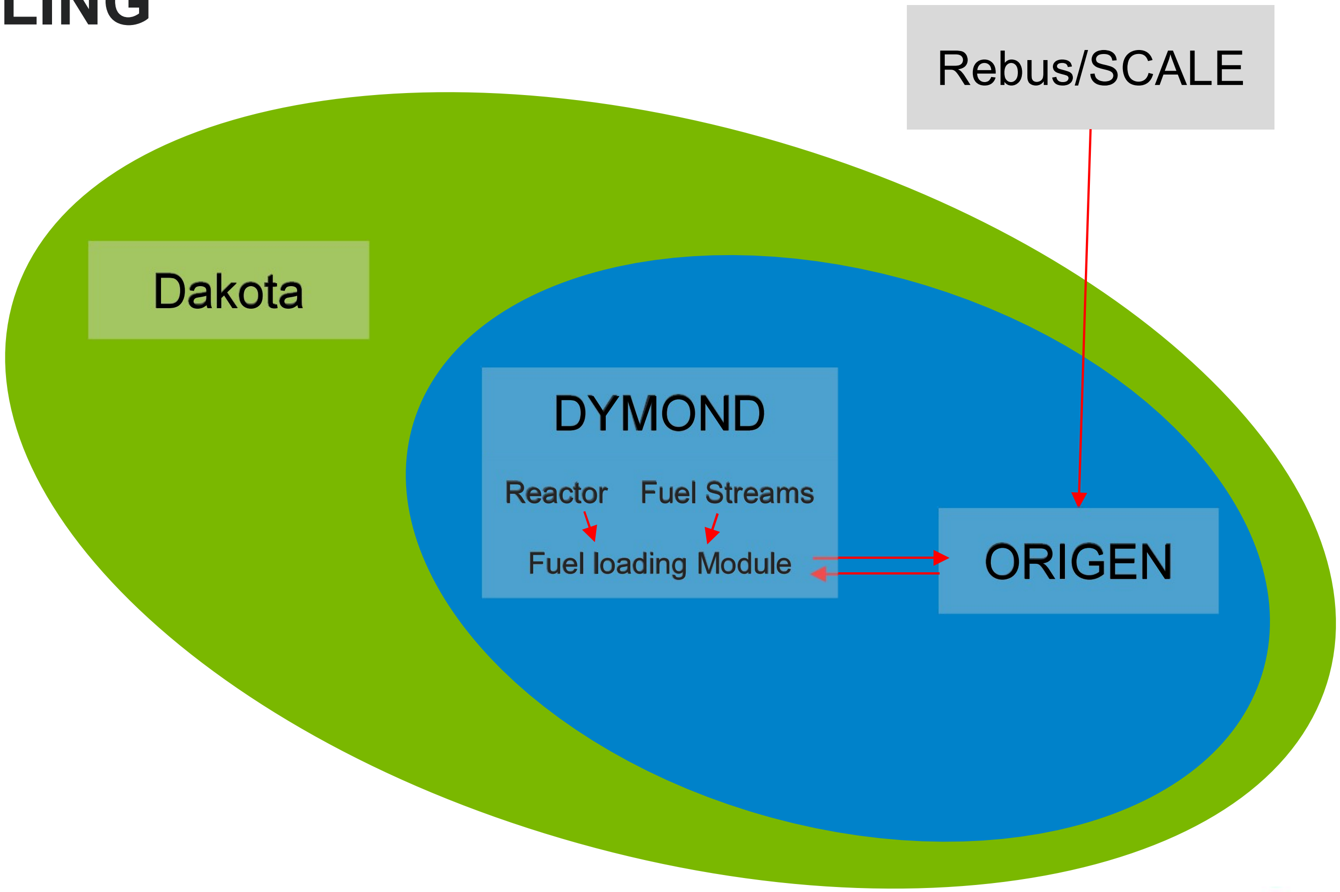
Composition (%) :
Th-232 : 0.0
Pa-233 : 0.0
U-232 : 0.0
U-233 : 0.0
U-234 : 0.0
U-235 : 4.95
U-236 : 0.0
U-238 : 95.05
Np-237 : 0.0
Np-238 : 0.0
Np-239 : 0.0
Pu-236 : 0.0
Pu-238 : 0.0
Pu-239 : 0.0
Pu-240 : 0.0
Pu-241 : 0.0
Pu-242 : 0.0
Am-241 : 0.0
Am-242m : 0.0
Am-243 : 0.0
Cm-242 : 0.0
Cm-243 : 0.0
Cm-244 : 0.0
Cm-245 : 0.0
Cm-246 : 0.0
Fission products : 0

In the reactor since 7
Number of cycles spent : 0
Maximum number of cycles : 4

DAKOTA COUPLING

Multiple layers of coupling

- Higher fidelity physics
- Dynamic fuel loading
- Sensitivity Analysis and Uncertainty Quantification
- Scenario optimization



EXAMPLE TRANSITION SCENARIO

ADVANCED REACTOR PARTIAL TRANSITION

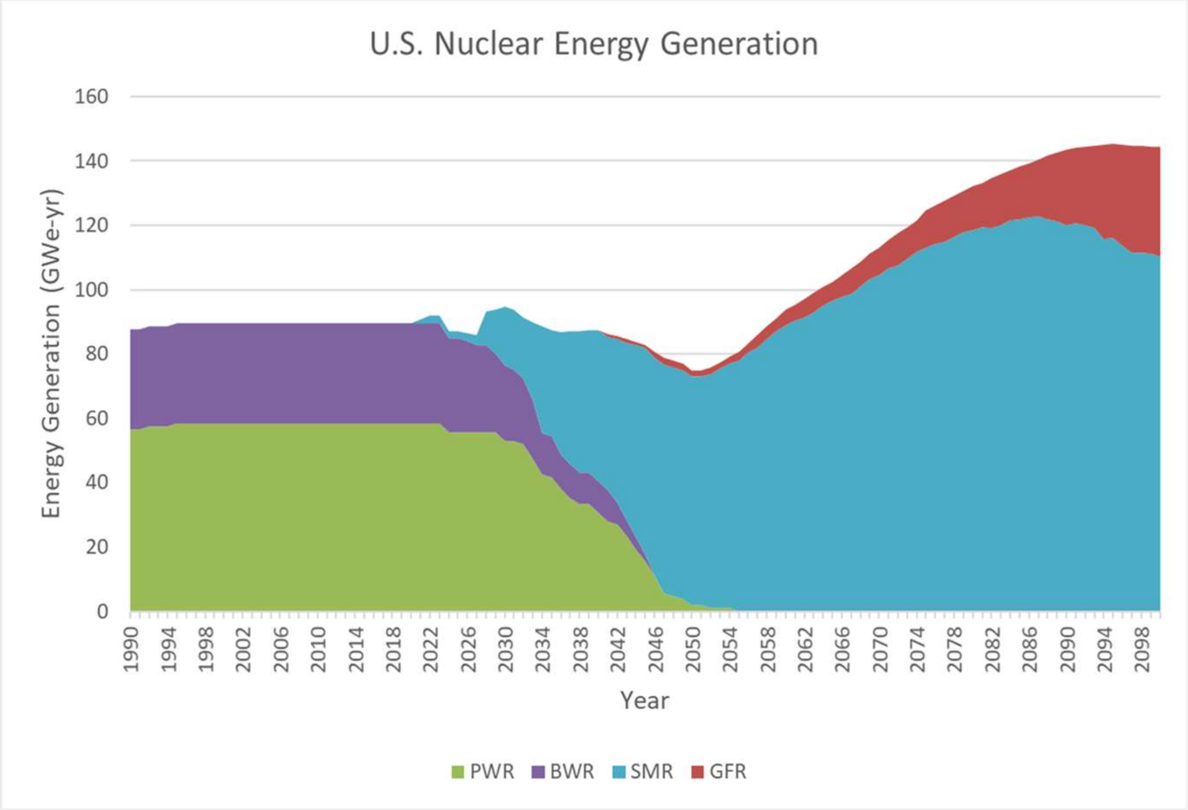
- Hypothetical transition of US nuclear fleet from legacy LWR to ALWR and Gas-cooled Fast Reactor (GFR) with unlimited recycle and 60-year lifetime
- ALWR is a small modular thermal reactor
  - 300 MWe capacity Pressurized Water-Cooled Reactor
  - LEU UOX fuel
- GFR is an advanced fast reactor operating in an actinide burning regime
  - 1100 MWe capacity
  - Accepts U+TRU fuel from all sources
  - Previous analyses have examined transitions to SFRs and fast MSRs
- Aqueous reprocessing of LWR UNF and pyroprocessing of GFR UNF
- Reactors deployed to meet projected nuclear energy demand with minimal excess capacity

BASE SCENARIO

Reactor and Facility Deployment

Transition Timeline

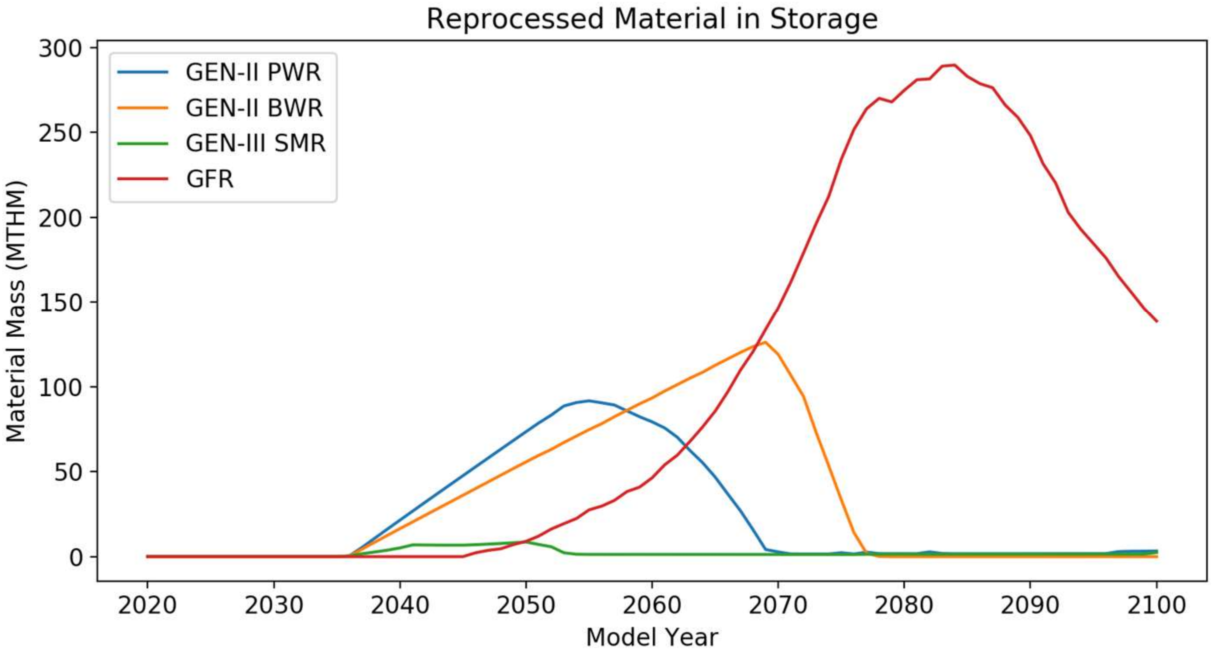
- 2020 start storing UNF for reprocessing
- 2035 start reprocessing with 1500 MTHM/year combined capacity
- 2040 first GFR deployed
- Linearly increasing GFR deployment to 40% new build capacity in 2100



BASE SCENARIO

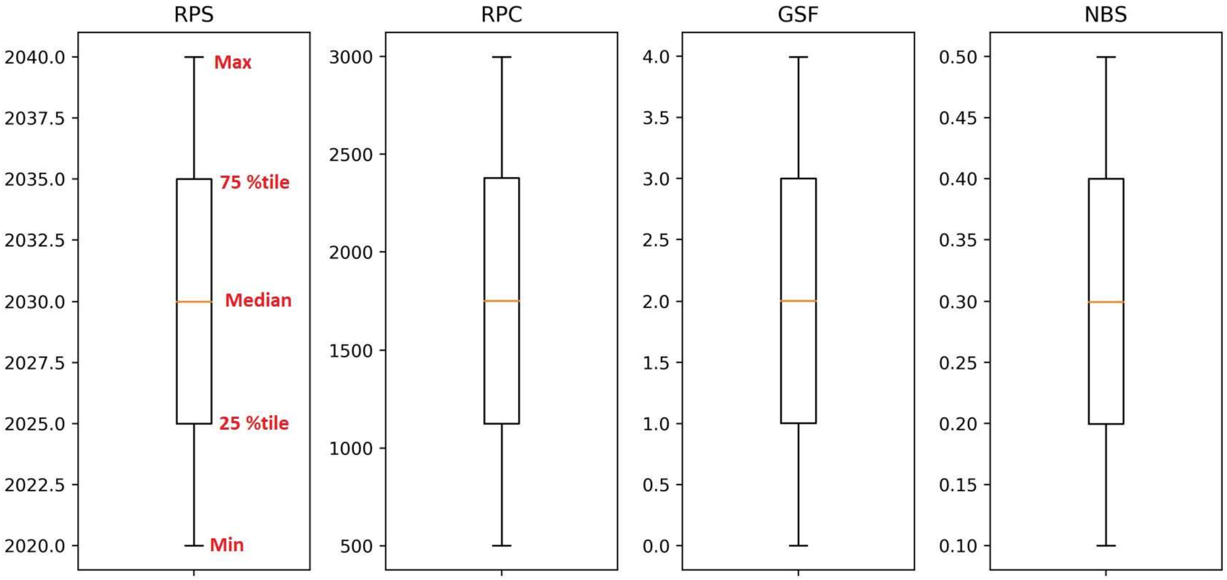
UNF utilization

- GFR fuel fabrication priority
  1. SMR
  2. Legacy PWR
  3. Legacy BWR
  4. GFR
- Bulk batch reprocessing and fuel fabrication
- Maximum stock of reprocessed material is 289.7 tonnes in 2084



SENSITIVITY ANALYSIS STUDY

- Parameters (2400 samples)
  - Start date of reprocessing facilities (RPS)
  - Capacity of reprocessing facilities (RPC)
  - Scaling of growth in demand for nuclear energy (GSF)
  - Share of new build capacity at end-of-simulation (NBS)



SENSITIVITY ANALYSIS STUDY

- Responses (normalized to total energy produced)
  - Natural uranium required
    - Measured as change in initial resource stock
  - Maximum enrichment capacity required
    - Measured as the combined annual Tonne-SWU to produce LEU for PWRs, BWRs, and SMRs
  - Mass of waste disposed
    - Measured as the total mass of UNF and HLW that has made it to interim and final waste storage by the end of the simulation
  - Total fuel cycle costs over the course of the transition
    - Measured using 20 separate fuel cycle factors and scaled to 2020$ based on the 2017 cost basis report[1]

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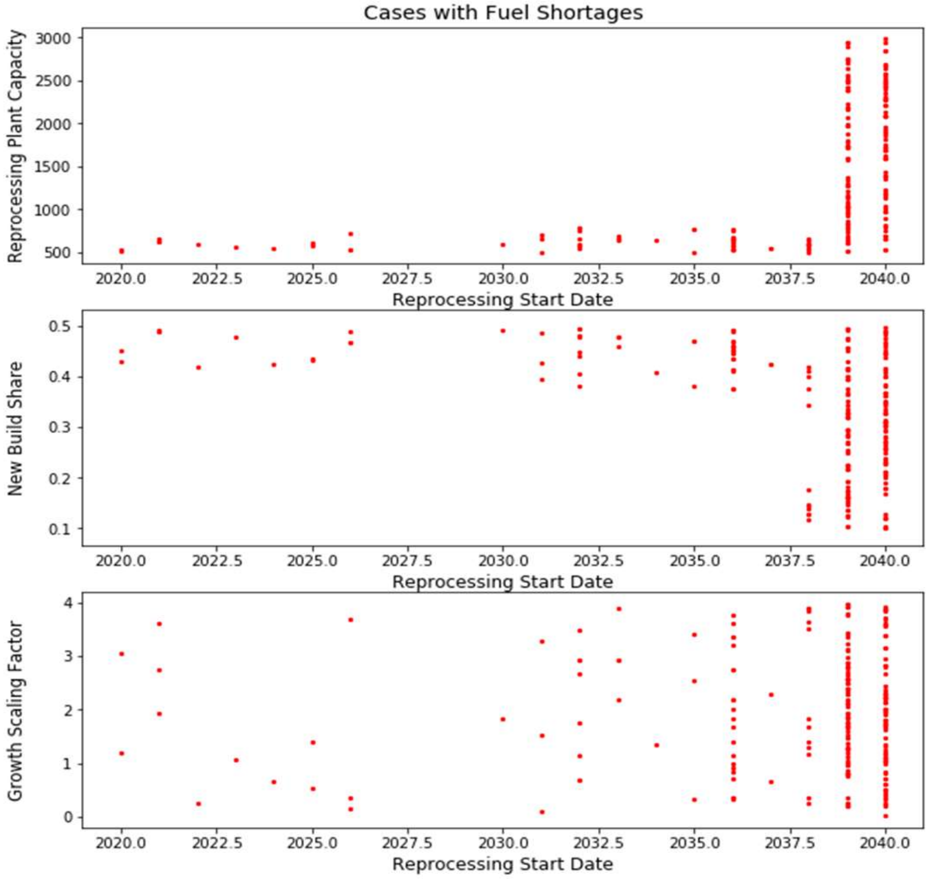
[1] U.S. Department of Energy. (2017). “Advanced Fuel Cycle Cost Basis - 2017 Edition”. NTRD-FCO-2017-000265

RESULTS

FAILURE SPACE

- Failure defined as any scenario in which there is fuel shortage.
- There is a single parameter (RPS) defined edge of the failure space.
- RPC and NBS together define a multi-parameter curved edge.



SOBOL' INDICES

- Provides two measures of the contribution of parameters to observed response variance based on
  - Main effect (S_i) is the fraction of total variance that can be contributed solely to that parameter
  - Total effect (S_{TOT}) measures the main effect and all synergistic effects the parameters has with other parameters on the response.

- Calculated using three methods of failure removal
  - Two surrogate models – Gaussian Process and Quadratic Regression
  - Parameter space reduction

SOBOL' INDICES

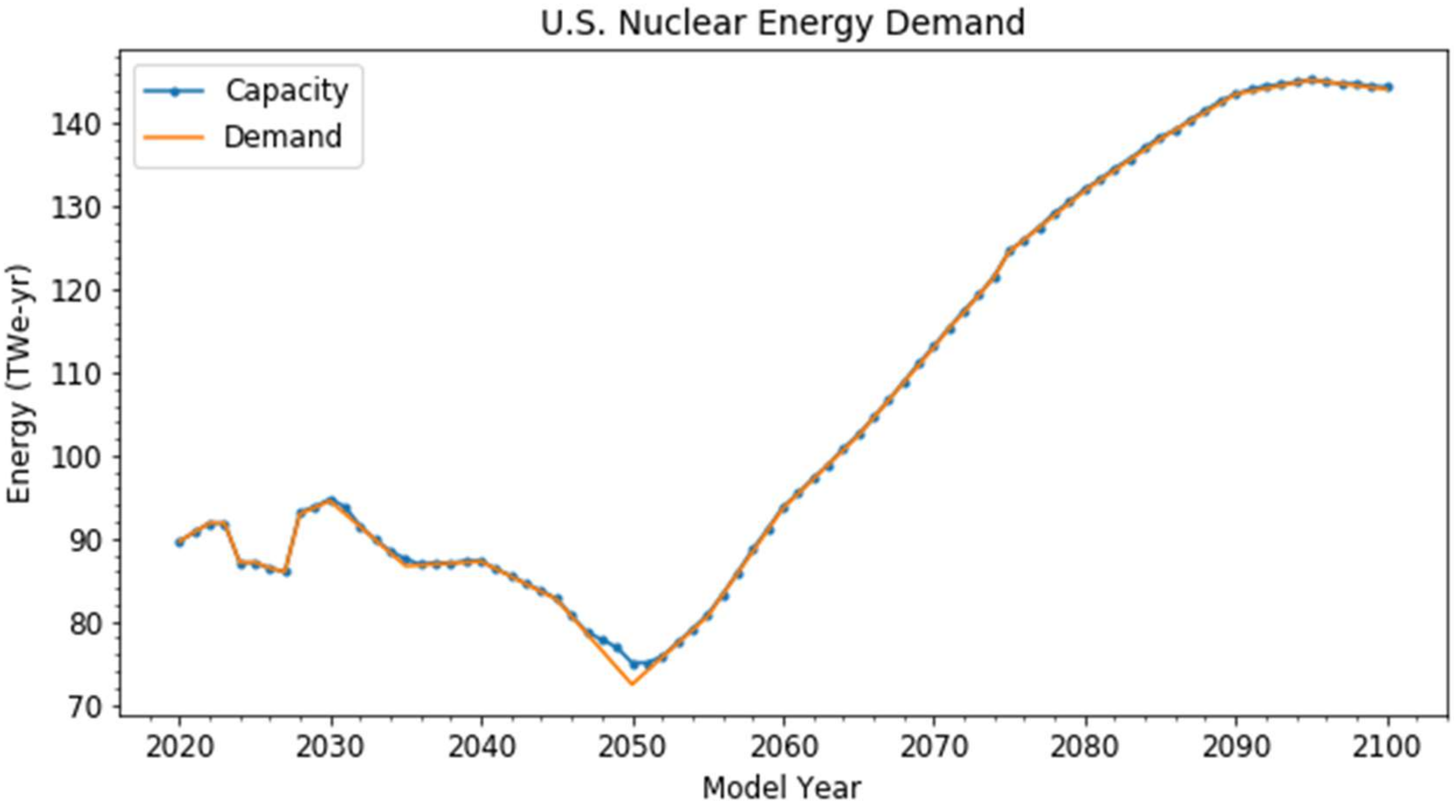
		Gaussian Proccess		Quadratic Regression		Reduced Parameter Space	
Response Metric	**Parameter**	**S_i – Main Effect**	**S_{TOT} – Total Effect**	**S_i – Main Effect**	**S_{TOT} – Total Effect**	**S_i – Main Effect**	**S_{TOT} – Total Effect**
Natural Uranium Consumed	Reprocessing Capacity (RPC)	0	0.001	0.001	0	0	0
	Demand Growth (GSF)	-0.001	0.006	0.001	0.004	0.041	0.019
	AR New Build Share (NBS)	0.968	0.972	0.972	0.974	0.937	0.916
	Reprocessing Start Date (RPS)	0.001	0	0	0	0	0
Maximum Tonne-SWU Required	Reprocessing Capacity	0	0.007	0	0	0	0
	Demand Growth	0.005	0.02	0.001	0.003	0.02	0.039
	AR New Build Share	0.95	0.98	0.972	0.975	0.892	0.87
	Reprocessing Start Date	0.005	0.004	0	0	0	0
Tonne Waste Disposed	Reprocessing Capacity	0.203	0.233	0.205	0.236	0.18	0.128
	Demand Growth	-0.003	0.005	0	0.002	0.024	0.013
	AR New Build Share	0.749	0.748	0.749	0.747	0.846	0.766
	Reprocessing Start Date	0.004	0.002	0.001	0.002	-0.007	0.001
Cost of Fuel Cycle	Reprocessing Capacity	0.007	0.058	0.007	0.011	0.006	0.004
	Demand Growth	0.762	0.827	0.798	0.784	0.486	0.831
	AR New Build Share	0.157	0.247	0.183	0.194	0.374	0.468
	Reprocessing Start Date	-0.008	0.013	-0.001	0.002	0.002	0.002

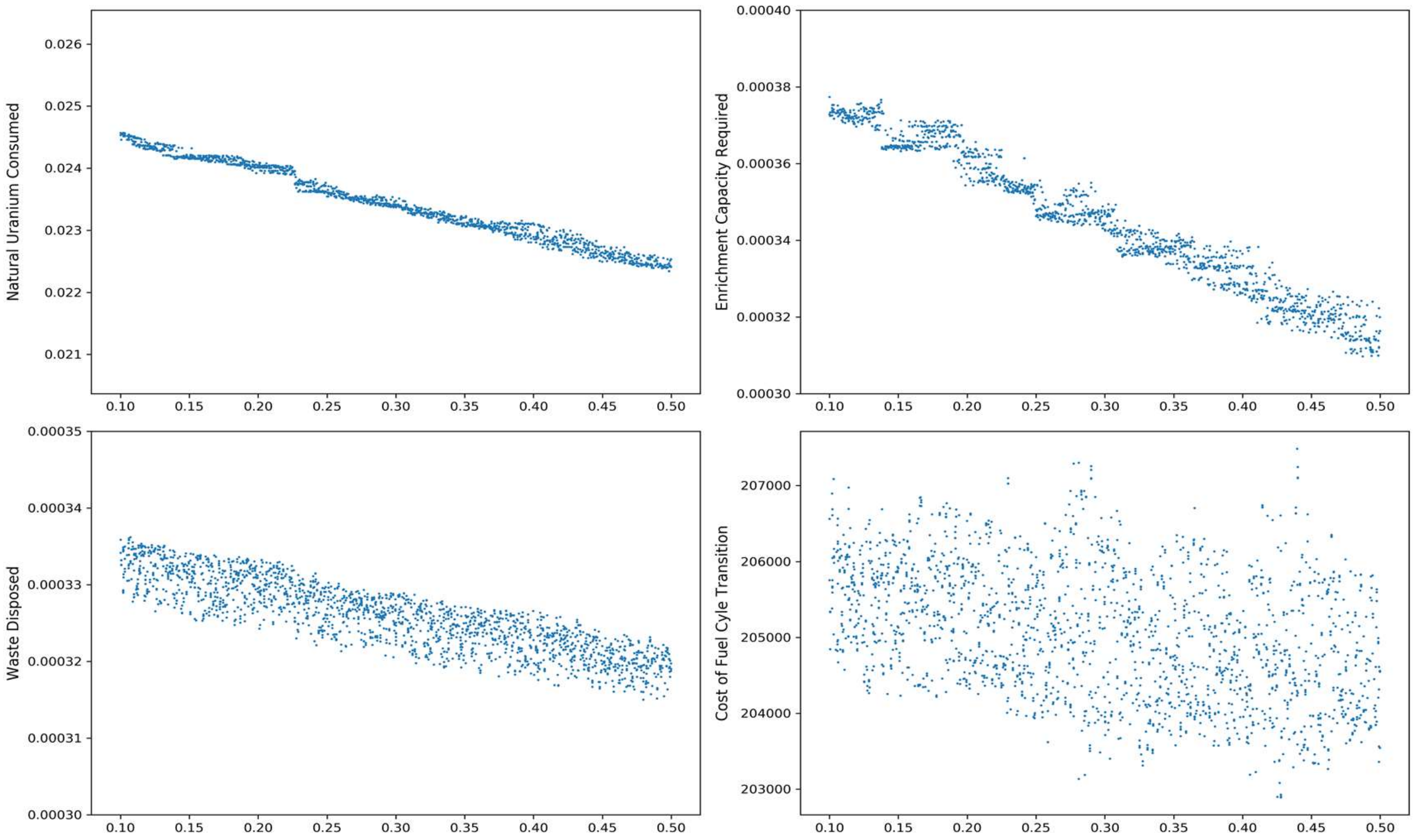
CONCLUSIONS AND FUTURE WORK

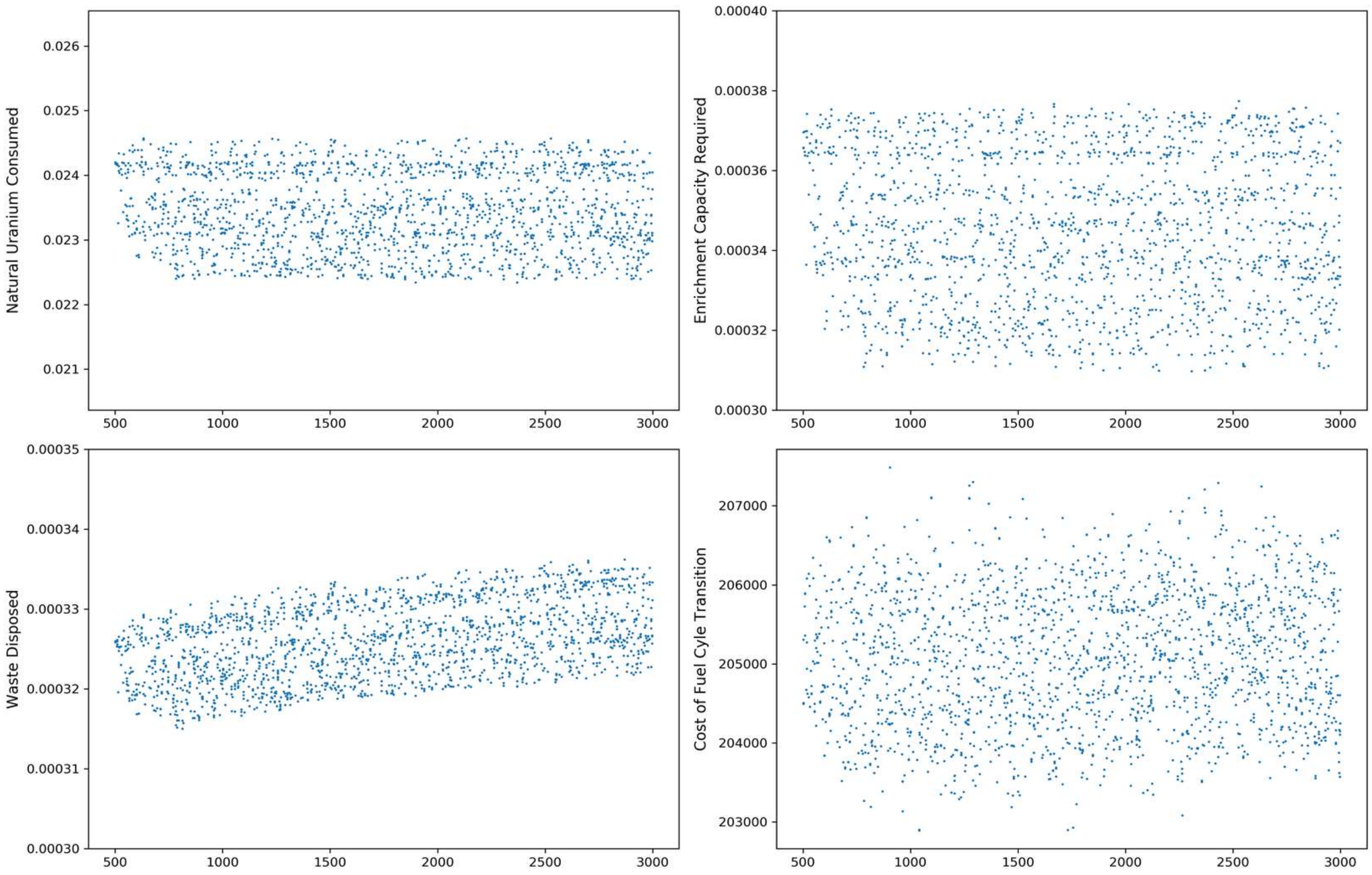
- **The multi-paradigm fuel cycle model in DYMOND 6 allows a physics driven approach that is more accurate than past versions and offers unique capabilities**
- **Successfully demonstrated the powerful new features for studying complex fuel cycle transitions enabled through DYMOND's coupling with Dakota**

- **Implementing multi-level fuel cycle transition optimization framework**
- **Improving process models for reprocessing and enrichment facilities**

APPENDIX SLIDES


U.S. Nuclear Energy Demand
Capacity
Demand
Energy (TWe-yr)
140
130
120
110
100
90
80
70
2020
2030
2040
2050
2060
2070
2080
2090
2100
Model Year


Natural Uranium Consumed
0.026
0.025
0.024
0.023
0.022
0.021
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Enrichment Capacity Required
0.00040
0.00038
0.00036
0.00034
0.00032
0.00030
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Waste Disposed
0.00035
0.00034
0.00033
0.00032
0.00031
0.00030
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Cost of Fuel Cyle Transition
207000
206000
205000
204000
203000
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50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0.00038
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0.00030
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0.00035
0.00034
0.00033
0.00032
0.00031
0.00030
Cost of Fuel Cyle Transition
207000
206000
205000
204000
203000
500
1000
1500
2000
2500
3000