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Situation Analysis and Collaborative Planning for Complex Operations

Topics: Topic 3-Modeling and Simulation; Topic 4-Cognitive and Social Issues; Topic 9-Collaborative Technologies for Network-Centric Operations

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Situation Analysis and Collaborative Planning for Complex Operations

Complex operations are conducted in environments that must be represented by large-scale systems of systems that include non-physical systems (e.g. political and, social networks, economies, information flows) intertwined with physical systems (e.g. infrastructures, military systems, etc.) that are adaptive and exhibit emergent (unexpected) behavior. Planning for such systems requires adaptive and robust approaches that are based in a comprehensive study of both the structure and the dynamics of these systems. This paper describes analysis and planning tools developed and evaluated in the DARPA Conflict Modeling, Planning and Outcomes Exploration (COMPOEX) Program for complex operations. The tools enable systems of systems analysts to compose conceptual, then computational models of regional and nation-level situations to explore the behavior of their interacting systems. The flexible simulation architecture allows agent-based models, systems dynamics models, Bayesian networks, linear program models, and other discrete-time models to be composed into an integrated political-military-economic-social-infrastructure and information (PMESII) simulation. The paper describes the concept of operations, the analysis and planning tools, and provides the results of formal experiments conducted with operational interagency teams on planning exercises using PMESII models across a range of lines of effort.

1. Complex Operations Planning

Complex operations are joint military and non-military operations that are characterized by:

- Situations that involve highly interconnected dynamic and adaptive political, social, economic, infrastructure and information systems, as well as the formal militaries and unstructured forces (insurgencies, criminal entities, etc) operating within that environment. Such systems of systems are often characterized by uncertainty and instability – and are inherently unpredictable.
- Necessity to plan, adapt and orchestrate all elements of national power to effectively perform shaping, deterrence, containment, defeat or restoration; this requires the coordination of interagency contributors, and an integrated plan that represents the whole of government.

Iraq, Afghanistan, Somalia, Bosnia, and Kosovo are all examples of complex contingencies characterized by complexity that challenged analysts and operational planners – demanding a deep understanding of the situation and operational adaptation to the changing environment.[1] One recent review of U.S. experiences noted that these, “complex contingencies in recent years have demonstrated the limitations of our stove-piped, single agency planning systems.” [2] The 2006 Quadrennial Defense Review (QDR) identified the requirement to “Implement Adaptive Planning across the Department by increasing the number of fully qualified planners, investing in advanced planning toolsets, and organizing planning staffs to exploit the advantages that new technology and highly trained, experienced planners provide.”[3] The COMPOEX program is developing a planning toolset to support complex operations, proving the capability to explicitly model the underlying situations, develop coordinated interagency planning options, and explore the dynamics of the situations and the range of effects of plans.

The newly issued Joint Operations and Planning doctrine (Joint Publications 3.0 and 5.0, respectively) acknowledge the need for systems analysis and dynamic simulation methods for complex contingencies:

- *The need to represent situations explicitly, in systems terms*- Current joint doctrine for situation assessment and planning emphasizes the importance of developing a systems understanding of targets to provide insight into structural characteristics and behavioral dynamics to reveal properties such as centers of gravity (COG's) and decisive points. Systems considerations allow commanders and their staffs to consider a broader set of options to create desired effects while avoiding undesired effects.[4]
- *The value of dynamic analysis of the potential effects of plans* – Behavioral analysis, performed by games, exercises or simulations to predict potential effects (consequences) stimulates in-depth thought about the operation, causing the planning staff to consider the underlying dynamics of target systems - gaining insights that otherwise might not have occurred. "This process highlights tasks that appear to be particularly important to the operation and provides a degree of familiarity with operational level possibilities that might otherwise be difficult to achieve…The most sophisticated form of wargaming is modern, computer-aided modeling and simulation." [5]

A recent National Research Council report on Defense Modeling and Simulation also emphasized the need for improved representations of complex situations, as described in this paper:

> Many aspects of military operations—for example, the implications of ubiquitous networking, the implications of different types and degrees of information, and the potential political, social, and economic consequences of alternative courses of action—are not yet well understood, so M&S does not yet represent them well. Although much is known about counterinsurgency, and even about terrorism, techniques by which M&S can codify or apply that knowledge have not been developed. Although the past successes of M&S, partially enumerated above, support further development, quantitative justification would reinforce that support.[6]

2. COMPOEX Approach

The COMPOEX capability provides systems of systems analysis, modeling, and wargaming capabilities to represent the dynamics between governments, civil populations, and a myriad of other actors (e.g. insurgent forces, regional powers, and economic interests) and the relevant PMESII systems. COMPOEX is an effects-based planning toolkit that allows interagency planners and commanders to perform three key functions (Figure 2-1):

- Model – Compose *conceptual* models of individual PMESII systems within a situation (e.g. static concept maps, network descriptions, etc.) and then translate these to *computational* models at multiple levels of resolution (causal granularity) that describe the underlying dynamics. Compose the individual model components into an integrated multi-resolutions model (MRM) that models the interactions between the PMESII system of systems for a target situation (e.g. PMESII systems within an urban area, nation state or a larger region of states).
- Plan – Compose courses of action and simulate the effects using the MRM's developed earlier, allowing coordinated teams of interagency planners to compose and evaluate plans along individual lines of effort (LOE's e.g. governance, security, reconstruction, etc.) before integrating the LOE's into a theater-level campaign plan.

- View – Compose custom views of the effects across all PMESII systems and the dynamics within and across the PMESII models. Allow analysts and planners to tailor custom views of critical subsystems, indicators, and metrics in temporal views (time impact of counternarcotics actions on production), spatial views (e.g. narcotics production by province), or functions views (e.g. the economic flow of narco-profits to warlords and traffickers).

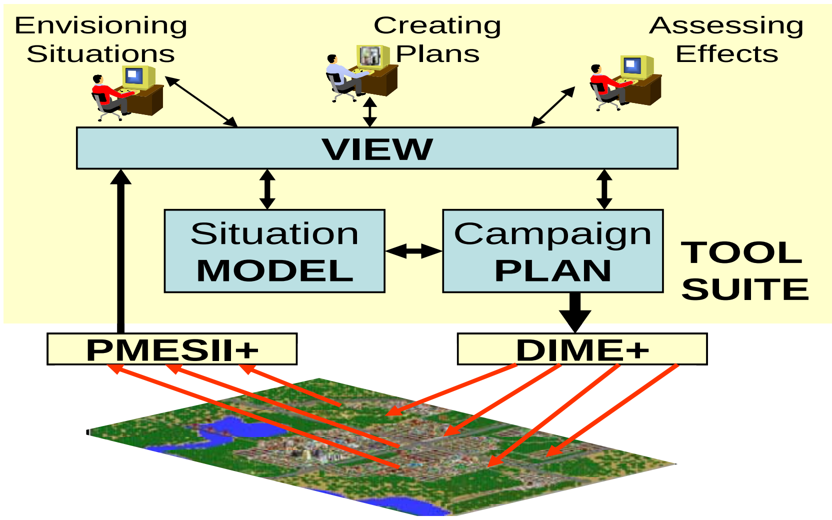


Figure 2-1 COMPOEX Toolset enables Interagency Teams to collaboratively *Envision* complex situations, *Create* campaign plans and *Assess* the expected effects of those plans

These functions allow users to simulate and anticipate the range of effects of inaction (the "baseline", or anticipated outcomes if no actions are taken) or planned course of action to explore the effects of candidate campaign plans. This capability also allows users to explore alternative *theories of conflict*, or alternative explanations of what underlies a situation in conflict. It also allows planners to assess the effects of alternative course of actions against alternative theories of the conflict (or system) to develop robust plans that account for uncertainties in the way a target system operates.

The use of a common dynamic model of a situation provides a common framework to achieve intelligence-operations collaboration, allowing intelligence (J2) and systems of systems analysts (J8) to share a common model (and understanding) of a PMESII environment with operations planners (J3) who seek to achieve effects and endstates in that environment.

The development of the COMPOEX toolset required solutions to several specific challenges:

- Explicit modeling of PMESII systems – Graphical model-building tools allow analysts to rapidly move from structural descriptions of target systems to dynamic models; this provides analysts a step beyond the current methods of compiling databases of static properties of effect-node-action networks.
- Composition of multiple models – The COMPOEX simulation architecture allows models of several different types, and at different levels of causal granularity to be integrated into a common operating framework.

- Exploratory analyses of causality – Visualization tools present the system behavior in a form that allows the user to trace effects back to causes (Was this effect a result of an action? Was this a second- or third-order effect?) and visually see the behavior of individual systems, and their interactions.

The COMPOEX toolset is comprised of three integrated tool elements (illustrated in Figure 2-2):

1. ConflictSpace Modeling Tools – Provide the capability to search data sources (e.g. open sources, SIPRNET, special holdings), capture relevant PMESII data, and construct graphical conceptual models of PMESII systems. Political-social-military network models are diagrammed as networks, economic infrastructure and information systems are diagrammed as systems flows. These *conceptual* representations are then translated to computational models by adapting a library of generic PMESII system model components, tailoring model parameters and structure to represent the specific systems being represented.

2. Option Exploration Tool – The collection of PMESII model components are composed into an integrated multiresolution model (MRM) that can now simulate a baseline of future behavior (e.g. stagnant growth, increasing corruption, expanded terrorist influence and unrest), and the effects from candidate US and coalition actions. The Option Exploration Tool allows planners to explore the behavior of targeted systems within the MRM and evaluate specific effects of optional sequences of actions.

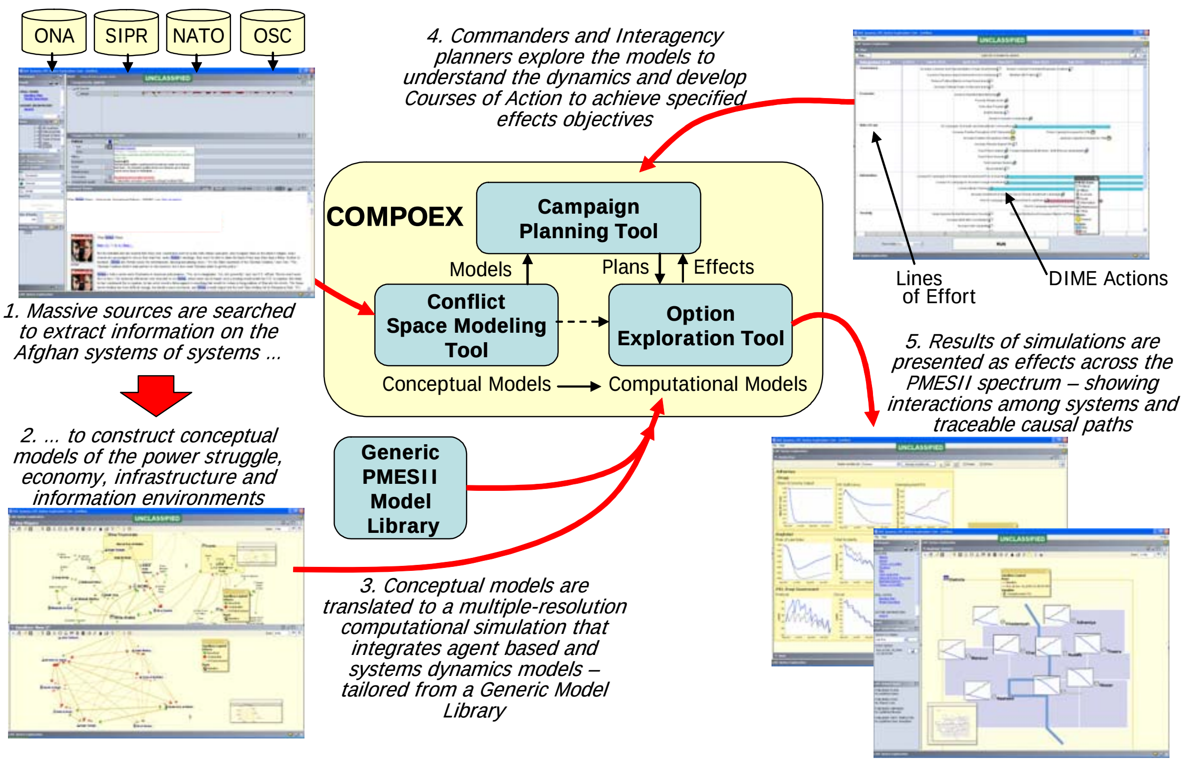


Figure 2-2 COMPOEX Tool Suite Major Components and Interactions

3. Campaign Planning Tool – This tool allows planners to schedule coordinated DIME actions along multiple lines of effort categories (e.g. economic, governance, strategic communications, etc.) in a standard planning synchronization matrix format. The planner enters the attributes unique to each discreet action (e.g. time of economic action start, action duration, rate of investment, source of investment, targeted economic sectors, targeted

geographic region or population, etc.) and the resources required (e.g. financial resources, personnel, etc.). The planner can also enter specific effect criteria (e.g. increase unemployment by 20% in a specified geographic region within 6 months) to be evaluated when the simulation is run to determine if the plan achieves specified desired (or undesired) effects.

2.1 Model Composition

COMPOEX provides a model-building process, model-building tools and a baseline library of reusable PMESII system models that can be composed (integrated) into a system of systems to support campaign planning. The models are integrated on a "backplane" that synchronizes all models in time and links model interactions such that all models operate as a single finite state machine.[1] The architecture enables model plug-and-play, fully-programmable interaction across models, and model reuse in accordance with COMPOEX backplane Application Program Interfaces (API's). COMPOEX has developed a set of generic PMESII models in a reusable model library; the principles that allow these models to be readily instantiated to a given geographic region are summarized below:

1. *Scope*- Models within the library represent the fundamental physical and nonphysical (e.g. human, economic, information) systems across the PMESII spectrum; the systems encompass wide range of human social domains (e.g. agricultural, industrial and information societies.)
2. *Focus* - Models within the library focus on the most common systems that represent the sources of competition and conflict (political, social, economic and armed sources of power) and the restraints on these sources (rule of law and other governance, social and cultural norms, global political, legal and economic norms).
3. *Reuse* - Models are reusable, in that they can readily be tailored to a particular environment by: 1) specifying model entities and attributes, 2) specifying relationships within the model between entities, and 3) specifying contextual parameters.
4. *Duplication* – Models may be reused multiple times within a composed simulation, allowing multiple version of a single model to be applied (e.g. ten versions of an economic model to represent ten provinces of a country).
5. *Multi-Resolution* – Models may be adapted to represent various levels of granularity within a single models (e.g. a generic meso-economy models may be used at the country level and a separate models may represent meso-economies within provincial areas).
6. *Compatibility* - All models operate within model services on the COMPOEX backplane architecture, allowing interaction between models each simulation cycle (typically one week).
7. *Causality* - All models represent physical and non-physical causality and expose that causality, presenting allowable actions and dynamic PMESII state data to the backplane.

The library contains a set of generic models that provide a starting point to compose an interactive model base to support campaign-level planning. A primary question from users is, "How long does it take to construct a model of an area using the model library?" Of course the answer depends on two factors: 1) the scale of the area (for example, a country, province, or urban area are quite different in scale) and, 2) the complexity of the area, measured in number of actors (non-physical systems) and physical systems and the degree of their interactions.

[1] A finite state machine is a mathematical model of an entity that describes its behavior as a result of its past history and current inputs; in COMPOEX the behavior of all models are described by their prior states (e.g. prior values fed back as inputs) and new inputs (e.g. variables fed from other models, or exogenous actions inserted into the model).

Table 2-1 provides a typical model library catalog, organized by the PMESII domains, containing models at different levels of granularity for integration within composed models. The model components, tailored and on the COMPOEX backplane to form a multi-resolution model (MRM).

Table 2-1 Representative set of basic Model Library components

PMESII Category		Model Components	Model Paradigm	Modeled functions
Political-Social Actor s	Political	Regional influences National government Government institutions Local government Military organization Criminal Network Non-Gov't Orgs	Generic agent-based models of interacting actors (individuals and institutions) that compete for power and sense the virtual world state	Each component is a network of actors with political, social, economic and military lines of influence.
	Social	Population segment attitude	Value functions or Bayesian	Aggregate attitudes based on local conditions and media influences
Virtual World Models	Economic	National Macroeconomy Mesoeconomy	Systems dynamics Systems dynamics	National aggregate GDP Interacting economic sector elements
	Infrastructure	Electrical Power Telecommunications Water service Sanitation service Health Care services Education services Manufacturing Agriculture Construction Food produce-distribute Transport Networks	Systems dynamics Systems dynamics Systems dynamics Systems dynamics Systems dynamics Systems dynamics Systems dynamics Systems dynamics System Dynamics System Dynamics Linear Programming	Infrastructure models represent performance and capacity, also may feed meso-economy models with production and consumption Nodal distribution networks
	Information	Media sources Media channels	Time-discrete Time discrete	Media message production Message access, flow, impact
	Military	Security by Rule of Law Military Deployment Military Engagement Insurgent Targeting	System Dynamics System Dynamics System Dynamics Bayesian net model	Police-Judicial-Prison Security-Civil impacts Basic Lanchester attrition Pol-Civil-Infrastructure. targeting

The COMPOEX tool architecture (Figure 2-3) distinguishes the campaign planning tool that organizes and schedules the injection of actions to models along the simulation time sequence, and the option exploration tool that hosts the integrated model. All models are plugged onto a "backplane" that represents the state vector of PMESII state variables. The models are stepped in time-discrete manner, generally in one-week increments, simulating behavior over a 2-3 year period of time. Characterizing the integrated simulation as a finite state machine, the state vector is the memory that stores current state; the sequence of states for any given variable over 156 weeks of a 3-year simulation represents the behavior of the variable. A typical COMPOEX model may include well over 10,000 such state variables. The visualization service allows users to customize views of any of the variables and their relationships; it also detects and displays discrete effects that should be brought to the attention of the planner. It furthermore allows the user to trace causality within the simulation – allowing the user to trace the (upstream) variables on which an effect is dependent, and the (downstream) variables that are dependent on the effect variable.

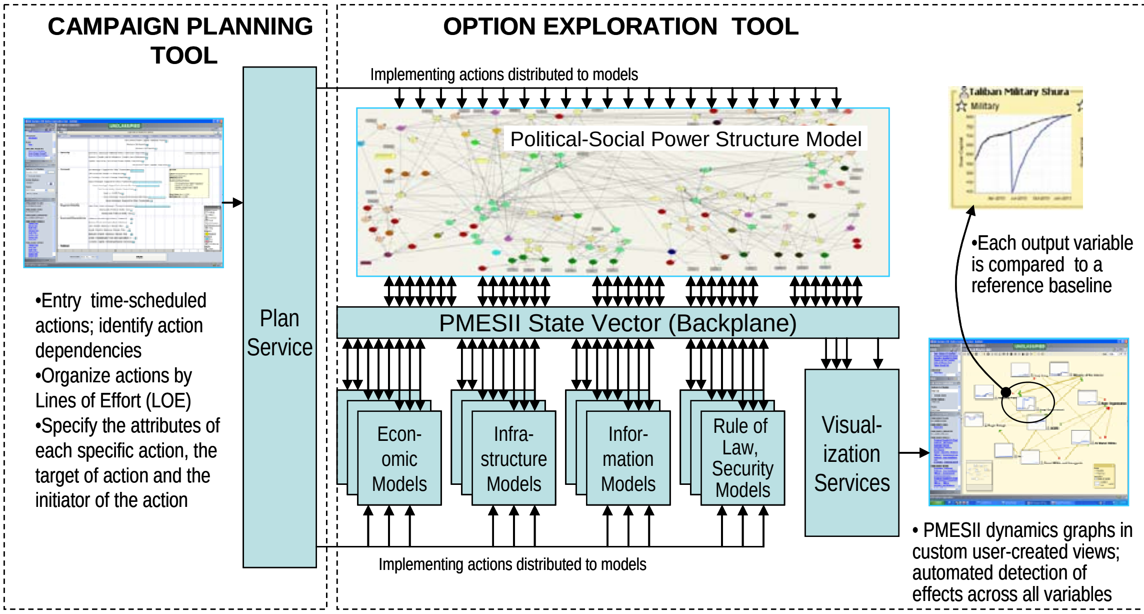
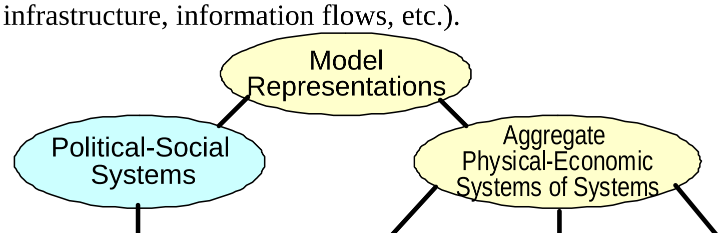


Figure 2-3 Integrated model within COMPEX tool architecture

COMPOEX allows the composition of the major categories of simulation models (Figure 2-4) that represent non-physical human systems (political and social domains, and the structure of power and competitions for power) and more-physical systems (including economic systems of production-consumption, infrastructure, information flows, etc.).



Behavior Modeled	Major human decision-making and interaction of inter-dependent actors	Dynamics of interconnected continuous systems	Probabilistic alternatives and sequences	Dynamics of discrete events systems
Modeling Paradigm	Agent based Models	Systems Dynamics	Bayes Nets	Discrete time models; Petri Nets; Markov models
Strengths of the Modeling Approach	•Accounts for the interactions between actors and their competition-cooperation for power across independent goal sets •Enables simulation of emergence of complex behavior	•Represents the non-linear behavior of highly coupled physical and hybrid physical-non-physical systems •Allows for feedback, delay, storage, queues	•Represents conditional probabilistic behavior •Models non-deterministic activities, and cognitive decision-making	•Represents activities that have timeconstrained sequential activities •Can estimate hidden sequential states
Modeling Tool	Power Structure Toolkit (PSTK) graphical agent simulation construction tool , developed on COMPOEX	iThink ™ or VenSim™ commercial tool	Netica™ commercial tool	Commercial, open source or custom tools

Figure 2-4 – Model Representations Composed within COMPOEX

Underlying the state crises and conflicts of COMPOEX models are inherent *power struggles* between competing actors and the dynamics of that struggle determine the duration, intensity, and ultimately the outcome of the struggle. The power struggle encompasses competing, and often mutually exclusive, interests and issues of values, ownership, and policy control. This struggle is at the core of the crisis and conflict - and must be understood to effectively perform a situation assessment and develop strategies and operational plans to influence the situation.[7] Consider the intra-state Viable Peace model (VPM) developed in *The Quest for Viable Peace: International Intervention and Strategies for Conflict Transformation*; the model describes the transfer of power from a political economy of conflict (a state captured by criminal elites, subservient to clients) to a self-sustaining peace model (Figure 2-5)[8].

COMPOEX models the VPM "political economy" where wealth and political power are inexorably related; the primary elements of the model include principal competing actors are the institutions of state government, political criminal elements, and the mass of society. Within the transformation process, the international community, external actors, join the struggle to move the state from conflict toward a viable peace. The VPM distinguishes the legitimate economy (white), unauthorized flow of new goods through distribution channels other than those authorized or intended by the producer (gray economy) and illegitimate economy (black) are modeled, with the flows of revenues to competing actors. The elements and structure of the model remain essentially the same, but the lines of influence and flows of power are changed to reduce the power of illegitimate actors and increase the power of the legitimate state actors; the effect of external international action is to increase the capacities and power of legitimate institutions of state.

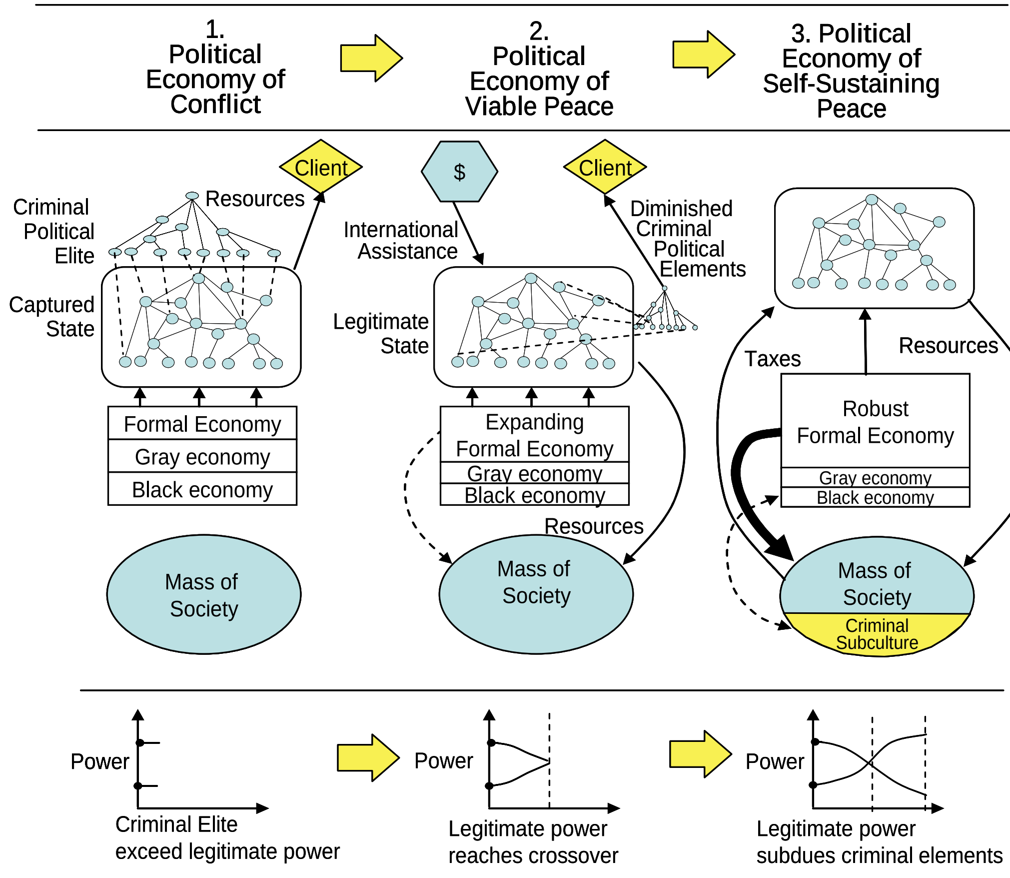


Figure 2-5 Power Transformation process in the Viable Peace Model (VPM)

2.2 Modeling Abstraction and Partitioning

COMPOEX models the dynamics of struggles for political, economic, armed (military) and social power that encompass, predominantly:

- *Political actors*, institutions or elites that are embroiled in competitions for the power to control and implement policy,
- *Social actors* including civil society and institutions whose consent, support, and even subservience, may be sought by the political actors,
- *Mediators* and *Spoiler actors* who may not be the primary political competitors, but may have significant influence on the dynamics of the struggle,
- *Military institutions* of the state and paramilitary organizations that provide armed power to enforce policy, threaten, or destroy human and physical resources.
- *Regional and International actors and influences* that take "sides" in the power competition
- *Economic systems*, both legitimate and illegitimate (black) that provide financial power to political actors and their clients,

The model of power actors and relationships is at the core of the COMPOEX simulation, providing the major abstract dynamic within a virtual world of economic, material services, media and sources of information exchange, physical violence (military, paramilitary and insurgence), and infrastructure. Power struggle behavior is included across the many composed models within the simulation environment. The COMPOEX approach to abstraction is based on two major partitions of the model:

- Power Influence Network - Competing actors for power are represented in agent-based models where autonomous agents compete for power, represented as the abstract capital commodity in four dimensions (Political, social, economic and armed military). This network represents all human decision-making, influence and action. The operation of the agent-based actor simulation is described in more detail in Taylor et. al. [9]

- Virtual World – the context within which the actors compete (or cooperate) for power is represented by a set of interconnected process models, implemented by a variety of modeling paradigms (e.g. systems dynamics, discrete time models, Bayesian networks, etc.). These models may represent aggregate human behavior (e.g. aggregate economics, production, large-scale population behavior), but do not represent the core competition for political power.

The structure of the composed power network and virtual world models (Figure 2-6) illustrates the interaction between the actor net and the virtual world. The agent-based actors that perform goal-directed behavior to compete in the power struggle; each actor behaves to achieve political, social, economic and armed power (capital) objectives relative to all other actors in the simulation.

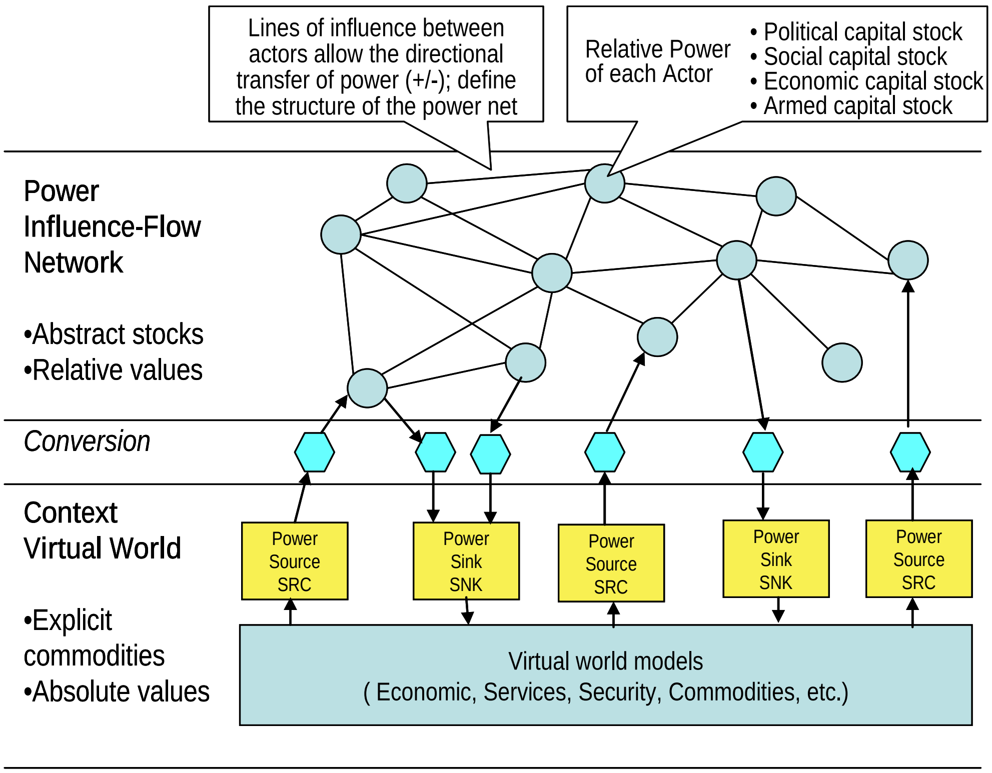


Figure 2-6 Power Structure Model Elements

The level of interaction between actors alone can become high, even in moderate models (Table 2-2) where analysts define the estimated lines of influence (directional power relations that allow the transfer of power) between actors. In addition, higher–order political power strategies will allow agents to add or delete these lines of influence (e.g. alliance-building and side-changing) to transfer power to achieve strategies. One representative COMPOEX power struggle model included over 1000 lines of influence.

Table 2-2 Representative Scale of Power Struggle Models

No. of Actors	Max. No. Lines of Influence[2]	Typical No. of Lines of Influence[3]	Representative Example Power Struggle
10	720	(10%) 72	Country top-level national political competition
40	12,480	(5%) 624	Urban area major urban political actors; above the district-level of power struggles
100	79,200	(2%) 1584	Country-wide multi-level resolution; national, Urban area, major institutions and regional actors.

[2] Each pair of actors may have 8 possible lines of influence (4 types: political, economic, social, armed x 2 directions). Therefore, a network of N actors may have a maximum of 8x N(N-1)=8(N^2-N) lines of influence.

[3] Presume a "typical" number of links is only a critical fraction of the maximum number; the percent is indicated in the cell with each value.

When actors represent broad population segments, they are supported by population segment models that provides refined estimates of the response of populations to the local PMESII conditions (e.g. economy, infrastructure services, etc.) and the media environment (e.g. the tone of the media relative to support for or against the current government). The population models must consider the potential effect of cognitive dissonance between what the segments experience (e.g. poor economy and high-levels of crime, corruption and violence) and what they hear (e.g. messages that promise improved employment and security).

2.3 The Structure of an Example COMPOEX Model

A representative COMPOEX model is a country model with focus on a major urban area evaluated in July 2006 to assess the dynamics of political power struggles and emerging insurgency in the context of reconstruction-stabilization in the volatile urban area. The key counterinsurgency (COIN) behavior is included within the simulation - distributed across the many composed models within the simulation environment. Unlike other dedicated models that focus on insurgency alone, the COMPOEX simulation modeled the larger PMESII operating environment with COIN as a major element of behavior that spreads the influence of insurgent behavior across the over-100 models that represent 9 of the urban area's districts.

In terms of the COMPOEX Library of models, one would not expect a single "model of the insurgency" to plug on the COMPOEX backplane; rather, the user will assemble a set of models and relationships to represent the actors, processes and relationships that make up insurgent behavior within a particular PMESII environment modeled.

The major component models that are affected by insurgent-COIN dynamics within the model can be identified to provide a high-level view of the major actors, processes and influences within the simulation (Figure 2-7); it is important to recognize that effects of the insurgency-COIN conflict extend beyond these models to other models throughout the simulation. These model elements follow the structure of Lynn's COIN model that emphasizes the competition between the government and insurgent forces for the acceptance, legitimacy and support of the civil population.[10]

Characteristics of the models shown in the figure include the following agent-based actors that perform goal-directed behavior to compete in a power struggle; each actor behaves to achieve political, social, economic and armed power (capital) objectives relative to all other actors in the simulation:

- National and City governments, relevant political institutions and the national security forces that oppose the insurgency. These actors seek to improve security, stability and services.
- Insurgency forces and other relevant combatant forces (e.g. militias, other organizations).
- Civilian population, (by district); these populations are directly affected by the state of security, services (EP, POL, Food, Human services), and the economy. Those factors influence their perception of, attitude toward, and support for the legitimate government.

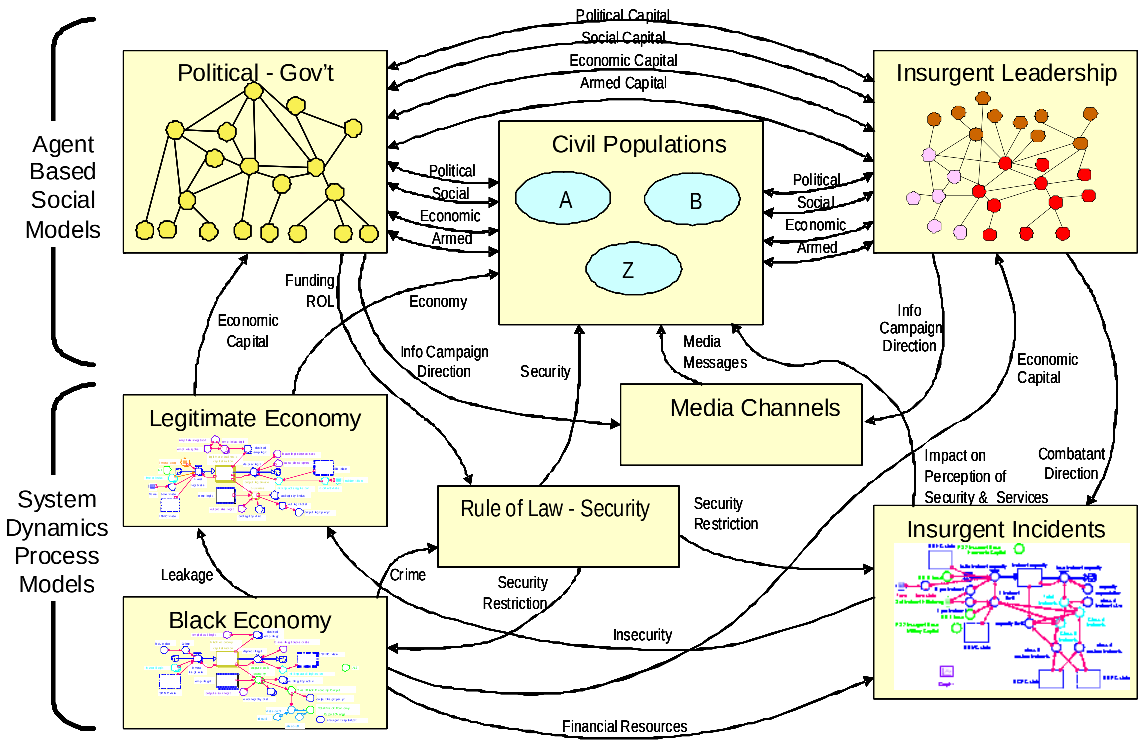


Figure 2-7 –Major elements of a COMPOEX Model of Counterinsurgency (COIN) Behavior

As distinguished in the figure, the following process models represent systems of systems that interact with the actors by systems dynamics models:

- Legitimate (white) and illegitimate (black) meso-economic models that compete for the civilian labor force and seek equilibrium at levels of production and consumption across multiple market segments.
- Media process model represents the flow of media messages across channels to the civil population target audiences. Information operations campaigns represent the types and intensities of messages from both sides to targeted actors and the efforts to saturate, disrupt or close media channels.
- Rule of Law model that represents the funding and maintenance of security force training-operations, justice systems and imprisonment. The model provides a level of security, integrity (anti-corruption) and legality (legal process) that affects the effectiveness of public and private activity.
- An incident generation process model represented the dynamics of insurgent recruiting, financing and support and the ability to generate violent incidents as directed by the insurgent leadership.
- Physical infrastructure models distribute electrical Power (EP) petroleum, oil, and lubricants (POL), sanitation (clean-waste water), and other services to civil populations and industry.

2.5 Achieving Confidence in the Validity of COMPOEX Models

George Box famously noted that "all models are wrong; some are useful."[11] This statement is true for the tacit mental models of experts, the conceptual models they create and explicitly represent in narrative and in qualitative forms, as well as for the quantitative forms of computational models implemented in COMPOEX. A major benefit of COMPOEX models is that they are *explicitly represented* and their dynamics can be compared to the dynamics of the real world to determine just how faithfully they represent an aspect of reality, as experienced by subject matter experts, or measured by careful observations. Unlike mental models, these models can be openly shared and tested, the degree to which they are wrong can be quantified, and they can be refined in a way that their collaborating users (analysts and planners) are learning about the underlying systems all the while.

Nevertheless, among the greatest challenges to approaches that attempt to faithfully represent the dynamics of complex operations is the necessity to develop confidence in the validity of the model – the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended uses of the model or simulation.[12] We distinguish five general categories of models and the corresponding methods to assess and refine the validity of the models (Table 2-3). Notice the distinction between the traditional validation process models of physical systems (Type 1) and the process for more soft and fluid social systems (Type 2).[13] The Type 2 validation process addresses the more difficult task of qualifying the representation of the power structure models that are characterized by soft attributes that are difficult to quantify (e.g. measures of social cohesion) and attributes that are dynamic (e.g. an actor's relative priorities among multiple goals). Unlike physical models that benefit from the unchangeable

Table 2-3 Categories of Models and Corresponding Approaches to Validation

Category Of Models and Simulated Variables	Example Quantitative Parameters in Simulation	Methodology for acquiring data and sources used	VV&A Methodology for determining fidelity and validity of simulated behavior
1. Certain physical measurements	- e.g. EP substation output (Megawatts), POL Pipeline flows and Oil production (Mbbls/day)	Direct measurement Infer by analysis from physical sensing via reconnaissance and surveillance	Type 1 Validation 1. Validate source data 2. Validate Model Reference Behavior 3. Validate model behavior when integrated into the MRM 4. Validate MRM overall behavior in ref environment – if appropriate accredit
2. Less certain, inferred physical measurements of stochastic variables	e.g. Inferred traffic activity based on no. of cars on highway estimated from MTI observations		
3. Measurable but not physical quantities	Economic estimates of commerce based on inferential data	Sampled data and inference; exploit third party data sets	Type 1 and/or Type 2
4.Inferred sociometric data on political-social groups	Structure of social groups, leaders, roles , goals and relative influence	Published reporting Pol-soc subject matter expert estimates	Type 2 Validation *In Situ* 1. Domain Subject matter expert (SME) review of model theory, structure (e.g. networks) 2. Domain SME review of behavior of model over range of situations 3. Area SME review of integrated MRM over range of situations
5. Political-Social Culturally relevant cognitive and emotive properties	Degree of social cohesion between two groups, or the political capital of a leader, or the leadership ability of an institution, etc.	Pol-soc subject matter experts	

nature of physical laws, power structures remain in flux – validation must be performed *continually* and *in situ*. A model of a terrorist power network believed to have a high degree of validity this month may be entirely invalid next month. Referring to the challenges of validating such models, the National Research Council recently noted, "There are many open questions about the analytical basis for such complex models, and validation is still more of an art than a science."[14] The Type 2 process applies two complementary processes: 1) verification that the *general* behavior of the model is consistent with a theory or understanding of phenomena or causality (e.g. a theory of leadership decision-making, or of population behavior), and 2) verification that the *specific* of model output is consistent with observed real world behavior. The first process can be performed by SME's *a priori*, but the second process must be performed *in situ* by the analysis team – and the model must be refined to adapt to the changing environment. Referring to the challenging task of increasing the confidence in such models, particularly integrated models at multiple resolutions as implemented in COMPOEX, Bigelow and Davis have asserted,

> "We believe that when working within this troubled but common domain, it is particularly important for two criteria to be met in assessing a model (and its associated data): The model should be *comprehensible* and *explainable*, often in a way conducive to explaining its workings with a credible and suitable "story."; The model and its data should deal effectively with uncertainty, possibly *massive uncertainty*.[15]

3. Concept of Operations

The COMPOEX Concept of Operations (CONOP) applies the toolset to first, perform systems-of-systems analysis of a situation, followed by model building and integration, and then campaign planning and effects exploration (Figure 3-1). These four steps and the tools applied are summarized:

1. Systems of Systems Analysis – SOSA analysts use the ConflictSpace tools to build conceptual models of PMESII systems based on information scanned from multiple sources, and link the models to source data. ConflictSpace includes Oculus tools that enable rapid scanning of source datasets (e.g. SIPRNET, classified databases, etc.), collection of free-form relevant data, and linking to graphical conceptual models. The conceptual models include network diagrams that link the major actors and PMESII systems, with hyperlinks to raw data sources.

2. Model Building – The conceptual models are translated to computational component models by either: 1) tailoring generic models of PMESII systems in the library of existing model, or, 2) constructing new models using a variety of model-building tools, including:
   - Soar Technology Power Structure Toolkit (PSTK) that allows drag-and-drop construction of agent-based models by graphically drawing power networks of actors, their lines of influence (pol-soc-econ-military), and agent goals to compete for power.
   - VensSim ™ or iThink™ commercial tools may be used to construct system dynamic models.
   - Netica™ commercial tool to construct Bayesian network models.
   - Distribution Network tool developed by BAE Systems to construct network topologies and assign costs for a linear programming simulation of distribution supply-demand between systems dynamics models of producers and consumers.

   These component models are composed into a large-scale (country or regional-level) multiple-resolution model (MRM) of the area of interest on the BAE Systems-developed

COMPOEX backplane using a model editor tool that creates model linkages (directly linked variables and functions of multiple variables) from model outputs to model inputs.

3. Campaign Planning – Planners enter candidate plans by entering discrete actions (e.g. invest $1.5M/week for 8 weeks in construction in a particular province) in a standard synchronization matrix format and run the MRM simulation to review the interacting effects of multiple, coordinated Diplomatic, Information, Military and Economic (DIME) actions. The COMPOEX backplane system schedules the actions to be applied across all models.

4. Effects Exploration – The MRM runs on the Option Exploration Tool simulation that allows rapid plug and integration of diverse models. A typical COMPOEX simulation can include a few hundred models and produce results of a candidate plan within 2 minutes. Visualization tools allow users to compose custom visualizations of the effects of campaign plans – typically over a 2 to 3-year period – to explore the dynamics of physical (infrastructure, military) and non-physical (political-social-economic) systems.

We can illustrate the "Plan campaign and explore effects" workflow (CONOP Figure 3-1 upper right) by following a single thread (Figure 3-2) from mission analysis to delivery of a campaign plan package. The thread is conducted by planning teams (typically a team of 3-5 planners per line of effort – e.g. governance , economy, security, strategic communications, etc.) Because

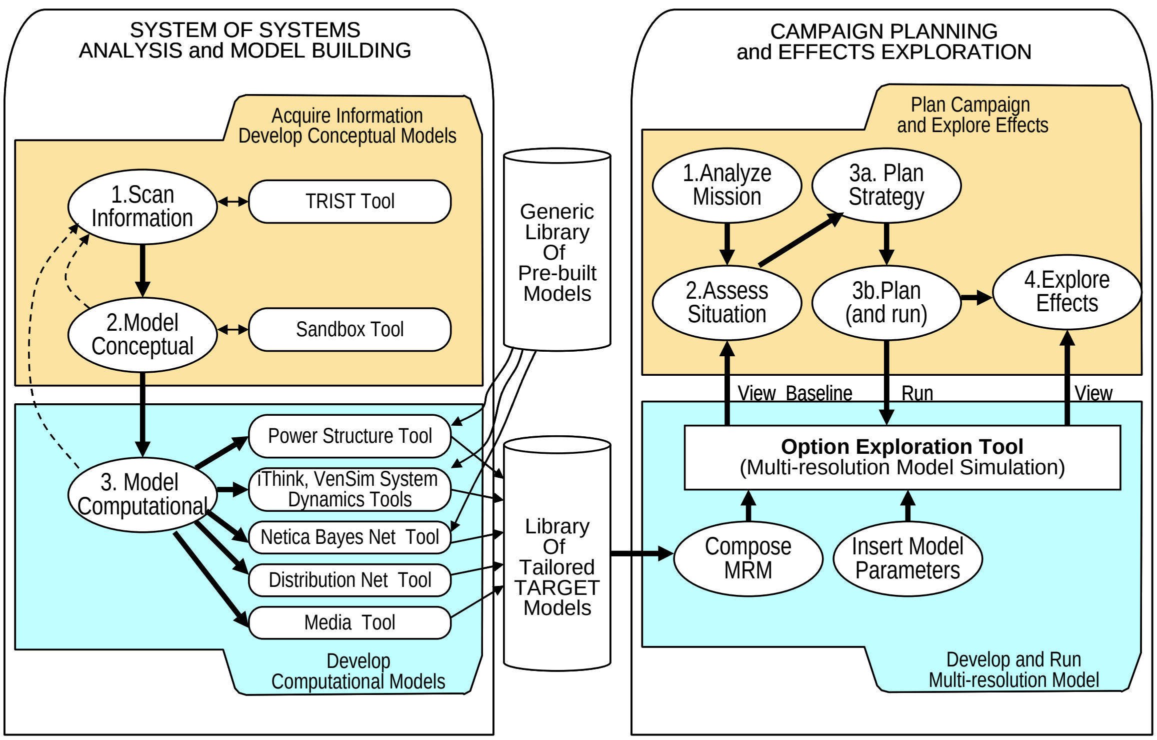


Figure 3-1 – COMPOEX Concept of Operations (CONOP) – Includes four steps (above): 1) SOSA analysts scan information sources to construct conceptual models of PMESII systems, then 2) Analysts use modeling tools to construct computational models of the PMESII system components, 3) The component models are integrated into a composite Multi-resolution Model, and 4) Planners develop campaign plans that can be run on the MRM to simulate interaction across PMESII systems to assess the effects of candidate campaigns.

Plan Campaign and Explore Effects Workflow
(Following the flow in upper right panel of the CONOP)

1. Analyze Mission: The narrative Commander's Intent is analyzed; the Lines of Effort and selected effects (high-level objectives) are identified; resources, constraints and restraints are explicitly identified and traced to the Intent.

2. Assess Situation: For each effect, the structure and projected behavior of the situation (PMESII systems) are explored by simulation of the baseline model to understand the dynamics of the current situation and the modeled PMESII systems interactions. Analysts identify the critical properties of *structure* (e.g. political power structure, military relationships, and terrorist organization relations) and *dynamics* of the systems (e.g. sensitivity of population groups to security and economy, dependence of warlords on illicit trade, etc.)

3a. Plan Strategy: Analysts and planners focus on specific targets of potential action, exploring relationships and power lines of influence (links) and capabilities of key systems entities (nodes) to conceive potential approaches to achieve desired detail effects that will achieve the high-level effects and endstates identified for the mission.

3b. Plan Campaign Actions: Planning teams (e.g. governance team, economy, security, reconstruction, etc.) develop candidate plans to achieve desired effects. Each team creates a plan fragment, scheduling specific actions, identifying dependencies and resources in a standard synchronization matrix form. (Independent plan components are first developed independently and then combined into the campaign plan to observe combined effects.)

4 Explore Effects: The planner reviews the effects (both intentional and unintentional) and the interactions between systems and overall behavior; critical effects and nodes are identified, and explanations of why the models produce these effects are revealed. Effects are enumerated and reviewed – and plan components are refined to counter undesired effects.

5. Prepare and Brief Planning Package: Once the plan is refined to achieve desired effects, within resource and other constraints and restraints, the plan package is prepared from the tool – illustrating effects sensitivities, undesired effect risks, and the overall behavior of PMESII systems to the campaign plan. If appropriate the simulation can be used within the brief to senior leaders to illustrate dynamics and answer "what-if" questions.

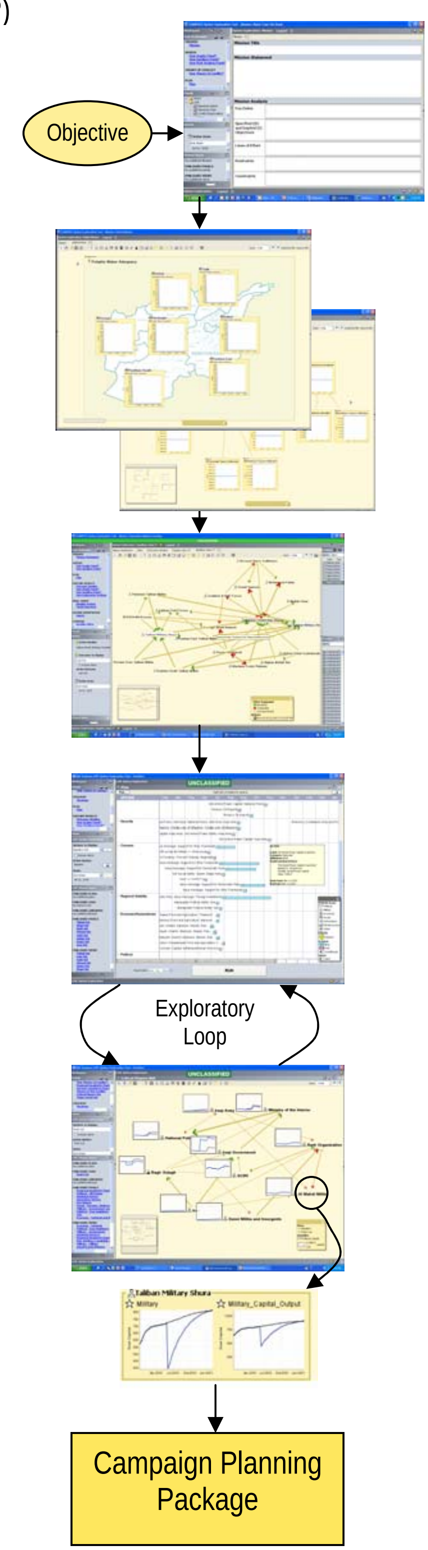


Figure 3-2 Typical Workflow Thread to Develop, Explore and Prepare a Campaign Plan

the COMPOEX tools operate on a client-server architecture, the teams develop independent plan components for each LOE on multiple clients (laptop computers networked to the COMPOEX server) while exploring effects concurrently on the simulation server. When each LOE has developed candidate plan components, all LOE components are integrated into a full campaign and simulated to explore the dynamics and effects of the actions of all LOE's.

5. Results of Experiments

The Campaign Planning and Effects Exploration capabilities have been evaluated in major Limited Objective Experiments in July 2006, and July 2007 demonstrating the ability of the tool suite to rapidly build comprehensive models of complex situations, and support intensive collaborative interagency campaign strategy and planning for complex operations. In both experiments, campaign planning was performed by planner teams led by senior interagency leaders (senior mentors at the level of experienced general officer, ambassador, and other DoD and Non-DoD agency representatives). Significant results derived by independent quantitative analysis of these experiments included:

- Planning Depth – Teams using the COMPOEX tools in the 2006 LOE were able to consistently produce plans that included the assessment of between 10 and 20 times more effects (desired and undesired, expected and unexpected) than those considered by planning teams without tools. The number of effects developed in the plans was considered a representative measure of the depth of analysis conducted by planners because they considered over an order of magnitude more results of planning actions.
- Shared Interagency Understanding – The use of the COMPOEX tools in the 2007 July LOE by 15 military and civilian planners showed that the incremental improvement in understanding for both the military and civilian personnel tracked over time, showing that their shared understanding is also improving over time.[16]
- Tool Acclimation - Patterns of coordination among the participants with COMPOEX showed that reliance on tool support personnel declined over time suggesting that participants were able to learn and increase their proficiency with the COMPOEX tools within two weeks.

6. Summary

DARPA has developed, evaluated and refined the COMPOEX analysis-planning methodology and suite of analysis, planning and simulation tools that allow military and interagency planners to develop and explore effects-based plans in complex operational environments. Experiments have quantified the decision-making improvements of these technologies in Joint Limited Objective Experiments. The methods and tools have demonstrated the ability to provide significantly deeper understanding of the interaction and dynamics of PMESII systems and to enable planning teams to develop more robust campaign-level plans. The COMPOEX tool set and its associated analysis and planning methodology is now being prepared for transition to operational application by military and interagency users.

COMPOEX is a program of the Defense Advanced Projects Agency (DARPA). This paper describes the results of work performed by BAE Systems under contract W15P7T-05-C-P032.

7. Endnotes

[1] Complex contingency operations are those large-scale peace operations (or elements thereof) conducted by a combination of military forces and nonmilitary organizations that involve one or more of the elements of peace operations that include one or more elements of other types of operations such as foreign humanitarian assistance, nation assistance, support to insurgency, or support to counterinsurgency. Joint Publication1-02, 17 October 2007); See also, "Managing Complex Contingency Operations," Presidential Decision Directive-56 (PDD/NSC-56), the White House, Washington, D.C., 17 May 1997.

[2] Collins, Joseph J., Planning Lessons from Afghanistan and Iraq, Joint Force Quarterly, Issue 41, 2d quarter 2006.

[3] Quadrennial Defense Review, Office of the Secretary of Defense, 6 February 2006, p.60.

[4] JP-3.0 Joint Operations, Joint Chiefs of Staff, 17 Sept. 2006, p. II-22.

[5] JP-5 Joint Operational Planning, 26 December, 2006, Section 9 – Intelligence Preparation of the Operational Environment (p. III-31)

[6] Defense Modeling, Simulation, and Analysis: Meeting the Challenge, Committee on Modeling and Simulation for Defense Transformation, National Research Council, 2006.

[7] The terms conflict, strategic game, contest, or competition are other terms used in the literature to represent the power struggle.

[8] Covey, Jock; Michael Dziedzic, and Leonard Hawley (eds.) *The Quest for Viable Peace: International Intervention and Strategies for Conflict Transformation, Washington DC*: U.S. Institute of Peace Press, 2005; the model described in figure 2.3-1 is based on Chapter 8; see figures 8.1, 8.2 and 8.3.

[9] Taylor, Glenn, Bechtel, Robert, Morgan, Geoffrey and Waltz, Ed, "A Framework for Modeling Social Power Structures", Proc. of Conference of the North American Association for Computational Social and Organizational Sciences, June 22-23, 2006.

[10] Lynn, John A., "Patterns of insurgency and counterinsurgency", *Military Review*, July-August, 2005, pp. 22-27.

[11] Box, G.E.P., "Robustness in the strategy of scientific model building", in *Robustness in Statistics,* R.L. Launer and G.N. Wilkinson, (eds.), New York: Academic Press, 1979.

[12] Validation is the process of determining the degree to which a model or simulation is an *accurate representation* of the real world from the perspective of the intended uses of the model or simulation. [DoD Directive 5000.59, "DoD Modeling and Simulation (M&S) Management," January 4, 1994.]

[13] For a description of Type 1 validation methods see, Averill M. Law, How to Build Valid and Credible Simulation models, *Proceedings of the 2005 Winter Simulation Conference, M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, eds.*

[14] *Defense Modeling, Simulation, and Analysis: Meeting the Challenge*, Committee on Modeling and Simulation for Defense Transformation, National Research Council, 2006, p. 22; furthermore, the Committee noted, "*How might one assess validity, even for limited purposes of exploration?* The committee is skeptical about the value of bureaucratic processes to assess validity, since they are expensive, time-consuming, and frequently reinforce conventional wisdom and standard databases even when the reality is massive uncertainty. Nonetheless, validity is an important matter." p. 31.

[15] Bigelow, James, and Paul K. Davis, *Implications for Model Validation of Multiresolution Modeling*. Santa Monica, Calif.: RAND, 2003, p. 16.

[16] Hansberger, J.T., Spain, R.D., Schreiber, C., & Johnson, M.T. (under review). A human-centered C2 assessment of model and simulation enhanced planning tools. Army Research Laboratory, to be published in DTIC in 2008.

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