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A methodology for determining the dynamic exchange of resources in nuclear fuel cycle simulation

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HIGHLIGHTS

- A novel fuel cycle simulation entity interaction mechanism is proposed.
- A framework and implementation of the mechanism is described.
- New facility outage and regional interaction scenario studies are described and analyzed.

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ABSTRACT

Simulation of the nuclear fuel cycle can be performed using a wide range of techniques and methodologies. Past efforts have focused on specific fuel cycles or reactor technologies. The CYCLUS fuel cycle simulator seeks to separate the design of the simulation from the fuel cycle or technologies of interest. In order to support this separation, a robust supply–demand communication and solution framework is required. Accordingly an agent-based supply-chain framework, the Dynamic Resource Exchange (DRE), has been designed implemented in CYCLUS. It supports the communication of complex resources, namely isotopic compositions of nuclear fuel, between fuel cycle facilities and their managers (e.g., institutions and regions). Instances of supply and demand are defined as an optimization problem and solved for each timestep. Importantly, the DRE allows each agent in the simulation to independently indicate preference for specific trading options in order to meet both physics requirements and satisfy constraints imposed by potential socio-political models. To display the variety of possible simulations that the DRE enables, example scenarios are formulated and described. Important features include key fuel-cycle facility outages, introduction of external recycled fuel sources (similar to the current mixed oxide (MOX) fuel fabrication facility in the United States), and nontrivial interactions between fuel cycles existing in different regions.

1. Introduction

The nuclear fuel cycle (NFC) is a complex, physics-dependent supply chain of uranium and thorium ore based fuels, recycled materials (such as reprocessed uranium, plutonium, and other minor actinides), and final disposal of some subset of isotopes of transmuted material. Uranium is mined, milled, and enriched to some level based on the type and fuel management scheme (e.g., a 12 or 18-month refueling schedule) of the reactor which is being fueled. Used fuel can then be stored for a period of time before either being disposed of via interment or being utilized in a advanced fuel cycle by recycling its fissile and fertile isotopes. The ability to model such a system while maintaining physical consistency due to transmutation and isotopic decay is a challenging simulation problem. Through simulation, nuclear systems can be analyzed in order to support decision-making processes addressing a variety of goals, e.g., reducing system cost, future planning of storage facilities, studying the dynamics governing system transitions, and estimating long-term system sustainability.

NFC simulation is performed by a variety of actors, including governments, national laboratories, universities, international governance organizations, and consulting agencies. Accordingly, many modeling strategies have been applied, spanning a wide range of modeling detail for both nuclear facilities and fuel in order to obtain sufficient simulation functionality (Brown et al., 2016). For instance, some simulators describe reactors by fleet (or type) and

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solve material balances for the entire fleet in aggregate (Busquim e Silva et al., 2008; Durpel et al., 2003; Yacout et al., 2006; Worrall and Gregg, 2007) while others instantiate individual (or discrete) facilities (Schneider et al., 2005). Similarly, some simulators make detailed calculations of fuel depletion due to reactor fluence (Boucher and Grouiller, 2006; Mouginot et al., 2012) whereas others use pre-tabulated values that depend (generally) on burnup values for thermal reactors and conversion ratios for fast reactors (Yacout et al., 2006).

There are, broadly, three categories of concern to the design of an NFC simulator. The first is facility deployment, i.e., how, why, and when certain facilities are instantiated in the simulation. The most common reactor deployment mechanism allows a user to define an energy growth curve and, for each type of reactor in the simulation, a percentage of that total energy demand to be met by that reactor type. It is also common for simulators to adjust deployments based on look-ahead heuristics of future material availability (Schweitzer, 2008; Durpel et al., 2009). The second design category is the fidelity with which the physical and chemical processes involved in the nuclear fuel cycle are modeled. Broadly, physical fidelity includes two processes, isotopic decay and isotopic transmutation due to fuel's residency in a reactor. To date, there is still disagreement as to the physical fidelity required to accurately capture sufficient system detail (Guerin and Kazimi, 2009). The third category concerns the communication of supply and demand between facilities, in other words, how facilities are connected in the simulation. In general, connections between facilities can either be static or dynamic and can either be fleet-based or facility-based. A static connection implies that material will always flow between two types of facilities, whereas a dynamic connection implies that a facility's input or output connection may change. Simulator design is dependent on the underlying modeling approach. For example, using system dynamics (Forrester, 1971) naturally leads to a static, fleet-based approach (Busquim e Silva et al., 2008; Durpel et al., 2003; Yacout et al., 2006), whereas developing a stand-alone, discrete event or time simulation (Law and Kelton, 1999) can lead to higher levels of modeling fidelity in areas of concern (Schneider et al., 2005; Mouginot et al., 2012; Boucher and Grouiller, 2006).

CYCLUS, a NFC simulator developed by the CNERG team at the University of Wisconsin, was designed to support different levels of model fidelity at different portions of the fuel cycle (Huff et al., 2016). By Law's definition (Law and Kelton, 1999), CYCLUS is a dynamic, discrete-event simulation that uses a fixed-increment time advance mechanism. Its design seeks to separate the design concerns of the three categories described above, supporting, for example, both fleet and individual facility models and allowing for either exogenous or endogenous facility deployment (Carlsen and Wilson, 2016). Further, one of the primary goals of CYCLUS is to separate the simulation environment from the specific fuel cycle or process being modeled. As such, the accuracy of any simulation will depend on the accuracy of the specific facility models being employed in that simulation.

However, a common infrastructure defining the method of facility connection and allowing communication between entities in the simulation is required. This infrastructure must be flexible in order to support different approaches to each of the categories of simulation design. To do so, it must allow for static simulation entities (e.g., facilities) as well as dynamic entities that enter and exit the simulation. Further, it must support the changing of relationships between those entities based on simulation state. Finally, it must allow for communication of complex resource types, e.g., isotopic fuel vectors that change with time.

This work describes a novel approach to addressing this complicated series of design problems associated with the exchange of resources in a dynamic, physics-dependent, supply-chain simulation. It combines methods of both discrete-event simulation and agent-based modeling with an optimization approach to determine the constrained transfer of resources. Inspiration for the entity communication framework was taken from the existing agent-based supply-chain modeling literature (Swaminathan et al., 1998; Julka et al., 2002; Van der Zee and Van der Vorst, 2005; Chatfield et al., 2007; Holmgren et al., 2007) which provides a natural methodological fit to the present use case. Given time-dependent supply and demand of nuclear fuel, a version of the constrained, multi-commodity transportation problem is solved to determine resource transfers within a simulation time-step.

The remainder of this paper is structured as follows. Section 2 describes in detail the communication framework, optimization problem formulation, and possible solution techniques. Section 2.5 also describes a new archetype in the Cyclus ecosystem that utilizes this framework to enable entity relationships to drive material routing decisions. Section 3 then describes a series of scenarios that display the enhanced modeling capabilities enabled by this new simulation framework. Finally, Section 4 provides concluding remarks and observations, reflecting on potential future work and use cases.

2. Methodology & implementation

Dynamic Resource Exchange (DRE) is a inter-simulation, optimization-based methodology for determining transactions between suppliers and consumers. The core solution strategy is agnostic to resource types. The DRE is designed to support fuel cycle simulation, which is highly dependent on specific resource properties (material isotopic vectors), through its agent communication framework. Because the communication framework can be specialized to any abstract resource type, the methodology and framework can be adapted to other complex supply chains.

The DRE enables the constrained transaction of complex resources between entities in a simulation given a measure of cardinal preference for each potential transactions. The full formulation of the description of supply and demand in the fuel-cycle context is denoted the Nuclear Fuel Cycle Transportation Problem (NFCTP), a variant of the classic family of transportation problems in optimization. Suppliers and consumers provide information about their supply and demand during an initial information gathering phase. Complex constraints can be supplied during this phase. Supply and demand is then translated into a resource-agnostic *exchange graph*. The graph can be solved feasibly with a heuristic or optimally by translating it into a mixed integer-linear program. Given a solution, final trades are constructed and executed. In order to provide a more concrete discussion, all descriptions of the DRE and its mechanisms assume an exchange based on nuclear materials, the particular type of resource most important to a fuel-cycle simulation context.

Section 2.1 begins by providing a short overview of the classic optimization tools on which this work is built. An outline of the DRE methodology's progression with respect to the simulation architecture is described in Section 2.2. Section 2.3 then details the interface that agents within the simulation have with the DRE in order to communicate supply and demand information. A description of the DRE's graph-based and formulation based definitions and solution techniques is provided in Section 2.4. Finally, Section 2.5 describes a new `Region` archetype in the CYCLUS ecosystem that utilizes the DRE to enable the *in situ* modeling of inter-state trade instruments, such as tariffs.

This section represents the culmination of significant previous effort (Gidden, 2013; Gidden et al., 2014; Gidden and Wilson, 2013). What follows constitutes the refinement of previous

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