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Title: **Model Interoperation for Effects Based Planning**

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Abstract

This paper describes an approach that broadens the capabilities of models used by command and control organizations to conduct effects based planning and operations by improving the understanding by which tactical actions affect the infrastructure and the civil environments in an area of operation. The premise is that the quality of the commodity services provided by the infrastructure is a main factor affecting the socio-cultural attitudes and the actions of the local population. The problem is that a lower-level tool provides quantification of commodity availability, but a higher-level tool needs belief quantification as its metric. Lacking, today, is a method on how to interface these two. The paper describes experimentation with the integration of two different modeling techniques that have been used to support effects based operations: Timed Influence Nets, and a civil environment modeling tool based on the W. Leontief input-output economics model. The paper describes the experiment design and the Iraqi scenario that were used to investigate the feasibility of three different types of interoperation between the models. The type and level of interoperation that was achieved and the impact on course of action evaluation is described along with overall observations and areas for further research.

1. Introduction

Since 1992 the type of objectives that the military must address has expanded well beyond those of traditional major combat operations. As military operations become other than conventional war – whether against transnational terrorist threats or conducting stabilization operations – the need to broaden the focus of models that support effects based planning and operations has become critical. One major challenge faced by command and control in the 21st century is to improve the understanding of the relationships between effects on the infrastructure and the civil environments in the area of operation. Actions taken by all (coalition forces, the adversary, and the civilian population) interact to affect the outcome of the coalition's course of action. The quality of the commodity services provided by the infrastructure is one of the main factors affecting the socio-cultural attitudes, especially including the actions of the local population.

Over the past 5 years, there have been efforts to develop different modeling techniques and tools to explore these concepts that are necessary for effects based planning. For the most part these have been separate efforts with little collaboration between tool developers. The research described in this paper was motivated by the desire to improve the quality of effects based analysis and planning by identifying methods of interoperation between two different modeling techniques that have been used to support effects based operations. The first technique is the probabilistic Timed Influence Net modeling approach and the second is a civil environment modeling tool that is based on the W. Leontief input-output economics model. The Timed Influence Net approach generally is used for analysis at the operational and strategic level of warfare while the civil environment modeling tool is more focused on the immediate effects of tactical actions on the infrastructure. This research effort was driven by the basic proposition that it is possible to improve effects based course of action evaluation by using these two models together exchanging information or data between them. Of course the modeling approaches are very different from one another, so the question of how data or information could be passed between the models was unknown. An experimental approach was taken to explore the potential interoperation between these two modeling techniques to determine if: 1) interoperation is possible, and 2) use of such interoperation would improve the overall analysis over that provided by the models independently. A case study approach was taken using the situation in Iraq.

Section 2 briefly describes the two modeling tools and approaches. Section 3 then discusses the design of the experiment to include procedures for determining the feasibility and utility of using three different types of interoperation: data exchange; automatic tool-to-tool interoperation; and human to human. The section also describes the Iraqi scenario that was used in the case study, the models that were developed based on that scenario, and the results of the effects based course of action analysis. Section 4 describes the experimental results and the paper concludes in Section 5 with overall observations and areas for further research.

2. Effects Based Operations Models

Planning for effects based operations relies on several modeling techniques to analyze how potential actions can lead to various effects in an area of operation. Two broad categories of models have been used to provide the framework for this analysis. The first category models an effects based plan (EBP) that relates actions to effects through a series of causal linkages. The EBP then identifies a set of actions together with their timing and shows how those actions are expected to lead to the desired higher level effects. The second category, System of System (SOS) models, represents the components of and links between various systems in the area of operation. These SOS models theoretically can be used to show how the state of various components or links in one system can affect the state of other components or links. These systems collectively are categorized as political, military, economic, social, infrastructure, and information (PMESII).

In the context of effects based operations there is a relationship between these two categories of models. The actions and the resulting effects described in the effects based plan should map to the SOS models that can indicate how affects on a component of a system can cause the nature or state of that system and perhaps other systems that are related to it to change. Thus the SOS models can provide the explanation for some of the causal linkages that are described in the effects based plan model. However, explicitly connecting these two models has not been the common practice.

Part of the difficulty is caused the by major differences in the levels of abstraction that exist in effects based plans and the SOS model. For some of the physical systems in the PMESII construct, engineering or physics based models have been developed that can predict the impact of various actions on systems and assess their vulnerabilities. When it comes to the cognitive belief and reasoning domain, engineering models are much less appropriate. The purpose of affecting the physical systems is to convince the leadership of an adversary to change its behavior, that is, to make decisions that it would not otherwise make. However, when an adversary is imbedded within a culture and depends upon elements of that culture for support, the effects of physical actions may influence not only the adversary but also the individuals and organizations within the culture that can choose to support, be neutral, or oppose the adversary. Thus, the effects on the physical systems influence the beliefs and the decision making of the adversary and the cultural environment in which the adversary operates. Because of the subjective nature of belief and reasoning, probabilistic modeling techniques such as Bayesian Nets and their influence net cousin have been applied to these types of problems. Models created using these techniques can relate actions to effects through probabilistic cause and effect relationships. Such probabilistic modeling techniques can be used to represent an effects based plan and they can be used to analyze how the actions affect the beliefs and decisions by the adversary.

2.1 Timed Influence Nets

Influence Nets (IN) [Rosen and Smith, 1996] and their Timed Influence Nets (TIN) extension are abstractions of Probabilistic Belief Nets, also called Bayesian Networks (BN) [Jenson 2001, Neopolitan, 2003], the popular tool among the Artificial Intelligence community for modeling uncertainty. BNs, INs and TINs use a graph theoretic representation that shows the relationships between random variables. These random variables can represent various elements of a situation that can be described in a declarative statement, e.g., X happened, Y likes Z, etc.

Influence Nets are Directed Acyclic Graphs where nodes in the graph represent random variables, while the edges between pairs of nodes represent causal relationships. Mathematically while Influence Nets are similar to Bayesian Networks, there are key differences. BNs suffer from the often intractable task of knowledge elicitation of conditional probabilities. To overcome this limitation, INs use CAST Logic [Chang, et al. 1994; Rosen 1996], a variant of Noisy-OR [Agosta, 1991], as a knowledge acquisition interface for eliciting conditional probability tables. This logic simplifies knowledge elicitation by reducing the number of parameters that must be provided. INs are appropriate for modeling situations in which the estimate of the conditional probability is subjective, e.g., when modeling potential human reactions and beliefs, and when subject matter experts find it difficult to fully specify all of the conditional probability pair values. TINs extend INs by adding the element of time as delays for both the random variable nodes as well as the edges between pairs of nodes.

The modeling of the causal relationships in TINs is accomplished by creating a series of cause and effect relationships between some desired effects and the set of actions that might impact their occurrence in the form of an acyclic graph. The actionable events in a TIN are drawn as root nodes (nodes without incoming edges). Generally, desired effects or objectives the decision maker is interested in, are modeled as leaf nodes (nodes without outgoing edges). In some cases, internal nodes are also effects of interest. Typically, the root nodes are drawn as rectangles while the non-root nodes are drawn as rounded rectangles. Figure 1 shows a partially specified TIN. Nodes B and E represent the actionable events (root nodes) while node C represents the objective node (leaf node). The directed edge with an arrowhead between two nodes shows the parent node promoting the chances of a child node being true, while the roundhead edge shows the parent node inhibiting the chances of a child node being true. The inscription associated with each arc shows the corresponding time delay it takes for a parent node to influence a child node. For instance, event B, in Figure 1, influences the occurrence of event A after 5 time units.

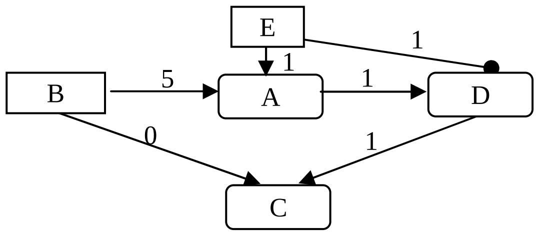

Figure 1 An Example Timed Influence Net (TIN)

The purpose of building a TIN is to evaluate and compare the performance of alternative courses of actions. The impact of a selected course of action on the desired effects is analyzed with the help of a probability profile. Consider the TIN shown in Figure 1. Suppose the following input scenario is decided: actions B and E are taken at times 1 and 7, respectively. Because of the propagation delay associated with each arc, the influences of these actions impact event C over a period of time. As a result, the probability of C changes at different time instants. A probability profile draws these probabilities against the corresponding time line. The probability profile of event C is shown in Figure 2.

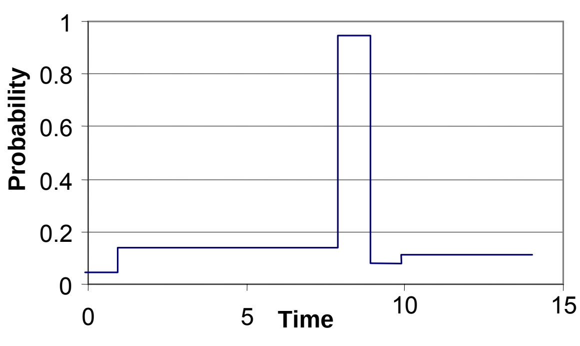

Figure 2 An Example Probability Profile

In building the IN, the modeler must assign values to the pair of parameters that show the causal strength for each directed link that connects pairs of nodes and a baseline probability for each non-root node. The CAST logic is based on a heuristic that uses these quantified relationships and the baseline parameter to compute the conditional probability matrix for each non-root node. Finally, each root node is given a prior probability, which is the initial probability that the random variable associated with the node (usually a potential action) is true. This last item is referred to as an input scenario.

When the modeler converts the IN into a TIN, each link is assigned a corresponding delay d that represents the communication delay. Each node has a corresponding delay e that represents the information processing delay. A pair (p, t) is assigned to each root node, where p is a list of real numbers representing probability values. For each probability value, a corresponding time interval is defined in t. Collectively the combination of the time ordered root-node set is (informally) the course of action.

To analyze the TIN, the analyst selects the leaf and/or internal nodes that represent the effects of interest and generates probability profiles for these nodes. The probability profiles for different courses of action can then be compared.

GMU has developed a tool called *Pythia* with support from ONR, AFOSR, and AFRL (and initially with support from AFIWC) that implements the TIN development technique and provides an analysis environment. The basic problem that it helps solve is given a set of actionable events, determine the Courses of Action that maximize the achievement of desired effects as a function of time.

2.2 Civil Environment Model

The Civil Environment Model (CEM) has been developed by Raytheon with support from the Air Force Electronic System Center. It is an effects-based operations logistics commodities model that reflects a nation's ability to wage war based on damage effects to its civil infrastructure. CEM uses damage models to determine strategic and cascading effects on the overall Battle Space Environment

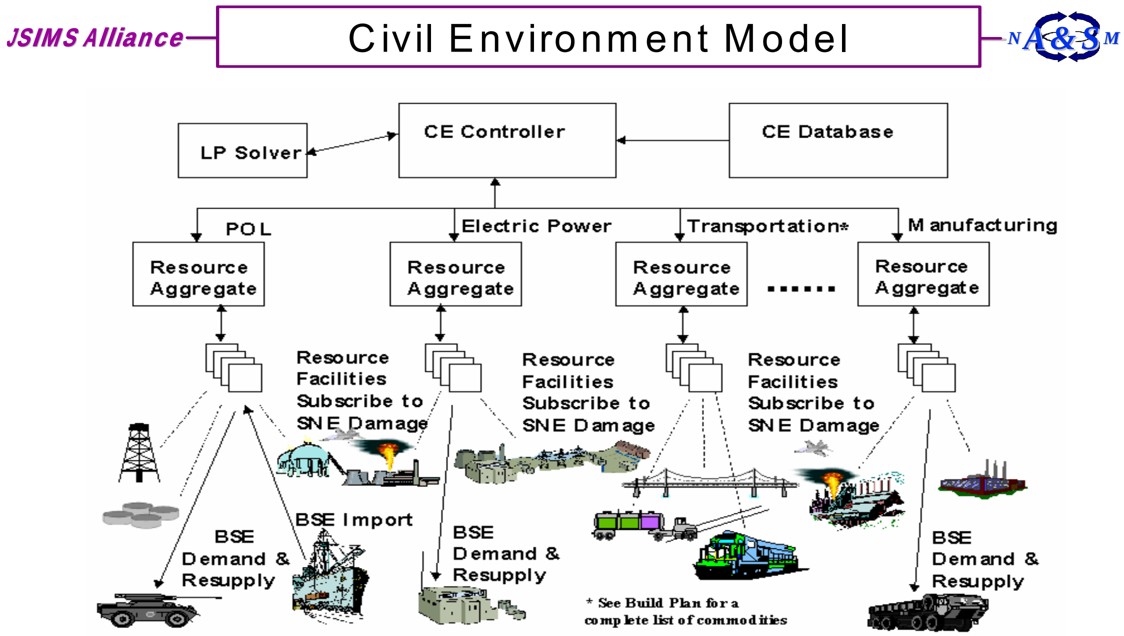

Figure 3 CEM Organization and Structure

(BSE). CEM algorithms are based on W. Leontief I/O Economic Model, which is a set of linear equations whose optimal solution expresses a balance between competing demands on an infrastructure.

The CEM functionality can be used to relate physical damage effects and repair capabilities; model cascading effects; monitor production, storage, and transportation capabilities; and project the long-term effects of damage on a national level.

Figure 3 graphically depicts the organization and structure of CEM. CEM uses a linear program solver to model the flow of commodities such as munitions, repair parts, food, Petroleum-Oil-Lubricants, and others (user defined) to the battlespace. Damage to the civil infrastructure, roads, railroads, inland waterways, factories, power plants, and the like, will result in smaller production, storage and/or transport capacity of the commodities. Repair of facilities restores their capacity to function. CEM employs a large database that contains descriptions of the various commodity systems that make up the infrastructure in the area of operation. Its output is usually a large data set that shows the amount of production, storage, transport, and consumption for each commodity at each location as a function of time.

3. Experiment Design and Execution

To conduct this research, an experimental approach was taken using Operation Iraqi Freedom (OIF) as the context. The basic concept was that it appeared to be likely that by combining the capabilities of *Pythia* TIN with CEM, one might model Iraqi behavior to get a more refined and useful analysis of courses of action.

The more general problem being addressed is: Given a data set about a region or area of operation, how can a common data set be used in different types of models to synergistically analyze the situation and enable effects-based planning and assessment? Figure 4 shows the basic construct. The modeler (stick figure) uses that appropriate data from the common data set to construct different models, specifically a CEM model and a *Pythia* model. The modeler uses the analysis capability of each model to generate its results as the figure shows. The proposition is that it is possible to refine the models and analysis by using knowledge, information or data from the output of one model to inform the creation or analysis of a sibling model. The question marks on the flows show the proposition being explored.

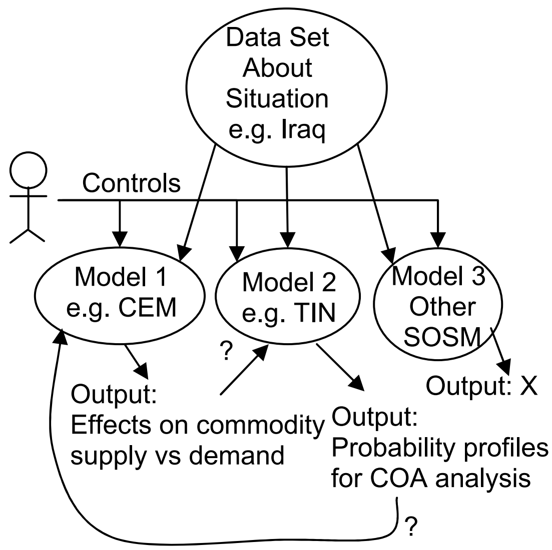

Figure 4 Using a Common Data Set in Different Model Types

The focus of the experiment was to discover useful interfaces between the Raytheon CEM capability and the GMU *Pythia* modeling tool and techniques. Such interfaces could be data-to-data, model-to-model, or model-to-human-to-model. The goal would be to improve the effectiveness of the combined evaluations that such interfaces might provide.

One of the challenges for this experiment was the lack of a clear definition of enhancement or improvement that can be quantified. To our knowledge, this approach had not been tried before, and therefore we decided to conduct a discovery experiment [Alberts and Hayes, 2002] to 1) determine if interoperation techniques could be found and 2) discover potential benefits such interoperation might yield.

To evaluate these premises two propositions were formulated to guide the conduct of the experiment.

Proposition 1: It is possible to use elements of the *Pythia*/Time Influence Net (TIN) model in the set up and analysis of the CEM models.

Proposition 2: It is possible to use outputs from a CEM model to refine TIN models.

To evaluate these two propositions it was necessary to define a process exchanging data and information between both modeling capabilities and a method for evaluating the "enhancement" of the analysis that occurs when the elements of one model are used by the other.

The following relationships between the two modeling approaches were first postulated:

The EBO analysts uses both Effects-Based Plans (part of which may be expressed through an Influence Net) and System-of-System model (SOSM). Note that CEM is a form of a SOSM. The EBP describes how actions that affect elements of the SOSM will cause other secondary and higher order effects that may be at the operational or even strategic level. First order effects tend to be physical and tactical; higher order effects may be cognitive and operational or strategic. The SOSM shows the interdependencies between elements of the physical system that are objects of the primary effects expected by the actions in the EBP (the actions in the Influence Net). Some SOSMs can show "dynamic" behavior given actions or effects on elements of the SOSM. Most are based on physical phenomenon.

Figure 5 shows the postulated relationships between CEM and *Pythia* in more detail. In the figure a fragment of a *Pythia* model is shown as the six blue boxes and the connecting blue arcs that are along the top and bottom of the figure. A CEM model is shown as the box in the center. The actions that are contained in a *Pythia* model are used to stimulate a CEM model. The CEM model is run and analyzed to provide detailed information about commodity effects from those actions and temporal information about how long it takes for the action to cause the commodity effect.

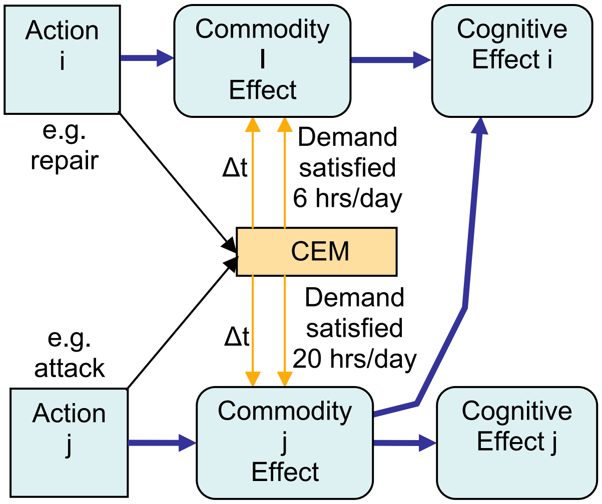

Figure 5 Relationships Between CEM and *Pythia* Models

These outputs are used to refine the estimates of the strength of the causal or influencing relationships (from actions to commodity effects) and the time delays between the actions and the commodity effects that needed to convert the Influence Net into the *Pythia* model. In the figure, the CEM showed that Actions i and j resulted in demand for Commodity i and j being satisfied for 6 and 20 hours a day, respectively. Note that the analyst will still have to estimate the causal strengths of the commodity effects on the cognitive effects; however, a CEM model adds confidence to the estimate of the commodity effects in *Pythia*. The refined *Pythia* can be used to calculate the probability of achieving various effects over time (probability profiles) when different potential courses of action are used. The result can be recommendations for course of action.

From this formulation of the problem, the following sub-propositions were established:

1. If CEM shows number of hours per day that demand is met for different commodities given certain actions, these values can be used to help define the premise(s) that go in the *Pythia* boxes.

2. The *Pythia* analyst will have to establish what the impact of meeting demand has on cognitive effects

3. CEM may also be able to provide estimates of time delays for *Pythia*

The following process for doing the analysis with the two models was formulated.

- Sketch out EBP in *Pythia* including physical effects on the infrastructure and cognitive effects on the adversary and the general population to define the relationships between potential actions and the overall desired effects.
- Set up the CEM to reflect the infrastructure in the Area of Operations and use it to identify possible tactical and operational level physical effects and identify "critical" physical effects.
- Add parameter values to the EBP with the help of information obtained from the CEM and other knowledge.
- Assess/compare COAs using both EBP and CEM.
- Select COA and develop detailed plan.
- Commence plan execution.
- Use EBP and CEM to assess progress, identify opportunities and problems, and formulate changes to the plan using indicator data.

Figure 6 shows the proposed process flow. The numbers in the figure are related to the process steps as follows:

1. Analyst sketches out the TIN with effects, actions, relationships and potential observable indicators that effects have or have not occurred. Some actions and effects can be mapped to the CEM.

2. CEM analysis shows detailed physical effects on commodities from various actions.

3. The analyst "translates" physical effects from CEM to refine the TIN including adding time delays and possibly adjusting action to commodity influence strength values.

4. CEM analysis gives detailed description of physical effects on the infrastructure.

5. Analyst uses TIN to produce probability profiles, comparing COAs for selection.

6; 7; 8. As the plan is executed, indicator data is used by both the TIN and the CEM to assess progress toward achieving objectives.

This process was followed during the experiment and the results obtained by following this process were subjectively compared to those that would be obtained by building and analyzing the models independently.

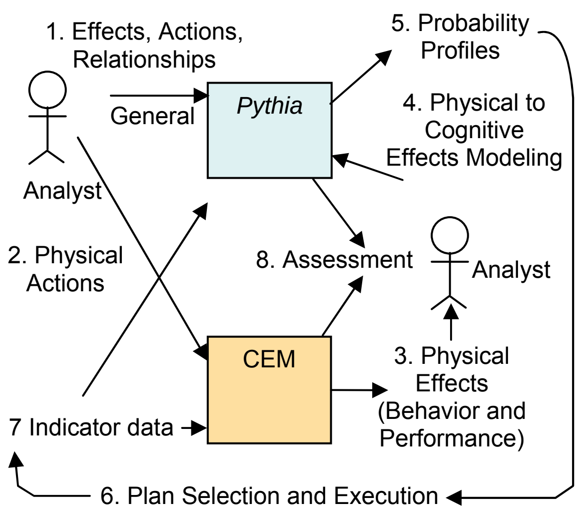

Figure 6 Sequence Diagram for Combined Analysis Process

3.1 The Operation Iraqi Freedom Scenario

The Operation Iraqi Freedom (OIF) provides the context to design an experiment that evaluates the propositions described above that it is possible to use *Pythia* and CEM, with different levels of abstraction, together to synergistically enhance the evaluation and selection of courses of action (COA) for the sample problem space.

After the successful toppling of the Iraqi government in the beginning of OIF, coalition forces, led by the United States, initially identified seven key areas that were the pillars of completing the mission and then added an additional area. These pillars are identified below.

- Defeat the terrorists and neutralize the insurgents.
- Transition to security self reliance by the Iraqi government.
- Support the establishment of a free and democratic Iraq.
- Provide essential services to the Iraqi people.
- Establish the foundation for a strong economy.
- Promote the Rule of Law and promote civil rights.
- Maintain international engagement and increase support for a democratic Iraq.
- Promote strategic communications promoting public understanding of coalition efforts and public isolation of the insurgents.

These eight pillars were judged to be critical in establishing a "democratic" Iraq that could survive and thrive. The first pillar was not originally present, but was added to the initial seven pillars as the terrorist and insurgent activity grew in intensity; in fact, it now has the potential to cause the other seven pillar efforts to fail.

The terrorist and insurgency efforts have been tailored to have maximum negative impact on coalition initiatives in each of the pillar areas. The impact of their activity has many interrelated ramifications on many factors important to achieving stability in Iraq. Primary areas of negative impact associated with terrorist/insurgency activity are associated with the following key elements:

- Development of an internal Iraqi economy that provides for generation of national revenue, functioning in-country industries and employment for its citizens;
- Establishment of national and local government structures with supporting police and judicial infrastructure to provide for personal security and a fair system of law and order to promote civil obedience and provide individual freedom of choice; and
- Existence of a supporting infrastructure of food, utilities (electricity, water and sanitation), housing and health services that promotes individual well being

Note that the first and third of these involve the production and consumption of commodities. There are complex interdependencies between key factors that create a real dilemma in terms of the way forward and represent very complex effects-based operations from the perspective of the coalition forces, the Iraqi government and the terrorist and insurgents. Examining both macro and micro effects is important in understanding effects base operations in this context.

3.2 Overview of a *Pythia* Model of OIF

Sketching out a build of a *Pythia* model for Iraqi Insurgency starts by capturing the behavioral aspects of the key pillars for mission completion and insurgency activities that can impact realization of these pillars identified in the previous section. These all fall into areas of action that the coalition (in support of Iraqi efforts) might take that, with the support of the Iraqi people, can realize desired end-state objectives. At a high-level they organize into the flow shown in Figure 7.

Examination of these key pillars and their inter-relationship (going beyond the top-level view of Figure 7) makes it clear that the role of the individual Iraqi citizen will be a major contributor to realization of these key pillars. Individual behavior is strongly impacted not only by good security and leadership in government, but also how the population perceives its own access to the necessary comforts of life and even the individual's opportunity for advancement. Specific pillars and areas directly impacted by terrorism include:

- Existence of a supporting infrastructure of food, utilities (electricity, water and sanitation), housing and health services that promote individual well being;
- Development of an internal Iraqi economy that provides for generation of national revenue, functioning in-country industries and employment for its citizens.

By in large these commodities and their availability have a significant impact on other OIF pillars such as providing essential services to the Iraqi people and establishing the foundation for a strong economy that helps the nation stand by itself. This in turn leads to a desire to explicitly model commodities and their impact on individual participation and commitment as well as higher level political and economic goals for Iraq.

The next step in sketching an EBP with *Pythia* is to take the general and high-level objectives of Figure 7 and identify more specific actions and effects necessary to realize the objectives. Typically, one first places at the right side of the *Pythia* model the final end-state or ultimate strategic objectives of Figure 7. Next, working from right to left, one identifies supportive strategic actions and other intermediate objectives from Figure 7 that are necessary to realize the end-state objectives. In doing this, an "influence structure" evolves and some of the pillars of Figure 7 are found to necessarily precede realization

Figure 7 Organizing the Key Pillars of OIF

of other pillars. Finally, one identifies independent action that participating forces, including the adversary, might take. Mostly, these input actions are tactical in nature that accomplish tactical objectives; with *Pythia* these are not just military actions but can be political and economic as well using all of the instruments of national power to effect the PMESII system of systems in the region. The result at this point is a view that begins to show the structural potential for relationships between the major pillars, and this view is shown in Figure 8. For purposes of aiding tracking, Figure 7 and Figure 8 use a matching coloring (light blue, light yellow and light green) scheme.

The creation of the *Pythia* TIN model accommodates identification of specific behavioral aspects that also have a role in realizing the OIF pillars, and Figure 8 shows three added aspects:

- The role of the Iraqi individual (in blue)
- Acts of terrorism (in red)
- Commodity categories that influence individual behavior (the green border around the yellow box).

Introducing commodity characterization into the behavioral *Pythia* TIN model lays the groundwork for testing the proposition that *Pythia* and CEM can work together.

There also may be aspects where behavior varies substantially by country region (geographic, political, ethnic, religion, etc.), and Figure 8 shows these possibilities with orange enclosure boxes.

Figure 8 sets Acts of Terrorism, as a separate independent actionable event, which has the same level of input independence control to the modeler as do Coalition and Iraqi input actions. (Note that Figure 8 only loosely alludes to downstream influence dependency; the actual *Pythia* model, discussed following, shows explicitly which influence paths were modeled.) This allows a direct look at realization of pillar objectives as influenced by the level of terrorism, not only on national and regional objectives, but also in the individual's behavior for support of the Iraqi government.

Second, this modeling evolution chose to realize that for Iraqi behavior in many aspects of influence, effects vary throughout the country based on geographic, religious and ethnic boundaries. In principal, the entirety of the model could be repeated region-by-region, but full use throughout all effects could lead to

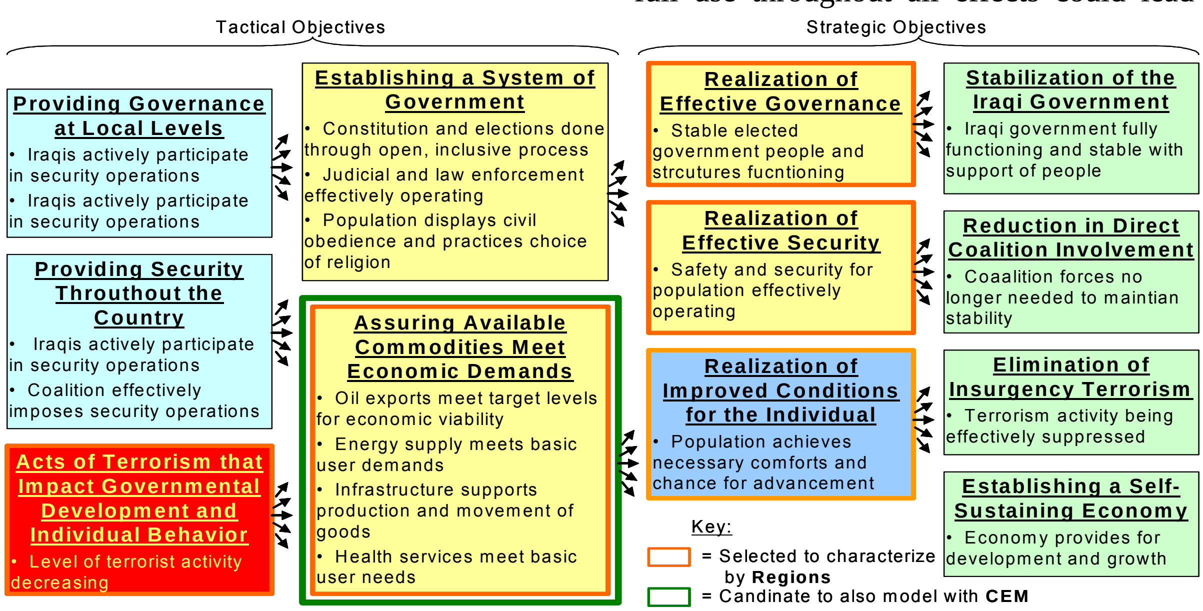

Figure 8 Major Elements and their Relational Roles

added modeling complexity beyond its worth in payoff for the experiment at hand here. Thus, Figure 8 identifies four areas, denoted by orange borders, where modeling should be expanded on a regional basis. On the left-side or input area, it seems surely necessary to characterize terrorism activities by region. In the area of "establish governance", it is likely that common methods throughout the country were employed and there is not a need for regionalization. But it was felt that response to the establishment of governance would vary by region, so those realizations are modeled separately for each region. Similarly, the end behavior of the individual in support of the new government and economy also merits separate model characterization by region. These refinements allow for setting some of the influence parameters of the model to better reflect expected regional behavior.

As discussed in beginning of Section 3, in an EBP the first-order effects tend to be physical and/or tactical. As such, this EBP sketch includes modeling of commodities in the realm of tactical objectives in Figure 8. For similar reasons, the behavior of the individual is placed in the downstream strategic objectives realm. This approach facilitates test of the experimental propositions in a couple of ways. First, it proposes an interface boundary across which the *Pythia* and CEM tools might exchange information (i.e, the green-bordered box in Figure 8). Secondly, it allows a *Pythia*-only to proceed forward so that a baseline for comparison based on added value by integrating the two tools might be made. Thirdly, with the Pythia model, the influences from other events and effects within the sketched EBP are more easily included in the test versus adding them to CEM for test purposes, wherein much additional work might be required due to the lower-level and more detailed nature of CEM. This approach does open the possibility, however, that there may have to be an examination of the quantization on commodity types that a higher-level *Pythia* uses versus the greater detail that CEM provides; this is discussed in Section 3.6.2. The intent with *Pythia*, then, is to explicitly model these commodities in a behavioral sense. Also in the spirit of Figure 8, these commodities, actually what will be a high-level grouping of commodity types, are modeled separately for each region since their availability is expected to have a significant impact on individual behavior by region (note the orange enclosure boxes of Figure 8).

Transitioning to the *Pythia* model involves expanding the organization and structure of Figure 8 by determining specific pair-wise influence associations and setting parameters of influence and timing from the parent effect to the child effect. Values for the influence associations are quantitative and can be determined from subject matter experts knowledgeable in the area. For the purposes of the test of the experimental proposition, data contained in unclassified public sources were employed here. The result of this is the *Pythia* model shown in Figure 9. It should be noted that explicit influences employed followed some general patterns:

First, most of the items shown in Figure 9 generally have a direct left-to-right influence on their "closer neighbors" as suggested by the pictorial layout in Figure 8.

Second, the area of "commodities" of Figure 9 shows grouping (See Sec. 3.6.2 for an elaboration on the groups) of three categories of effects (Health, Infrastructure and Energy) for each of three regions (Kurd, Baghdad and South). The *Pythia* model shows that these nine items have influences originating from each of their three regional counterparts (Level of Terrorism, Regional Governance and Regional Security). The modelers felt that these inputs (Terrorism, Governance and Security) have a key impact on the availability of commodities. Third, in Figure 9 it should be noted that the three sub-events of the Establishing a System of Government of Figure 8 have a "serial" casual influence (shown as

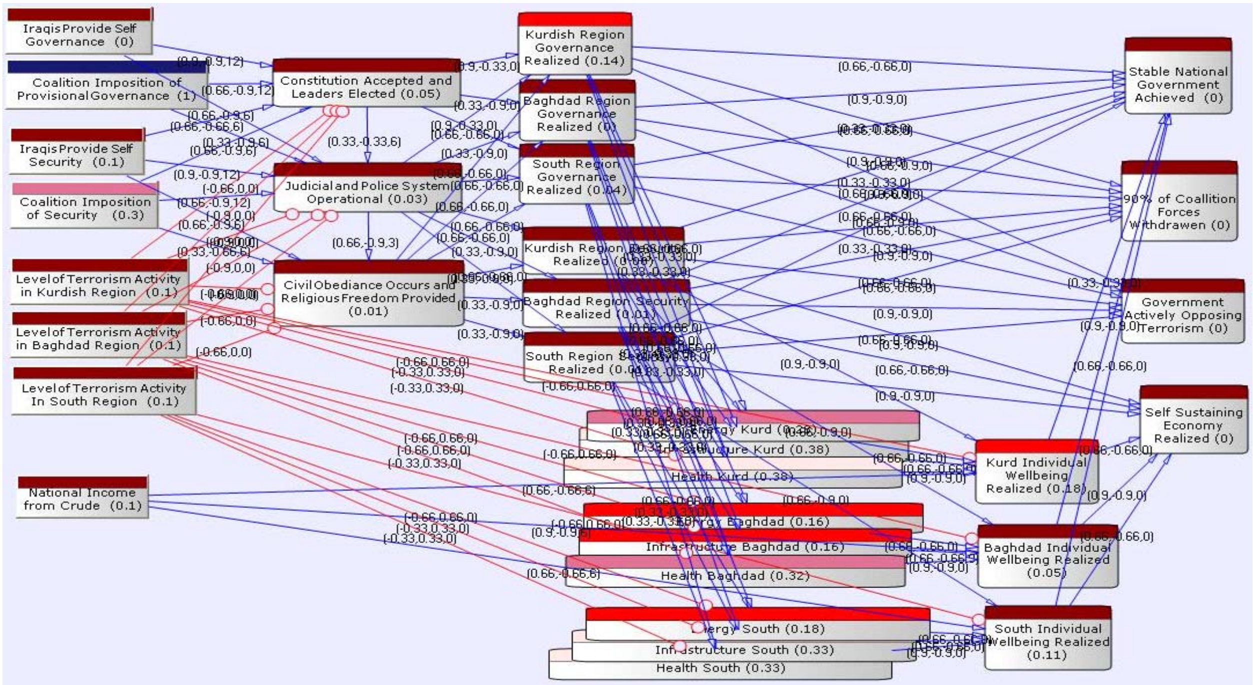

Figure 9 The *Pythia* Model for OIF

vertical arcs) not only on the commodities, but also the sense of well being and the final strategic objectives that will occur over time.

Finally, the commodity event "National Income from Crude" is shown to directly influence only the individual's wellbeing. This event is intended as a direct measure of money flowing into the country and as such, the model feeds its effect directly to the individual and thus also affecting wellbeing. This *Pythia*-only model handles commodities and their availability not in a quantitative, metric sense but rather in a behavioral satisfaction sense. The Bayesian probabilistic values (which range from 0 (or False) to 1 (or True) of the *Pythia* nodes are taken to represent a degree to which the individual/consumer demand for commodities might be met, and in turn how that might influence the attitude of the individual to support the country's government and economic goals.

For the proposition test purposes here, *Pythia* uses a high-level representation of commodities. Actually what is shown are categories of commodities that are aggregate groupings of specific, typical commodities. All commodities do affect the behavior of the individual, but here for purposes of test of the hypotheses, they have been aggregated.

Finally, in Figure 9 it should be noted that the commodity "*National Income from Crude*" is not regionalized as the other commodities are represented. Also, *National Income from Crude* is kept as an independent input variable in the model. While it is true that other events and actions in the model affect the national production of crude, keeping it as an independent variable allows full flexibility in studying its influence. Basically, this input action is the event that provides the country with money for success. Conversely, the other three commodity categories, Health, Energy and Infrastructure, have been made totally dependent events with their state being driven by terrorism activities and the success in realizing regional governance and security.

3.3 Overview of CEM Model of OIF

In contrast to traditional logistics models, CEM models deal with abstract flows that have no physical representation in the battle space. Logistics models track individual containers of commodities and are concerned with the paperwork to maintain supply levels at designated locations. For example, a single missile on a truck could be destroyed in a logistics system. Civil Environment would be concerned with the missile production facility, the roads (transport commodity), oil drilling/production and electric power facilities and the flow of an aggregate commodity, "electricity" or "oil". The actual facilities are represented as synthetic natural environment (SNE) features (See Figure 3). During the course of the OIF, IEDs and other forms of terrorism cause damage to some number of objects in the SNE. This is denoted by a change to the public damage state of the object(s). A consequence of the detonation is the issuance of an interaction, as defined in the Federated Object Model (FOM). The CE federate subscribes for the interactions and upon receipt, notes its position and polls known targets in the area for new damage.

The scope of the CEM modeling effort for this research is limited to a notional OIF scenario based on open, world wide web sources. The existing CEM databases for Iraq were adapted using this open source literature and by collaborating with the Rite Solutions-George Mason University EBO Modeling team. Various data sources were used; open source, State Department, etc. The time span was 2003 – 2006.

CEM was tailored to produce the type of commodities that would have a direct influence on the attitude of the Iraqi individuals. The database for this study was configured to produce estimates of the 14 commodities in Table 1. For each of these commodities, CEM calculates the following key parameter values at a function of time:

P: the amount of a commodity that entered a district from production

p: the amount of a commodity leaving a district to be used in production.

Z: the amount of a commodity remaining in stock after re-distribution.

C: the amount of consumption of a commodity in a district.

These output values can be interpreted in terms of meeting the demands of the individual and to determine whether or not satisfaction is sufficient to support the efforts for establishing a long-term, stable government structure.

3.4 *Pythia* Simulation Results

The *Pythia* model, Figure 9, was exercised for a set of courses of action (COAs) to establish its acceptability for a test of the interface propostions. The COA set for *Pythia* inputs is presented in Figure 10. *Pythia's* primary GUI interface is these probability profiles. A probability profile shows the calculated probability of a *Pythia* modeled event or effect versus time. Input Actionable Events actually are the input "forcing function" or COA; even so, the same probability profile display can be used to show the "time of actions" for each input ac-

Table 1 Fourteen Commodities Modeled by CEM

	Commodity Name (14)	
– CLT-Clothing	CMB-Comm_Broad	CMT-Comm_Tele
– CON-Construction Materials	CRD-Crude_Oil	ELE-Electric
– FOD-Food	MAN-Manufacturing	MCH-Machinery
– MED-Medical	PER-Personal	
– POL-Petroleum, Oil & Lubrications	RPT-Repair_Parts	WAT-Water

tionable event. Figure 10 shows the behavior forced for all of the input actionable events in Figure 9. The time scale is in weeks.

These input actionable events provide a dynamic time element to driving *Pythia*. Illustrating how probability profiles provide a view of the input forcing, the event "Coalition Imposition of Provisional Governance" reflects that the presence of coalition forces gives a dominating umbrella for provisional governance for the first 3 months. During this same period the Coalition is only moderately successful in imposing security and the same time the Iraqis' are just beginning their role in the restoration of self governance and self security. During the next months the Iraqis role and success in providing self governance and self security increases, reaching its largest values in the 24 month time frame. Illustrating further, the timing for the actionable event "National Income from Crude" was derived from published data that showed crude oil production levels for the mid 2003-2005 time frame. Time of actions and corresponding probabilities of occurrence for other input events, such as "Level of Terrorism Activity in Kurdish" regions were derived from more subjective observations of publicly available reports of insurgent behavior. In this case of terrorism across different regions, predictions were made also by comparing region-to-region over time and giving those regions a high probability if reported terrorism exceeded the levels in the other regions. Thus, for example, Figure 10 shows the more recent surge of terrorism activities in the Baghdad region. Now, it is at higher levels than the other two, even though terrorism in the South and Kurdish regions had peaked earlier and has since settled down.

The upper-central portion of Figure 9, in response to the time-varying inputs, models the establishment of a government and the regional progress toward realizing regional self-governance and security. Some of those results are illustrated by Figure 11.

They show that a greater success is achieved in getting a constitution accepted and leaders elected, closely followed by operational judicial and police systems. Civil obedience and religious freedom lag these, however. First insight into regional differences is also shown, wherein the Kurdish region does very well with self governance. The Baghdad region lags both in effective self governance and in realizing regional security.

There are four end-state events in Figure 9, and their results for the illustrated Coarse of Action are shown in Figure 12. These results show that the model predicts quite a low

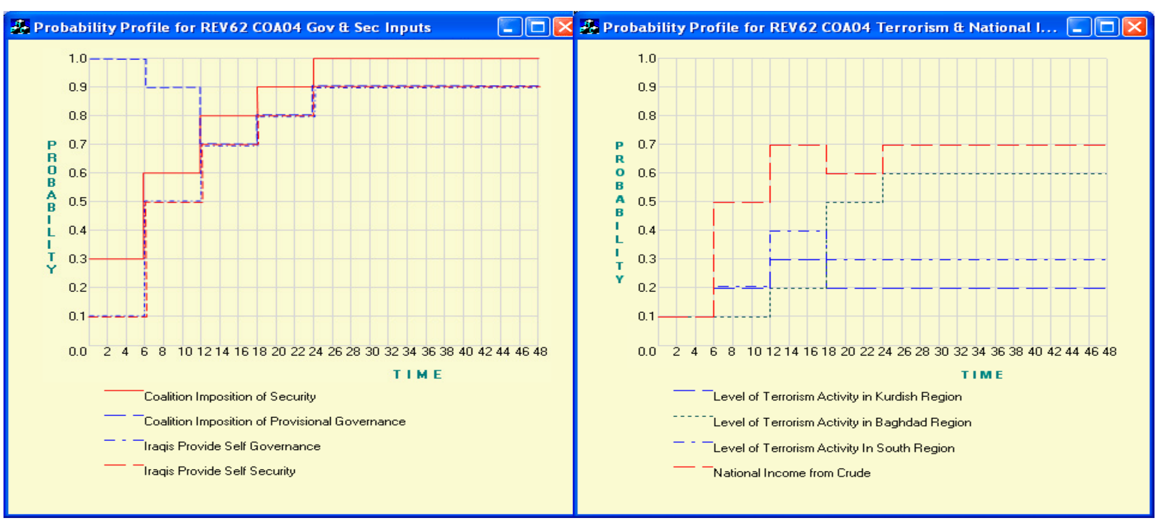

Figure 10 Input COA to the *Pythia* Model

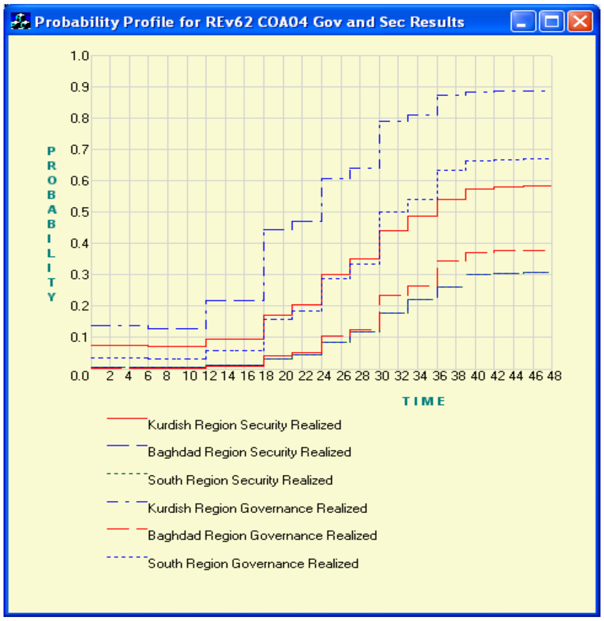

Figure 11 Establishing Security

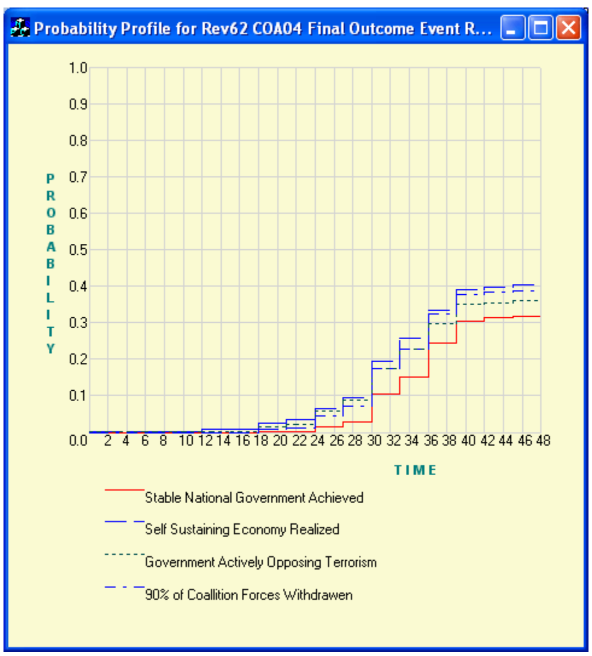

Figure 12 Realizing End-State Objectives

chance of success for the primary OIF end objectives. Any real progress toward the final end-state values does not become evident until into the third year after OIF commences. There is some progress initially and then it seems to level off during the fourth year. It is to be pointed out again, though, the primary purpose for this model was to be a vehicle for testing the hypotheses regards including and integrating *Pythia* and CEM methods. The primary purposes here are to insure that realistic inputs from subject matter expert data give a model that responds with cause/effect behavior. During the checkout of this model, other COAs (not presented here) were tried; they indicated that this model is programmed in a manner that can handle an acceptable range of possible COAs, and is sufficient for the test of the hypotheses.

3.5 CEM Simulation Results

The CEM model was set up to analyze the 14 commodities shown in Table 1 across 18 regions in Iraq. This set of commodities was determined from the examination of the *Pythia* model and the analyst's rationale that these commodities impact the local and region support of the Iraqis. The state of the various elements of the infrastructure was built as described in various open source descriptions. Thus they represent the understanding of the infrastructure elements during a period of moderate terrorism with some reconstruction actions completed and others in progress.

CEM outputs data results in a spreadsheet form. The spreadsheet list the four parameter values (P, p , Z, C) for each commodity by region for each one hour increment over a 168 hour (three week) period; a sample for the Repair Parts commodity is shown in Figure 13. Each line shows the hourly size of the stockpile for one of 18 regions in Iraq.

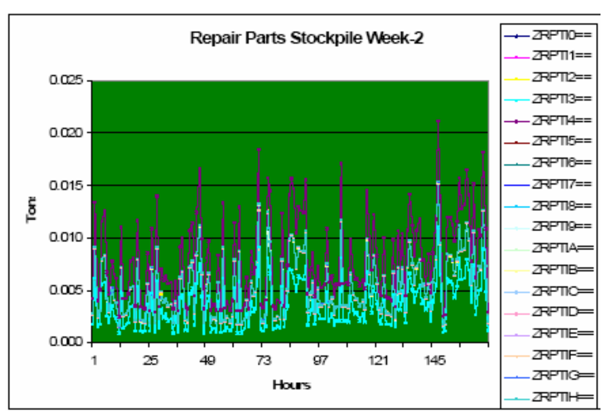

Figure 13 CEM Commodity Measures Over Time

CEM demonstrates its capabilities to model commodities at a detailed level. Much data is produced as spreadsheets that capture commodity values from their initial condition at the start of the CEM model to however long the model is run. The current CEM implementation performs these calculations on an hourly basis.

3.6 Model Interoperations

An evaluation of the propositions was conducted based on the types of interoperation that were achieved in the experiment. As shown in Figure 5 and Figure 6, the focus was on interoperation from *Pythia* to the CEM model and from the CEM to the *Pythia* model. Three types of interoperation were postulated. The first was human to human (or modeler to modeler) in which knowledge gained by analysis of one model helped inform the second modeler so that it impacts either the model construction or analysis technique. The second type of interoperation was model data to model data. In this type of interoperation, data derived from the analysis of one model can be used, either directly or through some quantifying formula or algorithm, to improve the estimates of parameter values in the other model. The actual transfer of the data occurs with human assistance, in part because the human is needed to determine the type and validity of the transfer. This could lead to the third type of interoperation which is direct model to model in which one model is able to automatically pass data to the second model either in a push mode or in a pull mode. This can lead to an automated federation of models that are connected via some protocol such as HLA. One criterion for any interoperation is that it improves the validity of one or both of the models. Each interoperation can be uni- or bi-directional. For example, it may be possible and useful to take data from the CEM model and use it in *Pythia*, but not possible or useful to go in the other direction. That would be unidirectional interoperation. Bi-directional would mean that the interoperation is possible and useful in both directions. Having built and analyzed both the *Pythia* model and the CEM model separately, the potential interoperations, first from *Pythia* to the CEM and then in the reverse direction, were then examined.

3.6.1 *Pythia* to CEM Interoperations

The development of the *Pythia* model in Figure 9, based on the discussion of the OIF in Section 3, introduced a concept of an importance of role for how commodity availability influenced individual wellbeing and how the wellbeing of the individual influenced the end states. It was clear that the original CEM was already well suited for making predictions of many of the traditional commodities. In a modeler to modeler exchange, this led the *Pythia* modelers to suggest to the CEM modelers that CEM needed to predict new commodity behaviors, such as medical services/supplies and clothing. CEM modelers agreed that such new commodities could be added. It was agreed that previous CEM databases could be used largely as is and those previously developed scenarios became the basis for the initial test runs of CEM.

It became apparent that insurgent activities would cause damage to the commodity production and delivery systems. For a data to data exchange, the *Pythia* TIN data for terrorism activity and security development can be made available for input to CEM to suggest damage and repair timings and probabilities. In previous CEM applications, such damage/repair guidance was found to be part of the initial setup of a CEM run. Once that CEM run starts, it runs entirely from these initial conditions. Ways were discussed wherein a series of CEM runs might be postulated with one CEM's outputs final state values being feed into another CEM run. Then, concepts for including repair could be handled by modifying the setup of the next, downstream CEM run. No method for direct model to model interoperation was readily evident.

Development time and resources limited the changes that could be made to CEM. Thus, for the purposes of testing the proposition, only a single-pass CEM run based on a single set of initial conditions was programmed and exercised.

3.6.2 CEM to *Pythia* Interoperations

Pythia characterizes event activities in a probabilistic sense and in this context would request CEM to provide a 0-to-1 measure that available commodities can meet consumer demand. CEM, as shown in Figure 13, produces consumption estimates for a commodity as well as a stockpile available for each commodity. Actual demand is met when there is a positive level of stockpile. Stockpile is determined by current stockpile minus consumption plus amount of production and flow into stockpile. Consumption per capita can be calculated if one knows the number of consumers in each sub-region. Three types of potential outputs that can be calculated from the CEM runs were considered. The first is a timed average of met demand based on the hourly amount of stockpile and the flow from the stockpile. This yields a metric of the percentage time that demand is meet for each commodity. The second concept is to not provide all of the detail from CEM, just the end-of-week levels of supply and the projected level of supply for the next week. The ratio of these numbers may be an indicator or "happiness" with the commodity situation. For commodities that cannot be "stored", such as electricity, a third type of output might be useful for practices such as "rolling blackouts". There may be sufficient capability to meet demand, but flow rates cause rolling blackouts. Consumers may end up being "somewhat satisfied" or dissatisfied even though their full demands are not strictly being met.

The first of these three possibilities, a timed average of met demand, was chosen for this study to examine the interface issues from CEM to *Pythia*.

It is also evident that CEM details the inter-relationships between many commodities and realizes its accuracy by using, as much as it can, specific, real commodity details. The CEM model calculates 14 different commodities over 18 regions. This granularity, while fine for CEM, becomes a large complication for the high-level *Pythia* mode. A resolve is to consolidate CEM's commodities into "categories", possibly as shown in Table 2. The intent of defining these four categories (Health, Energy, Infrastructure and National Income) is to make their relationships to CEM commodities be as much non-overlapping as is possible. This is done to simplify the setting of the influence probabilities within the *Pythia* model.

Table 2 Grouping CEM Commodities into Categories for *Pythia*

	Consolidated Categories			
CEM Commodity	Health	Energy	Infrastructure	National Income
CLT	x			
CMB			x	
CMT			x	
COM			x	
CRD				x
ELE		x		
FOD	x			
MAN			x	
MCH			x	
MED	x			
PER	x			
POL		x		
RPT			x	
WAT	x			

Having developed the *Pythia* and CEM models in concert together, the category/commodity relationships of Table 2 becomes a candidate mechanism for data to data interfacing of the two. This is the basis that fostered the definition in the *Pythia* model shown in Figure 9 of its four categories of commodities (Health, Energy, Infrastructure and National Income). Creating these categories represents a form of human to human interoperation. Knowledge gained from the CEM model is used to inform the development of the *Pythia* model.

The CEM model was run for a three week period. The data collected was then consolidated into a single table showing the percentage to time that demand was met for each commodity in each of the 18 provinces over the three week period. These results were further aggregated into the three regions and four categories of commodities used in the *Pythia* model so that the results could be used to evaluate the *Pythia* model and make potential changes to its parameters in a data to data exchange. These results are shown in Table 3.

Table 3 CEM Percent of Time Supply Met Demand

	South	Bagdad	Kurd (North)
Health	83	84	77
Energy	83	25	56
Infrastructure	75	71	70
Income	89	100	100

When the *Pythia* model was exercised, probability profiles of the four internal events related to commodities results. An example is shown in Figure 14. These profiles of commodity measure show a view of *Pythia* alone. The values drop from their initial values at time t = 0, primarily due to the rise in terrorism levels (Figure 10). As success is realized through establishment of a Government, Governance and Security (Figure 11), the availability of commodities predicted by *Pythia* begins to increase. Ultimately *Pythia*'s measure of individual wellbeing increases, with the Kurdish Region leading the pace and the Baghdad Region remaining the most troubling. The model indicates that only in the Kurdish Region are reasonable abundant commodity level reached by month 48. And as in the previous discussion, the Baghdad Region falls behind the other two regions.

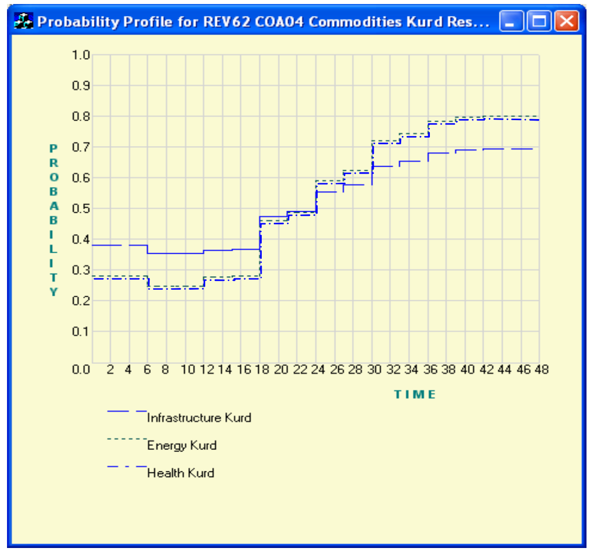

Figure 14 *Pythia* Representation of Commodities for the Kurd Region

The results of the CEM run were compared to the *Pythia* (TIN) outputs as shown in Table 4. To do this it was assumed that the CEM run occurred during a certain window in the time line of the *Pythia* run shown in Figure 14. Since the CEM run was based on data that had the infrastructure fairly well intact, it was assumed that the CEM run was representative of the later time period in the *Pythia* run (months 39-42).

The behavioral aspects provided by *Pythia* to indicate commodity levels is very encouraging regards a useful interface boundary from CEM to *Pythia*. These examples of commodity availability generated totally from *Pythia* parallel what one might expect that CEM would produce, given a similarity of inputs and time scale. It indicates the feasibility of taking CEM outputs that measure commodity output and substituting them into the *Pythia* model of Figure 9 by replacing these dependent *Pythia* events with independent actionable events whose a priori probabilities versus time are set to duplicate the commodity

Table 4 CEM Percent of Time Supply Met Demand vs *Pythia* Probabilities

	South-CEM	South-*Pythia*	Bagdad-CEM	Bagdad-*Pythia*	Kurd (North) - CEM	Kurd (North) - *Pythia*
Health	83	0.5	84	0.4	77	0.7
Energy	83	0.6	25	0.3	56	0.8
Infrastructure	75	0.5	71	0.4	70	0.7
Income	89	0.7	100	0.7	100	0.7

availabilities predicted by CEM. This could be done either using data to data interoperation or direct model to model interoperation. Alternatively, it may be possible to make several snapshot runs of CEM at different points in time and use those results to adjust the parameters within the *Pythia* model so that the *Pythia* commodity results closely match those predicted by the CEM.

4. Experiment Results

When this research started, it was not at all clear what types of interoperation would be possible between *Pythia* and a CEM model in support of effects based planning. Three levels of interoperation were postulated, and a procedure for building and using the two modeling techniques was formulated and followed. Table 5 summarizes the findings with respect to the interoperation between these two types of models.

Regards an interface from *Pythia* to CEM, neither a direct model–to-model interface nor a data to data interface from *Pythia* to CEM was found. A human to human interface was found and used. The *Pythia* modelers informed the CEM modelers what the main commodities were in the *Pythia* model and provided the concept that repair to elements of the infrastructure would occur. In addition, insurgents could damage elements of the infrastructure so these concepts needed to be incorporated in the CEM model. This provided better focus for the CEM model and provided the questions that were needed to be answered by CEM.

Regards an interface from CEM to *Pythia*, we did find and show a method for all three types of interoperation. At the *Pythia* level events were defined that provided behavioral estimates of commodity availability with these events being influenced by other *Pythia* events that model the political and security environments of OIF, which provide for safe generation of commodities. The more accurate and detailed commodity information provided by CEM then becomes a substitution for the be-

Table 5 Summary of Experimental Results

		Human to Human	Data to Data	Model to Model
CEM to *Pythia*	Verified	Yes	Yes	Yes
	Comments	Structural Modifications and improvements to *Pythia* (grouping of commodities)	Verification of Probability Values Postulated Adjustments to g, h, and t values	Postulated CEM outputs directly feeding inputs to *Pythia*
Pythia to CEM	Verified	Yes	No	No
	Comments	Structural Modifications to CEM (Commodity Types, Repair or Damage Types)	Postulated Damage or Repair Levels (Probabilities) for multiple time periods	Significant interface issues yet to be explored.

havioral-derived *Pythia* events. The CEM-derived commodity metrics become the "Time of Action" COAs that then drive the remainder of the higher-level *Pythia* model. With this method, the development of the two modeling methods can proceed in parallel followed by substitution of CEM's results into *Pythia* where more accurate modeling results are required.

5. Conclusions

This preliminary research revealed some promising insights into the possibility of obtaining better effects based analysis by employing various levels of interoperation between very different modeling techniques. The question of the feasibility of integrating the use of Effects Based Plans, represented as probabilistic models, and System of System models, which provide a physical quantification, has been explored in some detail through the conduct of a discovery experiment. Three levels of potential interoperation were explored. Each level provided some perceived improvement to the collective analysis of the individual models. The first level was a basic human to human interoperation where the knowledge generate from one modeling techniques is used to inform the other technique. The cost of doing this is rather modest and the return is possibly quite significant in terms of improved modeling. The second level, data to data interoperation, was shown also to be feasible from the more detailed CEM model to the more abstract *Pythia* model and to provide added insight into model results. The cost is somewhat higher to achieve this level of interoperation because of the need to develop tailored algorithms or techniques for translating the results of one model into values that can be used to improve the other. The most costly approach would be a direct model to model interoperation. This requires not only the data exchange to be defined but also requires the model to model interface to be created so that the automatic transfer can occur. The degree of difficulty and the worth of this form of interoperation is an area for further research. In addition to conducting the experiment to explore the interoperation between the models, a process and various techniques to create that interoperation were developed. These may be useful in further efforts to support the interoperation between EBP and SOS modeling techniques.

In the case study used in this research, the value of creating the interoperation between a *Pythia* model of the EBP and a CEM model of the commodity system of system has been illustrated. Having developed and interoperated with both models means that there is increased confidence in the *Pythia* TIN because key probability values generated therein have been confirmed by the much more detailed CEM. The operational and strategic focus of *Pythia* helped set up CEM and thus focus its analytical findings. *Pythia* provides a more strategic view of the situation that can be used to support analysis at this level, while CEM can be used to support more tactical level analysis about specific actions on the commodity system of systems.

Overall, this effort points to a more robust approach for conducting effects based operations in the 21st Century and illustrates the use of experimentation to explore and discover new approaches. This research may sharpen the focus of further efforts to better combine and integrate the variety of models and techniques that are available to support effects based operations.

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