PSTK: A Toolkit for Modeling Dynamic Power Structures

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Keywords:
Agent-based Models, Computational Models, Power Structure Model, DIME-PMESII modeling

ABSTRACT: *To be effective, military and interagency planners must consider the full spectrum of activities that could achieve operational goals, and must understand the effects of using those actions on a target area. To do this, planning tools must support analysis in the DIME-PMESII space. Furthermore, these tools must be in the hands of the domain experts such that they can build and use their own models that represent their own theory of the conflict. This paper describes a toolkit (called PSTK) for building social models of the power structures in a region of interest. This toolkit allows an analyst to build models representing hypotheses about the social power relationships and dynamics in region, and to experiment with those models in service of operations planning. We also describe how this tool is being used in a program for integrating a range of models into the planning process.*

1. Introduction

Full Spectrum Operations (FSO) (Chiarelli & Michaelis, 2005) involves the use of all instruments of power, going beyond pure kinetic military operations to include economic, social, informational and other kinds of actions to affect the modern battlespace. This has sometimes been described as DIME-PMESII: diplomatic, informational, military and economic (DIME) actions to accomplish political, military, economic, social, infrastructure, and informational (PMESII) effects. The U.S. experience in conflict and post conflict situations in Iraq, the Balkans, Somalia, Lebanon, and elsewhere demonstrates that essential to the successful use of FSO is understanding the impact of those operations on multiple dimensions of the target region. Kinetic operations and their impact on physical targets are well understood phenomena, at least compared to the understanding of non-kinetic operations. Our goal is to develop a set of tools that allows subject matter experts (SMEs) to build their own computational models of the power structures in a region – representing the key power players, their goals and interrelationships – first to develop greater understanding of these power structures and, second, to allow experimentation with DIME actions to explore potential PMESII effects.

This paper describes the Power Structure Toolkit (PSTK), an agent-based modeling framework that is drawn from social and cognitive theories, and which allows for easy specification, execution, and analysis of models and results. PSTK is currently being used and evaluated within an ongoing DoD program, with use by intelligence analysts and regional political science experts.

2. Design Goals

At the outset of this project, we faced a number of requirements on how such a system would work:

- Must be easy for domain experts who are not scientists or computer programmers to build computational models (“no PhD’s required”)

- Must be based on representative scientific theory (social, political, cognitive)
- Must cover a range of applications (e.g., different regions of interest) without needing to change the underlying framework – just build new models
- Must be able to model different grain sizes (individual, small groups, populations) within the same framework
- Must be able to be integrated into a larger multi-model framework

This document focuses on the theoretical basis for power struggle modeling, the design of the underlying modeling framework, how models are built and used in practice, and lessons learned in the process.

3. Theoretical Foundations

The purpose of the PSTK is to help SMEs understand the power and influence which shape political, military, economic, and social behavior in a system, and which ultimately determine outcomes in full spectrum operations. In order to provide grounding for a model-builder to focus on a particular analytic problem, a modeling framework like PSTK lends the general theoretical scaffolding for building models. The modeler can focus on the conflict instance – e.g., the power struggle in Iraq – with particular players and their relationships, while the underlying architecture implements more general theories.

The major concepts within PSTK are drawn from social science theory, relating to conflict as a struggle for *power* among a set of *actors* who are trying to achieve some set of *goals*. The rest of this section describes these concepts in more detail: the theoretical constructs we have drawn from and how these concepts relate to the PSTK.

3.1 Power

The concept of *power* is pervasive in the political science and sociology literature (Dowding, 1996; Mann, 1986). Generically, it is thought of as the ability to bring about change, and is sometimes treated synonymously with *influence*. While a pervasive concept, there is a range of often conflicting social science theory that relates to power. One thread is a tradition in international relations (Bueno de Mesquita, 2003) that tends to describe power in terms the relative strengths of nations in struggle (economic, armed, etc). There is also a tradition of *social power* as drawn from political science and sociology, though is also by no means uniformly used or described (Bourdieu, 1986; Putnam, 2000; Siisiäinen, 2000). There are some common concepts about power in most of the literature (though details of these are still debated) from which we draw on for PSTK: instrumentality, relativity, fungibility, power sources, quantification, and universality.

Instrumentality of Power. Power is generally not an end in itself, rather a means to an end. Actors accumulate power in order to accomplish something – for example, to fulfill a goal.

Relativity of Power. The measure of power for an actor is useful only when measured against another's. The result of using power can only be measured with respect to other's power – those an actor is trying to affect.

Multiple Sources of Power. Social and political science theory often distinguishes between different fields or domains of power. Bourdieu distinguishes *economic, political, social and cultural* capital – where capital is the "currency" of power, whose transfer is facilitated by social networks (Bourdieu, 1991). Mann (1986) distinguishes ideological, *economic, military, and political (IEMP)* networks of power. Others theorists (e.g., (Bueno de Mesquita, 2003)) do not have fixed categories of power, but rather refer to any kind of resource in the domains of interest as the basis of power.

Quantifying Power. With different approaches to defining power, there are different ways to measure power. Political science/international relations approaches often aggregate physical (e.g., people, tanks) and economic (e.g., dollars) kinds of resources (often called *capital)*. Other kinds of "soft power" tend to be more difficult to measure, though there have been several efforts, such as by public policy groups who have developed measurements of social capital for the purpose of quantifying the current state of developing countries (Franke, 2005). Overall, there is no universally used method of measuring power or capital. Even those that take into account seemingly straightforward measures such as the size of a fighting force as a measure of military capital may need to take into account the effectiveness of that fighting force, which itself may be a fuzzy measure.

Universality of Power. Rather than treating power as a universal quality of an actor, some theorists draw out power as related to particular issues, such as a state's power with respect to trade or human rights (Organski & Kugler, 1980). One advantage to this view is that power can be "localized" to a narrow aspect of a conflict.

Fungibility of Power. some conceptualizations of power include the concept of *fungibility* (Bueno de Mesquita, 2003)—that one kind of power can be transformed into another form, perhaps with some cost. For example,

economic power can be converted to military power by purchasing military weapons.

3.2 Decision Theory and BDI Theory

The idea of decision making in the sciences is as varied that the concepts of power. Here, we focus on a few ideas; namely, utility, rationality and the Beliefs-Desires-Intents framework. While understood as very idealized, Rational Choice Theory ((Allingham, 2002); reinforced in the Rational Actor Model – (Allison & Zelikow, 1999)) often forms the basis for many political and economic models of human behavior. (Simon, 1957) refined this to a *bounded rationality* perspective, in which actors do not have infinite capacity (cognitive or temporal) to reason through all aspects of a problem to make a decision. Part of rational actor theories is the idea of utility – that actors will measure their options along some gain/loss criteria as a basis for deciding what to do. This most simply is a decision-theoretic approach to decision making: choose the action that has the highest utility. Beliefs-Desires-Intents (BDI) is a framework that describes constructs a rational actor would have for decision-making (Bratman, 1987). Beliefs represent, in part, an understanding of the world. Desires represent a description of a desirable end-state (a "goal"). Intents represent a commitment to act.

3.3 Relationship to PSTK

In PSTK, agents (as actors) "accumulate and fight for" (in Bourdieu's terms) capital across the range of four domains we have implemented (Political, Military, Economic, and Social/Ideological). These four categories relate very strongly to Mann's sources of power (Mann, 1986). Our usage is also inspired by categorizations drawn from intelligence analyses of current conflicts (Eisenstadt & White, 2006), which describes *lines of operation*, by which an actor might exert multiple forms of power simultaneously to achieve its goals – for example, using military/armed power and political power to affect an election. Our *social power* tends to be an aggregation of ideological (religious) and kinship power, though others separate these out (Bourdieu, 1986).

In PSTK, we relate power and capital quite closely. Power is defined in each of these domains as "effective capital." In essence, *capital* refers to the amount of resources an actor has, and *power* refers to the resources that actor can muster at any given time, in a particular domain, for the purposes of achieving its goals. The scalar value *ability* limits how much capital an actor can effectively use: *Power = Capital X Ability*. In PSTK, each domain of power works the same, and can only affect the same kind of capital in other actors. This simplifies most conceptualizations of power in the literature: political capital sometimes is thought of as having a "use it or lose it" character, whereas economic capital accumulates, and social capital may *increase* by exercising it. PSTK simplifies these down to simple accumulation over time.

As with typical conceptions of power in social science, power in PSTK is *instrumental* – it is a means to an end. Agents exercise power to accomplish their goals by expending (or keeping) their resources. Power in PSTK can be used by one actor to help or prevent other actors from accomplishing their own goals. Exerted power affects capital directly, as additive or subtractive.

PSTK does not prescribe how to measure absolute capital in the target groups, and instead focuses on relative power in defining how one actor relates to another along each power dimension. We leave the initial assessment of capital in each domain up to the modeler. PSTK allows for modeling at different levels, including coarse grain size, where universal assumptions of power might be useful, or at finer grain sizes where the model deals with narrow issues in time. This is a modeling choice, rather than a prescription by the toolkit. Likewise, PSTK does not commit on power fungibility. Fungibility seems to be very domain-dependent, meaning it is difficult to commit to a particular scheme that will be universal across models. The PSTK supports fungibility in that a modeler can write arbitrary functions to convert one kind of power for another. However, PSTK does not provide a fixed set of functions like this.

The decision modeling approach in PSTK is bounded decision-theoretic BDI agents, in which the agents measure utility based by how well they estimate (via beliefs) that an action will help them achieve their goals. With a decision made, an agent commits resources (an 'intent') to try to achieve its goals. Agents work within the power/capital framework, where the actions they can take are choices to exert power over other actors (to whom, and how much), using their understanding of how those choices impact the world.

4. Power Structure Toolkit Description

Part of our effort involved reviewing existing agent-based modeling tools (such as RePast, NetLogo, OpenCybele, Cougaar) to determine if any would serve as a good basis for developing a power struggle toolkit. Many tools described as agent-based frameworks are very thin, object-oriented implementations of agents, in which an agent is little more than a container for the developer to do what he or she pleases. They often provide functionality for distributing agents, inter-agent communication, security, etc. (valid distributed processing

concerns, to be sure), but few provide agents as autonomous entities with goals, beliefs, intents, etc., and fewer still are natively imbued with social theory. This latter is understandable, since most of the users of these frameworks are scientists who extend them to incorporate their theories. Our goal instead is to provide our users with a system already built around a theory, to allow them to focus on modeling a particular conflict.

Our conclusion from this review was that we could create our own agent modeling framework to meet our requirements much faster than adapting an existing tool, and without the baggage of features like load distribution, etc. The PSTK agent architecture, while lightweight, implements the theoretical concepts as described earlier. Table 4.1 summarizes the primitives that exist in the system. Figure 4.1 depicts most of these concepts relative to each other.

Table 4.1: Primitives in the PSTK Framework.

Agent – a software representation actor in the system under study (an actor can refer to an individual, group, or population)
Goal – descriptions of ideal world conditions, specified in terms of capital
Capital – the resources an actor has to try to achieve goals: political, military, economic, and social
Power – the effective capital/resources an actor can bring to bear to achieve goals.
Ability – a scalar affecting how much of an agent's capital it can use to exercise power
Line of Influence (LOI) – specifies a path by which capital can flow between agents
Belief – Description of how the agent thinks the world works in terms of the network connectivity and the tendencies of other actors
Context – descriptions of a subset of the world; can be used to activate or deactivate goals
Process – transducers of data from/to other models; can be used as sources or sinks for capital
Turn – one round simulation activity
Action – an application of power to affect another actor, positively or negatively

Execution in PSTK is turn-based, where each actor gets a cycle to perform its decision-making, and then the next system state is computed from those decisions before the next turn starts. Within a single agent's decision-making process, the agent determines how it wants to exercise its power to achieve its goals. Goals may be active or inactive based on activation contexts and the current situation; those that are active are then worked on in priority order, which is set initially at model development time. (Some example goals might be: "Actor A wants to have more economic power than Actor B" or "Actor A wants Actor C to have more military power than Actor B." Agents may have multiple goals that define the bounds of their behavior.)

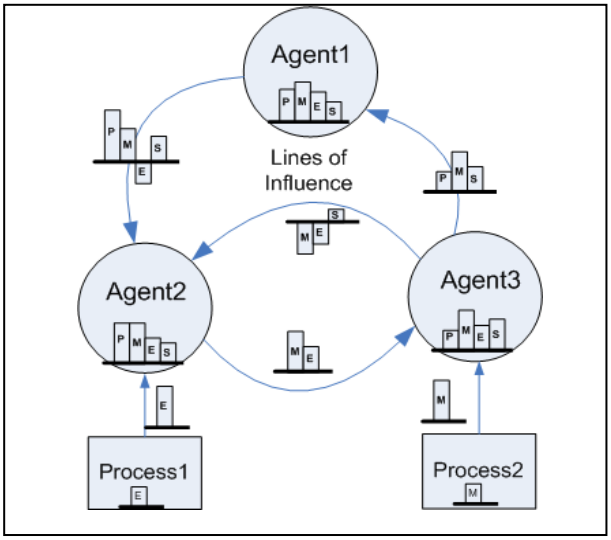

Figure 4.1: Basic PSTK Modeling Framework

For each goal under consideration, the agent determines a best course of action: whether to exercise power, and if so, for which target agent, how much power to exercise, and along which path to exercise that power. Beliefs are used to determine the best action at any given time – e.g., whether taking an action will result in a goal being accomplished. An example belief might be "Actor A believes that Actor C tends to support Actor B." (Currently, the agents' beliefs do not change over time.) Agents affect other agents' capital by exercising power: an action is a transfer of capital. Positive transfer of capital is akin to giving someone else resources; negative transfer of capital is akin to attacking someone else's resources. When each active goal in an agent has been considered, and actions constructed to work toward the goal, that agent's turn is done, and the next agent gets a chance. When all agents have completed, the system collects all their selected actions and computes the next turn's state.

Determining the "best" action for a goal is generally a utility-based decision procedure, where a set of proposed actions' effects are projected into the future, and the one that most positively affects the goal under consideration is selected. We have also been experimenting with a number of different utility-based decision procedures, some taking more information into account than others, for example considering different timescales for projection or taking into account past behavior of other agents. At the fringes of our experimentation are procedures for incorporating cultural and personality effects – for example, tendencies to prefer bold actions incremental adjustments. Each

decision process tends to have different performance profiles – the more information taken into account for a decision, the slower the execution of the overall system. We have implemented these extensions in such a way that we can use different decision process for different models, even selecting them on a per-agent basis within a model. This allows us to experiment with and extend the framework easily, as well as to address different performance requirements for different applications.

The system can be viewed from a traditional systems dynamics view of stocks and flows: capital represents the stocks, and lines of influence represent the flow pathways. However, unlike conventional stock-and-flow approaches, PSTK agents are goal-driven, controlling the flow type, quantity, timing, and pathway, based on their goals and the current situation. Within the flow decision process, the agents themselves can effectively change the structure of the network by deciding to use or ignore a line of influence for the transfer of capital: effectively turning the LOI on or off. The resulting flows alter the distribution of different kinds of capital across the networks. This is effectively one output of the system: the dynamic distribution of power over time.

So, in contrast to "thin" agent-based frameworks, PSTK primitive elements such as goals, beliefs, and lines of influence, as well as decision procedures for how agents interact, imbues the PSTK agent framework with an implementation of a theory of social power. This extra layer of functionality allows user then to build models at a higher level of specification using these primitives and, further, allows us to develop a graphical toolkit that uses these primitives for model building and execution, which is the topic of the next section.

5. Model Specification and Execution

Because the PSTK is intended to be used by regional domain experts rather than engineers, we have devoted a significant effort in building a usable tool that supports the analytic process. Model development in PSTK is typically an iterative process involving three major steps: model building, model execution, and model run analysis. These steps, and their related interfaces, are described here.

5.1 Model Building

Usually, the first step in creating a PSTK model is identification of the "major players" – those actors who are thought to be significant in the area being modeled. This list may be derived from literature analysis or simply from modeler familiarity with the area. (Social power structure analysis has been formalized in the literature, for example (Tait, Bokemeier, & Bohlen, 1988), and the methods described can be used to build PSTK models.) Actors are usually added to a PSTK model through the model graph view, as shown in Figure 5.1. Once added, the actors are then connected by positive and negative lines of influence to form a high-level power network. At one level of description, this is essentially a social network diagram of actors and relationships.

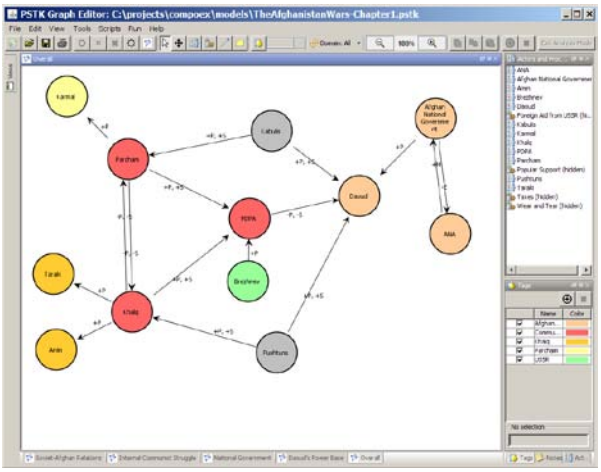

Figure 5.1: Graph view of major players from *The Afghanistan Wars* (Maley, 2002)

In support of model development, the PSTK editor provides a continuously updated list of "issues" showing any model structure errors or warnings. For example, an actor with no outgoing LOI generates a warning. In addition to the network view, there is also a tabular view of actors, which makes it easier to provide supporting information such as a description or other annotations. In the tabular view, there is a simple text filtering function that hides all actors that do not match the user-supplied filter.

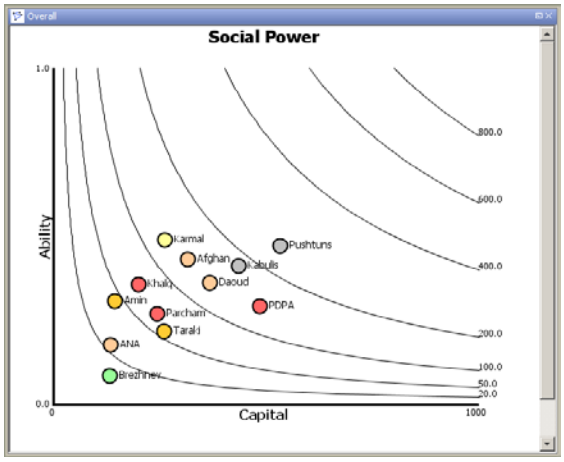

Figure 5.2: Relative Social Power Chart

Actors are given default values at creation, but unless all actors can be expected to be equal in all domains, it is common to adjust the default values. The PSTK editor provides both a spreadsheet-like table and a "Relative Power Chart" (Figure 5.2) that uses a contour plot for specifying these values. The relative power chart allows modelers to set capital and ability values simultaneously by moving actor nodes on the horizontal and vertical axes, respectively. The curved lines show power bands along which agents fall for a single domain. Goals may be added for each actor via a separate table in the PSTK, and may include contexts for defining when the goals are active. Alternately, to speed the model-building process, the editor can automatically generate goals for each actor based on lines of influence. These might serve as default values, or as a starting point for a model for later tailoring.

5.2 Model Execution and Analysis

Once a model is defined, it can be executed from within the PSTK editor. Execution is a batch process: the modeler cannot adjust values during a run. When starting a simulation, the modeler can indicate how many turns to run and whether or not to display model results in the PSTK analysis windows, or to launch Excel to view raw model results. If the modeler has selected the option in the run configuration dialog, the PSTK editor will enter Analysis Mode on completion of a simulation run.

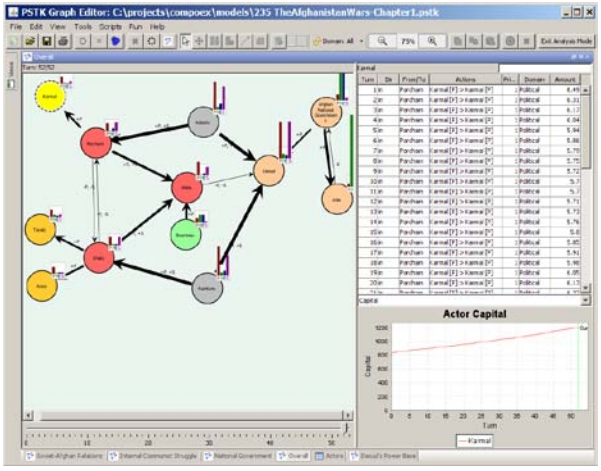

Figure 5.3: Network View of Analysis Mode Panel

Analysis Mode allows the user to walk through the simulation results one turn at a time. The power graphs on individual actors are adjusted, and the weight of the LOIs indicates the cumulative flow over them since the start of the simulation run (Figure 5.3). Analysis Mode also provides a tabular view of all flows, which can be sorted and filtered to focus on specific interactions. Selecting an actor in the network creates a chart showing the history of the selected value (capital or power) for that actor over the course of the simulation run, with a cursor line showing the currently selected turn. The modeler can also select multiple actors to see how their values compare, using the same history chart component (Figure 5.4).

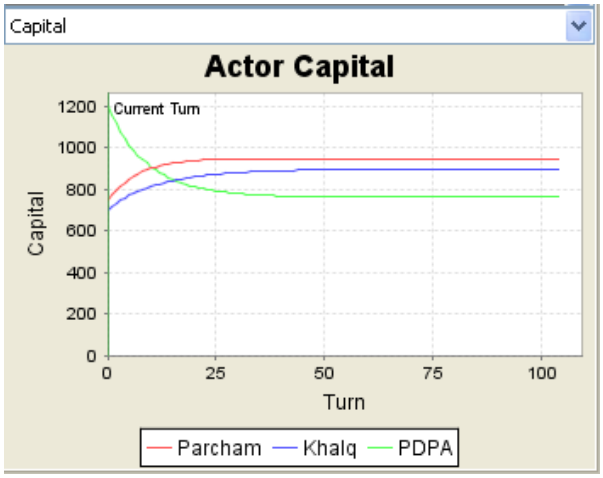

Figure 5.4: History Chart for Multiple Actors

Analysis Mode is heavily used during iterative model development – a model is built, run, and then "tuned" to meet the expectations of the modeler. After a modeler is satisfied that the necessary actors and lines of influence have been created, and that the initial values and goals are at least approximately correct, the model will be executed for tuning. By observing the output shown in different Analysis Mode displays, the modeler can judge whether or not the behavior of selected actors is as expected and either continue tuning the model, or use it for analysis.

5.4 Framework Extensibility

The PSTK simulation engine provides a default decision-theoretic process for expending power. The modeler can rely on this default, can select from a small number of pre-defined alternatives, or can choose to write an alternate decision process in Javascript. All model components and values are available to the Javascript execution environment, and so can be used to control the decision process, including what properties to consider in measuring utility and how to value them in considering potential actions. We do not expect most end-users to take advantage of this scripting feature. However, to allow for easy extensions to the underlying theory (and so the basic execution of the model) this feature is essential. Furthermore, these scripts can be stored in a library for other non-programmers to draw upon if they wish to change the basic operation of the model.

5.5 Multi-Model integration

PSTK is currently being used in an ongoing program for the Department of Defense. One objective of this parent program is to develop techniques for integrating models developed using different modeling paradigms (e.g., systems dynamics models, Bayesian network models, agent based models) in order to capture the full richness of the DIME-PMESII landscape. The integrated models are referred to as multi-resolution models (MRMs). The basic mechanism provided for model integration is a shared data backplane, where models can exchange data. The MRM runs in a turn-based manner, allowing each model a chance to run in each turn, before computing the final result to be used as input to the models in the next turn.

The PSTK publishes to the backplane values for capital, ability, and power for each actor and process node. This allows other models to access information about the agents as input to their own processes. PSTK gets data from the backplane to serve as inputs to its current turn. PSTK allows for process node values to be set from the backplane, which in turn become inputs to the agent's decision-making. Agent beliefs and goals can also refer to external model data using an 'external variable' reference defined during model specification. PSTK actors can also be affected by other models in terms of modifying agent capital, abilities, or goals. This capabilities is used to model, for example, the effects of media on power dynamics.

6. Usage and Evaluation

PSTK is used currently by SMEs to create models of various areas of the world. These domain experts are retired military and intelligence analysts as well as academics with specialties in the areas of interest. The resulting models are integrated with other models built using a variety of modeling paradigms into a single multi-resolution model (MRM). DIME Planners, who are the ultimate end-users of the system, specify actions to be taken, such as making investments in manufacturing or carrying out a media campaign, and use the output of simulation runs of the MRM (which includes running the PSTK models) to assess the utility and effectiveness of the actions. The planners who have used the system have been active military and State Department personnel and retired flag rank and ambassadorial consultants.

To date, three significant models have been in PSTK. The models have increased in complexity over the life of the program, as shown in Table 6.1. In the current MRM under development, PSTK interacts with seven other computational models through approximately 2000 process values, external variables, and exposed outputs. Model execution times vary based on the number of actors, their interconnections, the complexity of their decision processes, and the number of turns for a simulation run. For the models we have built to date, we experienced execution time ranges from a few seconds to under a minute, which fits within the time bound requirements for the DoD experiments.

Table 6.1: Example PSTK Model Sizes

	Model 1	Model 2	Model 3
Actors	69	91	148
Processes	79	42	71
LOI	216	445	1023
Goals	116	369	900
Contexts	0	0	1164

Actual modeler experience shows that creation of a PSTK model, Iraq for example, by SMEs is a relatively intuitive and straightforward task. The PSTK GUI lends itself to the representation of much of what experts know about the "worlds" they are dealing with. While they tend not to be social scientists, analysts are generally comfortable with the concepts of capital, power, relative power, ability, the exercise of influence through networks, and the pursuit of goals by actors in political-social systems. Fixing specific values is often less intuitive but SMEs have adapted to this requirement. In these models, analysts are able to see the results of a power struggle in a system of interest to them, in fact which they have built, and which play out over time frames they specify. The "power plots" generated as outputs from the simulation are comprehensible and can be explored in detail through the available analysis tools.

Depending on its complexity (number of actors, goals, LOI, etc), the creation of a PSTK model can require substantial effort. Careful consideration of the model subject and the "theory of conflict", underlying the selection of actors, the specification of relationships, goals, etc, is necessary to produce a model that is useful and whose results are explainable. Creating a solid PSTK model is the equivalent of writing a solid academic paper.

The model builders and analysts (such as the last author), in particular have been very positive about the utility of PSTK (in the words of one user, the ability to play with a dynamic model has been "exciting and compelling.") Feedback from planners has also been good, though more temperate. There has been excellent response to the basic capability of model building and simulation-based analysis, but some criticism of overall model coverage and

fidelity. Interestingly, the senior planners have been the most enthusiastic. As a group, these users have been less interested in the precise validity and accuracy of the models, focusing instead on the ability to use the modeling and simulation toolset as a means of exploring a problem and learning what questions to ask.

We have spent a great deal of time working with different these users to understand their mental models of a theory of conflict. We have used this to formulate both the framework and the user interfaces. We have not run a formal evaluation with any users, either model builders or planners. However, we do interact with them on a regular basis as they use the system, and they provide feedback for continual improvement.

Model validation, to the extent that it has been done, happens at the level of the expert model builders and related area subject-matter experts. The only method used so far is informal face validation as they are building and tuning the models – *do the models look right from their perspective?* For this, we have elicited feedback from area experts such as the political science department at University of Michigan and McGill University. For our purposes as *framework builders*, our concern is about the capabilities of the framework to capture the right kinds of power dynamics, and if modelers can build the kinds of models they need. While we have anecdotal evidence as given above, we have not yet formally evaluated this aspect of the framework. The DoD work is itself an ongoing evaluation of PSTK.

7. Related Work

There are certainly many agent-based social science modeling frameworks (e.g., NetLogo, Repast) that provide good general-purpose modeling environments for those inclined to do programming to build models. Other agent-based frameworks built for the DoD/analytic community include systems like SEAS (Chaturvedi, Dehncke, & Snyder, 2004) for DIME-PMESII modeling, and Senturion (Abdollahian, Baranick, Efird, & Kugler, 2006) for stakeholder analysis modeling, but neither are designed for SMEs to build models themselves. DyNet (Carley, Lee, & Krackhardt, 2001) is a similar kind of agent-based social network simulation, but is focused on task performance rather than power structures, and does not include tools for end-user specification of models. A conceptual precursor to PSTK is AGILE (Taylor, Frederiksen, Vane, & Waltz, 2004), developed for the intelligence community as a similar model-building toolkit, but operates at a different level of specification, is less grounded in theory, and requires more model building effort comparatively.

8. Conclusions and Future Work

The DoD's attention to Full Spectrum Operations has created a need for tools that help analysts and planners understand the implications of their actions in the full DIME-PMESII spectrum. In service of these efforts, we have developed PSTK, a toolkit for building models of power struggles in support of FSO planning. PSTK is currently in experimental use in a host of experiments in support of a few DoD planning centers nationwide. It has also being used under academic licenses by a few political and social science groups at the University of Michigan and Old Dominion University. We continue to improve the PSTK based on feedback from our users so far, and they applications to new modeling problems. We are currently experimenting with different variations, including different decision-making and goal-seeking styles, and other end-user tailoring abilities.

9. Acknowledgements

This work was performed under DARPA Contract # W15P7T-05-C-P032. Approved for Public Release, Distribution Unlimited. Thanks to Dr. Allen Hicken and Siafa Hage for their expertise.

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