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INTEGRATED MODELING OF CONFLICT AND ENERGY

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ABSTRACT

The present paper summarizes the integration of two models, an energy security model and a national stability (conflict) model. The Energy Security Model uses system dynamics to represent national interactions in global markets for oil and natural gas. The Conflict Model employs multiscale agent-based modeling to represent international, national and subnational actors that must address complex scenarios in international relations. While this is a work in progress, the models are being integrated in order to support model interaction. So, instability in a major oil producing country can restrict global oil supplies and increase prices. Similarly, a fall in oil price might weaken a nation that is heavily dependent on oil revenue for stability. This overview provides an informative description of two alternate methods used to integrate two substantively distinct models.

1 INTRODUCTION

This paper details the current status of the integration of a system dynamics energy security model (Martinez-Moyano, Macal, and Sallach 2012) and an agent-based national stability model (Ozik *et al.* 2012). Although this project is still under development, the models have been integrated to allow changes in either model to affect the other. One of the contributions of the present discussion is to detail two distinct methods that are used to integrate the models.

The paper's organization is as follows. Related work is reviewed in the second section. The third section discusses the Conflict Model. The fourth section provides an overview of the Energy Security Model. The fifth section details two different methods used to integrate the models. The sixth section provides a notional scenario. The final section offers several steps that define the direction of future work.

2 RELATED WORK

The related work for this paper comes from four research directions. The first subsection is energy security modeling. The second is international, national, and subnational conflict modeling. The third is research into general model integration infrastructures. The fourth is the specific application of model integration infrastructures to the energy security and conflict problem. Each of these research directions is reviewed in turn in the remainder of this section.

2.1 Energy Security Modeling

System dynamics modeling (Forrester 1958; Forrester 1961; Richardson and Pugh 1981; Sterman 2000) is used to represent the structure of oil production in a prototypical country in order to identify the elements that can influence energy security. System dynamics has been used to understand energy and its effects in the world since the development of the field (Forrester 1971; Meadows et al. 1972; Sterman and Richardson 1985). This work builds on the existing oil studies literature (Salant 1982), and previous work on oil modeling (Sterman and Richardson 1985; Conrad, Blankenship, and Madrid 2004), by addressing potential impacts of conflict on energy availability.

2.2 Conflict Modeling

There is a rich literature exploring international conflict with computational social science modeling tools. Examples include: a study of mobilization of social groups (Srbljinovic *et al.* 2003); a study of proxy wars for resources (Martinez-Moyano *et al.* 2012); a study of conflict in Syria (Łatek, Mussavi Rizi, and Geller 2013); and a study of conflict between groups (Alizadeh *et al.* 2014). The present project advances earlier research by integrating energy and conflict modeling as discussed further in section 2.4.

2.3 General Model Integration Infrastructure

The present analysis develops an infrastructure that is used to integrate two specific models. More generally, there have been many published model integration papers, including those introducing supporting theory (Vangheluwe, de Lara, and Mosterman 2002; North 2014), conceptual frameworks (Vangheluwe and de Lara 2003; Liang and Paredis 2003; Brown *et al.* 2005), software tools (IEEE 2010; IEEE 2012; Villa and Costanza 2000; Villa 2001; Vangheluwe and de Lara 2003; North *et al.* 2006; North *et al.* 2007), and applied case studies (Dubiel and Tsimhoni 2005; Bithell and Brasington 2009; Teose *et al.* 2011). Notwithstanding their documented successes, the published work suggests, on an empirical basis, that adequately specifying model integration strategies remains challenging (Rizzoli *et al.* 2008). This discussion advances the existing literature by presenting a case study showing two different model integration strategies.

2.4 Model Integration Applications for Energy Security and Conflict

Other than a study by Martinez-Moyano, Macal, and Sallach (2012), on which we directly build, none of the open literature we found on U.S. energy security ties together possible sources of conflict and disruptions in the world oil market. Understanding the human, social, cultural, and behavioral factors that affect stability in the region will allow us to anticipate possible events and plan for contingencies. This project provides a preliminary model that can support this type of analysis.

3 THE CONFLICT MODEL

The Conflict Model is designed to allow analysts to create a scenario reflecting an empirical situation in which interacting entities at multiple scales operate in a strategic space with moves determined by the perceived positions and strengths of the other actors. Note that the Conflict Model employed here draws upon and extends an earlier exploratory model, named the Virtual Multiscale Strategist (*vmStrat*) (Ozik, *et al.* 2012). Scenarios can range from regional international conflict to internal local or factional disputes. Each actor in the Conflict Model has a small collection of attributes, of which the most important is strength, which represents an actor's capacity for action. It can be thought of as composed of relevant resources. While there can be many varieties of strength in the empirical world, at this point, the model reduces these to a single axis. In the model, strength is represented by a single value for each actor. This value ranges continuously from 0.0 to 1.0.

In addition to strength, each actor has three orientations about each other actor. These orientations are composed of unofficial affect, official affect, and strategy coupled with their targets (whether actors, objects or symbols). These orientations can range continuously from negative 1.0 to positive 1.0. Orientations near -1.0 are considered antagonistic, while orientations near +1.0 are favorable. The three orientations contribute related but distinct influences within the current simulation situation. Unofficial affect may be said to represent an actor's experienced affect toward another actor. Official affect, conversely, is an actor's expressed affect, which may be different from its unexpressed affect. As but one example, a common situation is one in which a weak actor has strongly negative unofficial affect toward a strong actor, but does not feel free express this, and instead professes a positive official affect, thus masking its true views.

The value for strategy is a basis for interactions between two (or more) actors. A highly negative strategic value is likely to give rise to coercive moves that are designed to harm the other party, while a highly positive strategic value tends to generate supportive or beneficent action. Values for strategies that are in the region of 0.0 arise from an instrumental or pragmatic orientation. In the conflict model, official affect and strategy values determine the actions that an actor will select from available options. These two values lie on orthogonal axes, forming the affect/strategy space (or 'A/S' space).

Additionally, all actors have another set of orientations that they apply to the other actors in the simulation. These are termed 'punitive parochial altruism' values, or 'PPA' values. The PPA orientation that one actor holds toward another is a range. It can be considered to be either a minimum and maximum value pair (e.g., (-0.5, -0.3)) or a centroid and a width (e.g. center = -4.0 and width = 0.2). PPA ranges are used to specify that certain actors have special relationships with other actors that can be stated in advance of the simulation and that impact the strategy options that are available to a given actor relative to another actor.

Finally, all actors have a set of values that express their affect toward a given set of non-actor entities termed 'referents.' A referent can represent any of a wide array of important issues or concepts with which the actors might find themselves concerned. An actor's orientation toward a referent is represented, just as are the other affect values, as a value from -1.0 to 1.0.

In addition to these fundamental attributes, actors may be considered to have two additional attributes that are not stored directly but that are calculated from the fundamental attributes just described. Power is an extension of the concept of strength. In contrast to strength, it is a relative value. An actor may have a 'strength' in an abstract sense, but it only has a 'power' relative to another actor (alter), and the power it has toward one alter may be different than the power it has relative to another. Power is defined as deriving from the strength values of the other actors. Qualitatively, it is an assessment of the network of support that might be expected from the other actors when a specific actor considers a particular alter. The actor may have a low strength value, but there may be other actors who have higher strength values, and if these other actors are allies of the first, then that actor's power will be raised as well. The definition of ally is a relative one, and again requires a specific alter. If the third party's official affect toward the first actor is higher than it is toward alter, then the third party can contribute positively toward that actor's power relative to the focal alter.

The formula for calculating power is as follows:

$$P_{i,j} = \frac{\sum_{k \neq i,j}^{k} \left(O_{k,i} - O_{k,j}\right) * S_k}{n-2}$$

where $O_{a,b}$ is the official affect of a toward b, S_a is the strength of a, and n is the number of actors. The formula means that the power of i toward j is equal to the average, for all other actors k, of k's official affect toward i minus its official affect toward j, multiplied by k's strength. Using this formula, actor k can contribute highly to i's power toward j if k's strength is high or if its official affect toward i is very high compared its official affect toward k, or both. It is not necessary that k's affect toward i be positive, so long as it is higher than its affect toward *k*. It is the relative value that matters. Note that power could be implemented to include both the actor's and alter's strength values, but currently does not.

Ideational alignment is a measure of how two actors' affect values toward a set of referents are similar or different. The set of referents represents topics or concepts and is given for a specific context. Each actor has an affect toward each referent, and these also range from -1.0 to 1.0. Ideational alignment between two actors is expressed as a value from 0.0 to 1.0, where 0.0 means no alignment and 1.0 means perfect alignment. This value between two actors is calculated from prime referent values. Importantly, the calculation is based on the perspective of that actor. To do this, the calculation is weighted according to the magnitude of the values that each actor uses. For example, there might be two actors such that Actor A has an orientation of 0.1 for a given prime referent and actor B has an orientation of 0.9 toward the same referent. Actor A considers that there is not much distance between A and B. This is because it does not regard the prime referent as having a high affect value. Actor B, conversely, sees a great distance between B and A, because the prime referent in question is as vital.

The simulation proceeds in steps wherein all actors are given the opportunity to act with respect to all other actors. Conceptually, a complete turn, when one actor (i.e., the first) moves for or against another (i.e., alter), proceeds as follows:

1. A decision by an actor to reposition alter in its own A/S space (that is, to change official affect and strategy) based on unofficial affect, power, and strength;
2. A selection of a strategic move based on this repositioning;
3. Communicating this to the observer, which calculates an outcome (e.g., relative success or failure);
4. Both the actor and alter receive a benefit or cost assessed to the move in terms of strength; and
5. Alter can then immediately update its unofficial affect toward the actor based on the move made toward it.

The actual moves in this model are in steps one and five, in which the agents readjust their view of opponent positions in affect/strategy space and with respect to unofficial affect. Two forms of moves are available, continuous and discrete, with discrete moves selected from a catalog based on empirical moves and responses.

The result of such actions can be represented as the dynamic evolution of a strategy space. The positions of the actors with respect to the other actors change through time, reflecting increasing hostility and aggression or shifting patterns of alliance and cooperation.

4 ENERGY SECURITY MODEL

Energy security is becoming a strategic issue for the U.S. as conventional energy sources are depleted and energy prices show increasing volatility due to threats of market disruptions. Currently, there are no near-term energy alternatives to alleviate U.S. dependence on foreign sources of oil. Although U.S. oil imports are down in recent years, and domestic oil supplies are increasing, the best estimates suggest that it will be many years before U.S. dependence on foreign sources of energy could be eliminated. From a global perspective, estimates are that the point of peak oil—the point when the world's production of conventional crude cannot be increased—has been surpassed. Dwindling oil supplies force the U.S. into energy alternatives having strategic implications.

The main issues in energy security involve the availability of oil imports to the U.S., the unimpeded shipments of oil through transit chokepoints, the potential disruption of major pipeline networks, and lastly, the effects of disruptions or perceived possible disruptions in supply on world oil prices. Although the availability of oil imports to the U.S. from the Middle East has declined in recent years due to increasing imports from Canada, any disruption, or threat of disruption, in the availability of resources from the Middle East would increase prices and likely draw the U.S. into a potential conflict.

As previously discussed, system dynamics modeling is used (Forrester 1958; Forrester 1961; Richardson and Pugh 1981; Sterman 2000) to understand the structure of oil production in a prototypical country in order to identify the elements that can influence energy security. The model was originally created in Vensim (Ventana Systems 2015). The version discussed in this paper uses Repast Simphony (2015). In order to conceptualize oil production structure, we use subject matter expertise, publicly available data, oil studies literature (Salant 1982), and previous work on oil modeling (Sterman and Richardson 1985; Conrad, Blankenship and Madrid 2004). Here we provide a high level description of the model. More detail can be found in Martinez-Moyano, Macal, and Sallach (2012).

We model the flow of oil from crust deposits to refined products. The stock of undiscovered and uneconomic oil indicates the amount of oil that exists in the earth's crust that, through a process of discovery and/or innovation, becomes a stock of proven oil reserves which, in turn, captures the amount of oil that a country can use to generate revenue. The oil production rate takes oil from the reserves stock to the stock of intermediate oil storage that represents the immediately available oil for a given country. In this stock, we also accumulate the amount of oil that each country receives from foreign sources (i.e., oil imports). The intermediate storage of oil, consequently, acts as a buffer between supply and demand of oil in the country.

Natural gas production is represented as coming from two distinct types of reservoirs, namely non-associated and associated reservoirs. Natural gas release is a by-product of oil production. When natural gas is produced as a derivative of oil production, it is referred to as coming from an associated reservoir. Natural gas, however, can also exist in reservoirs that are not linked to oil deposits; these reservoirs are non-associated reservoirs. Most of the natural gas that comes from reservoirs is used for consumption, after the completion of an industrial process needed to dry and purify the gas, while some small fraction of it is used to maintain pressure levels in the reservoir and avoid production degradation. The natural gas used for maintaining pressure returns to the reservoir adding to the preexisting amount. In some cases, the natural gas derived from oil production is not processed or kept. It is just vented and burned as part of the oil production process.

At the core of the Conflict Model is the effect that social unrest has on energy production via crude oil, refined oil products, and natural gas. The model addresses the effect that instability in a country has on energy production capacity utilization and how changes in capacity utilization influence operations and revenue streams. In this short-term effect model, the focus is more on changes in utilization than in capacity itself. It is hypothesized that, at low levels of social unrest, the most likely change that countries will experience will be a change in utilization instead of a change in actual capacity, which may be disrupted during social unrest. However, it is not in the best interest of the government, or any opposing faction that may revolt, to permanently damage the oil production infrastructure. Disruptions to the utilization of the infrastructure seem to be a normal outcome of social instability: a way to gain negotiating leverage, and a mechanism by which production can be disrupted or halted without damaging the production infrastructure in a permanent way. Those interested in disrupting production to gain control or notoriety are often amenable to allowing the revenue generation related to oil production to continue as soon as their demands are met.

In the model, four modes of social functioning may take place, namely base line (i.e., status quo), limited disruption, institutional disruption, and anti-market state. The social stability state of the country is exogenous to this model and computed in the previously discussed Conflict Model. More specifically, in the Conflict Model, social unrest is produced endogenously by multiple factors that include affect vectors, levels of social cooperation, attitude toward current groups in power, and how the current group in power benefits the other social groups in the country. Using two aggregate constructs, social unrest and instability are the focus. Associated constructs are the level of governmental change experienced in the country and the level of social upheaval. The level of governmental change, depending on endogenous pressures, may fluctuate among four values, namely routine changes, non-routine changes, government restructuring, and state collapse. The level of social upheaval also changes endogenously in the model and may settle into one of five states, namely: no upheaval, civil protests, limited violent upheaval, intermediate violent upheaval, and widespread violent upheaval. Depending on the combination of the two aggregate constructs just described, social instability changes emerge from the Conflict Model.

5 BRIDGING THE CONFLICT AND ENERGY-SECURITY MODELS

Two different approaches have been used to integrate the Energy Security Model and the Conflict Model. This section discusses these approaches, specifically, the light and heavy integration strategies.

5.1 Light Integration

One method used to integrate the Conflict Model and the Energy Security Model is termed a 'light' integration strategy because it assumes that data will be packaged from one model and sent to the other as part of the model's standard operational time step. This 'packaging' is accomplished using in-memory Java in the existing code, but could easily rely on some intermediate serialization because only a small map of values is passed in each direction. The Conflict Model provides to the Energy Security Model values for 'upheaval' and 'instability' for each appropriate actor. The previously discussed Energy Security Model uses these values in its calculations and, in reply, provides values for current revenue, baseline revenue, and, for select countries, GDP. Of the 21 countries in the model, Iran, Bahrain, and Saudi Arabia are selected for the current illustration. The Conflict Model adjusts the actors' strength values based on the energy security values by an amount, S, scaled by the ratio of current revenue, C, to baseline revenue, B, and by the proportion that baseline revenue occupies from GDP, giving:

$$S = (C/B - 1) * (B / GDP) + 1$$

where *S* is a strength multiplier and is further bounded by a maximum allowable absolute change and a minimum increase that is applied even if the starting strength value is small or zero.

The advantage to this method of integration is modularity. With it, the project has the ability to consider the two models independently and thus, if needed, to add new elements to the package of data sent between them or alter the method by which this information is passed without requiring other substantial code revisions.

5.2 Heavy Integration

As discussed above, the Energy Security Model is a systems dynamics model originally created in Vensim but ported to Repast Simphony. It is distinguished from many other systems dynamics models in that it makes active use of subscripted variables. These subscripts make individual stocks multidimensional. The different subscript sets, and hence the different dimensional axes, include several distinctions (e.g., among oil, natural gas, and refinery products; or between foreign and domestic products). The most salient dimension is one that instantiates different variables for each of the 21 countries in the model.

The 'heavy' integration strategy leverages the fact that the Repast Simphony implementation of the Energy Security Model is a Java program, and thus shares the Java virtual machine with the Conflict Model, to expose these 21 countries as first-class agents in the Conflict Model. All of the data in the Energy Security Model is maintained in a collection of n-dimensional double value arrays. To convert these to agents, the following steps are taken:

- Create an 'I_EnergySecurityEntity' interface that exposes the collection of values that an agent in the Energy Security Model has. This additionally includes a setter method that takes a class implementing I_EnergySecurityEntity as its argument.

- Create an 'Energy Security Entity' class, called ESEntity, implements this interface, and also stores a pointer to the collection of double arrays and the index value that is associated with a specific country.
- Provide, in the Energy Security Model, a method that can be used to request instances of all Energy Security Entities, one for each subscript value.

The Conflict Model provides the model for the use of these structures. Our research strategy is to extend Conflict Model classes to implement the I_EnergySecurityEntity interface, and 'wrap' the instances of ESEnergy provided by the Energy Security Model. Basic Government and Basic Strategic Actor classes are created that implement the I_EnergySecurityEntity interface. During initialization, the Conflict Model creates an instance of the Energy Security Model, and polls this for the set of ESEntity instances. It then collects these and, if an ESEntity with a name matching a Conflict Model actor is found, the ESEntity is added to the actor using the setter method provided in the I_EnergySecurityEntity. Thereafter, the Conflict Model actor has direct access to the Energy Security values for the corresponding entity. This also means that the values from the Energy Security Model are available using Repast Simphony's native user interface and data collection tools. Any actors from the Energy Security model that do not correspond with actors in the Conflict Model scenario can be added to the Repast Simphony context as separate agents, if appropriate.

6 A NOTIONAL SCENARIO: WEST AFRICA

A notional Conflict Model scenario with four actors] serves as an illustration. The scenario shown in Figure 1 is drawn from West Africa and includes actors representing two states, Nigeria and Saudi Arabia, and two non-state actors, Boko Haram and Tuareg rebels. Both of the state actors are in the Energy Security Model. The Conflict Model actors do not yet have assigned data beyond their location and identity. Figure 2 shows the text output of move-by-move action in the Conflict Model, which is also shown in Figure 3, and the graph of world oil price from the Energy Security Model, part of which is also shown in Figure 4.

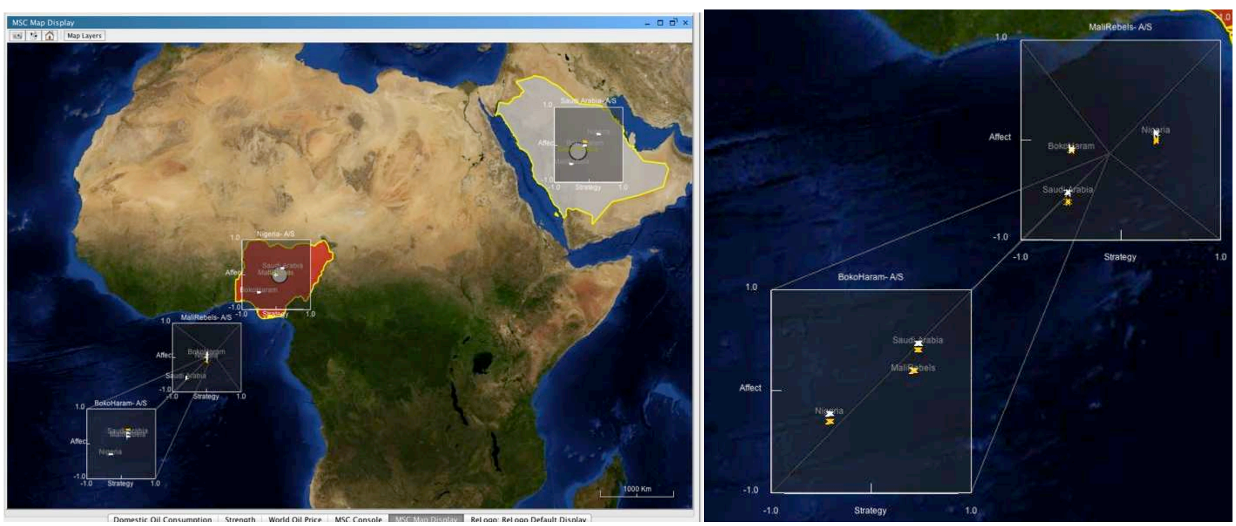

Figure 1: The Conflict Model showing (left) an overview of the West Africa Scenario and (right) a closer view showing the two non-state actors and the position of each relative to the other actors in A/S space, including official affect (white) and unofficial affect (orange).

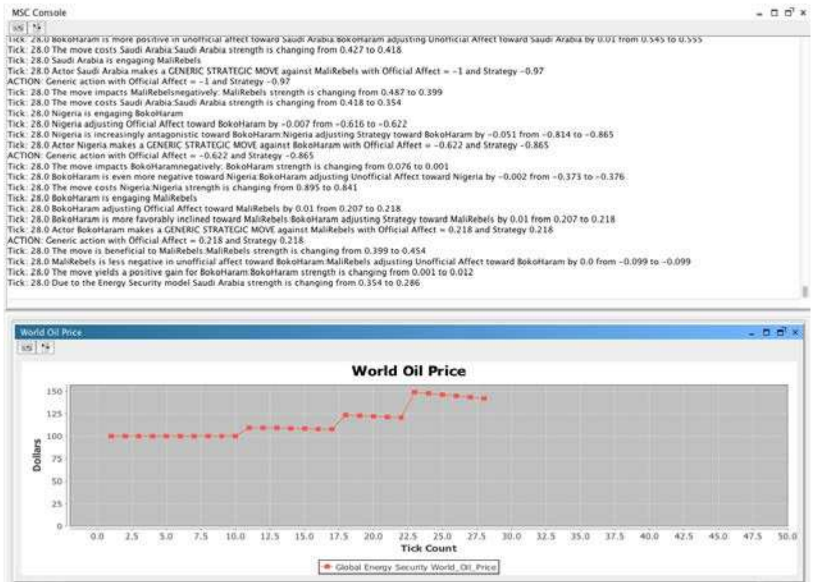

Figure 2: A screen capture showing the text output of move-by-move action in the Conflict Model and the graph of world oil price from the Energy Security Model.

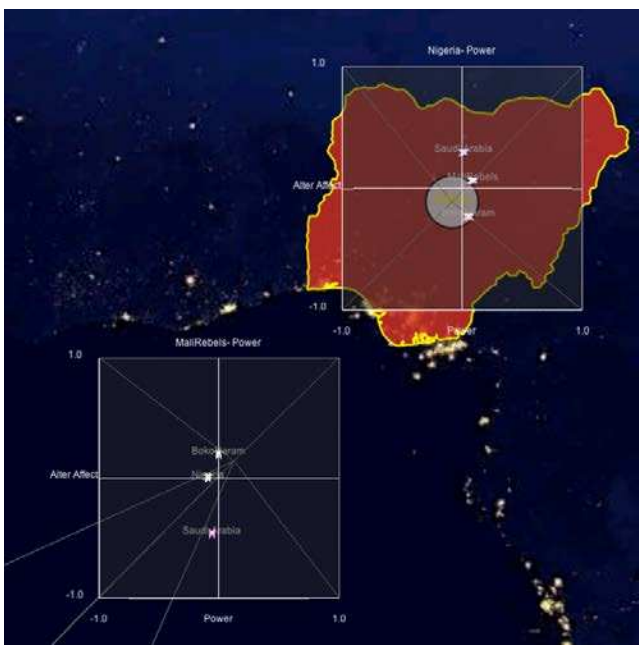

Figure 3: Tuareg rebels' and Nigeria's relative power versus all other actors, plotted against official affect.

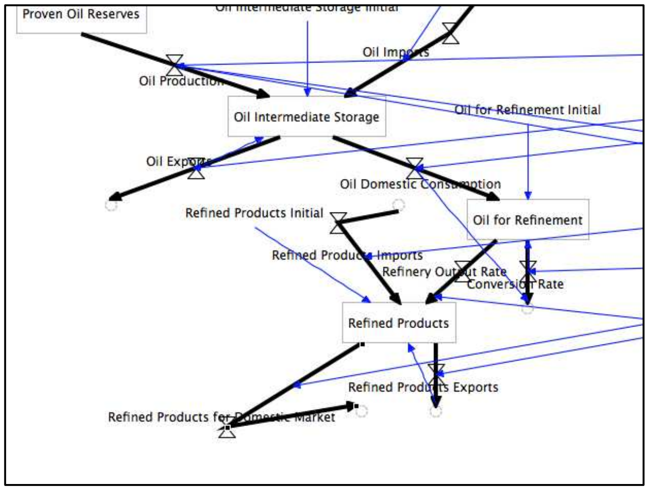

Figure 4: A section of the Energy Security Models systems dynamics model.

7 NEXT STEPS

There are many potential next steps. Planned activities include completing full scenarios and running a comparative analysis of the two integration methods discussed in Section 5.

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REFERENCES

Alizadeh, M., A. Coman, M. Lewis, and C. Cioffi-Revilla. 2014. "Intergroup Conflict Escalation Leads to More Extremism." *Journal of Artificial Societies and Social Simulation* 17.

Bithell, M., and J. Brasington. 2009. "Coupling Agent-based Models of Subsistence Farming with Individual-based Forest Models and Dynamic Models of Water Distribution." *Environmental Modelling & Software* 24: 173–190.

Brown, D. G., R. Riolo, D. T. Robinson, M. North, and W. Rand. 2005. "Spatial Process and Data Models: Toward Integration of Agent-based Models and GIS." *Journal of Geographical Systems* 7:25–47.

Conrad, S., D. Blankenship, and N. Madrid. 2004. *World Oil: A Simple Dynamic Model*.

Dubiel, B., and O. Tsimhoni. 2005. "Integrating Agent Based Modeling into a Discrete Event Simulation." In *Proceedings of the 2005 Winter Simulation Conference*, edited by M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, 1029–1037. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.

Forrester, J. W. 1958 "Industrial Dynamics: A Major Breakthrough for Decision Makers." *Harvard Business Review* 36:37–66.

Forrester, J. W. 1961. *Industrial Dynamics*. Cambridge, MA. Productivity Press.

Forrester, J. W. 1971. *World Dynamics*. Cambridge, MA. Wright-Allen Press.

IEEE. 2010. *1516TM-2010 IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA) – Framework and Rules*.

IEEE. 2012. *1278.1-2012 IEEE Standard for Distributed Interactive Simulation – Application Protocols*.

Łatek, M. M., S. M. Mussavi Rizi, and A. Geller. 2013. "Verification Through Calibration: An Approach and a Case Study of a Model of Conflict in Syria." In *Proceedings of the 2013 Winter Simulation Conference*, edited by R. Pasupathy, S.-H. Kim, A. Tolk, R. Hill, and M. E. Kuhl, 1649–1660. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.

Liang, V., and C. J. J. Paredis. 2003. "A Port Ontology for Automated Model Composition." In *Proceedings of the 2003 Winter Simulation Conference*, edited by S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, 613–622. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Martinez-Moyano, I. J., C. M. Macal, and D. L. Sallach. 2012. "Energy Security Dynamics." *30th International Conference of the System Dynamics Society*. University of St. Gallen, St. Gallen, Switzerland.

Martinez-Moyano, I. J., M. J. North, E. R. Tatara, M. R. Altaweel, and D. L. Sallach. 2012. "Using System Dynamics and Agent-based Modeling to Simulate a Proxy War for Resources." *28th International Conference of the System Dynamics Society*. Seoul, South Korea.

Meadows, D. H., D. L. Meadows, J. Randers, and W. W. Behrens. 1972. *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. New York, Universe Books.

North, M. J. 2014. "A Time and Space Complexity Analysis of Model Integration." In *Proceedings of the 2014 Winter Simulation Conference*, edited by A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, 1645–1651. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.

North, M. J., P. Sydelko, J. R. Vos, T. R. Howe, and N. T. Collier. 2006. "Legacy Model Integration with Repast Simphony." In *Proceedings of the Agent 2006 Conference on Social Agents: Results and Prospects*. Edited by D. L. Sallach, C. M. Macal, and M. J. North, 95–106. Argonne National Laboratory. Argonne, IL, USA.

North, M. J., T. R. Howe, N. T. Collier, and J. R. Vos. 2007. "A Declarative Model Assembly Infrastructure for Verification and Validation." In *Advancing Social Simulation: The First World Congress*. Edited by S. Takahashi, D. L. Sallach, and J. Rouchier, 129–140. Heidelberg, FRG: Springer.

Ozik, J., N. T. Collier, M. J. North, W. A. Rivera, E. Palomaa, and D. L. Sallach. 2012. "The *vmStrat* Domain-Specific Language." *3rd International Conference on Applied Human Factors and Ergonomics*. San Francisco, CA, USA.

Repast Simphony. 2015. Available from http://repast.sourceforge.net

Richardson, G. P., and A. L. Pugh, III. 1981. *Introduction to System Dynamics Modeling with DYNAMO*. Cambridge MA: Productivity Press.

Rizzoli A. E., M. Donatelli, I. N. Athanasiadis, F. Villa, and D. Huber. 2008. "Semantic Links in Integrated Modelling Frameworks." *Mathematics and Computers in Simulation* 78:412–423.

Salant, S. W. 1982. "Imperfect Competition in the International Energy Market: A Computerized Nash-Cournot Model." *Operations Research* 30:252–280.

Srbljinovic, A., D. Penzar, P. Rodik, and K. Kardov. 2003. "An Agent-Based Model of Ethnic Mobilisation." *Journal of Artificial Societies and Social Simulation*. 6.

Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston, MA: Irwin McGraw-Hill.

Sterman, J. D., and G. P. Richardson. 1985. "An Experiment to Evaluate Methods for Estimating Fossil Fuel Resources." *Journal of Forecasting* 4:197–226.

Teose, M., Z. Lu, K. Ahmadizadeh, S. P. Ellner, E. O'Mahony, C. Gomes, R. L. Smith, and Y. Grohn. 2011. "Embedding System Dynamics in Agent Based Models for Complex Adaptive Systems." In *Proceedings of the Twenty-Second International Joint Conference on Artificial Intelligence*. 2531–2538.

Vangheluwe, H., J. de Lara, and P. J. Mosterman. 2002. "An Introduction to Multi-paradigm Modelling and Simulation." In *Proceedings of the AIS 2002 Conference*. Edited by F. Barros, and N. Giambiasi, 9–20. Lisboa, Portugal.

Vangheluwe, H., and J. de Lara. 2003. "Computer Automated Multi-Paradigm Modelling: Meta-Modelling and Graph Transformation." In *Proceedings of the 2003 Winter Simulation Conference*, edited by S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, 595–603. Piscataway, NJ: Institute of Electrical and Electronics Engineers, Inc.

Ventana Systems Inc. 2015. *Vensim*. Available from http://vensim.com

Villa, F. 2001. "Integrating Modelling Architecture: A Declarative Framework for Multi-Paradigm, Multi-Scale Ecological Modeling." *Ecological Modelling* 137:23–42.

Villa, F., and R. Costanza. 2000. "Design of Multi-Paradigm Integrating Modelling Tools for Ecological Research." *Environmental Modelling & Software* 15:169–177.

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